Food and Package Engineering

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Scott A. Morris

WILEY-BLACKWELL
A John Wiley & Sons, Ltd., Publication

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Registered office: John Wiley & Sons Ltd, The Atrium, Southern Gate, Chichester, West Sussex,
PO19 8SQ, UK

Editorial offices: 2121 State Avenue, Ames, Iowa 50014-8300, USA
The Atrium, Southern Gate, Chichester, West Sussex, PO19 8SQ, UK
9600 Garsington Road, Oxford, OX4 2DQ, UK

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Library of Congress Cataloging-in-Publication Data

Morris, Scott A.
Food and package engineering / Scott A. Morris.
p. cm.
Includes bibliographical references and index.
ISBN 978-0-8138-1479-7 (hardcover : alk. paper) 1. Food–Packaging. 2. Food industry and trade.
I. Title.
TP374.M67 2011
664′.09–dc22

2010052428

A catalogue record for this book is available from the British Library.

This book is published in the following electronic formats: ePDF 9781119949770; Wiley Online Library 9781119949794; ePub 9781119949787

Set in 10/12 pt Times by Aptara® Inc., New Delhi, India

1 2011

Dedication

To my parents, Frances Stearns Morris and the late Dr. Allan J. Morris, and to my wife Kathleen and stepson Michael. Also, to my sister and brother-in-law, Pamela Morris-Carlson and Ross Carlson, as well as my nephews Grant and Pierce, who have all been eternally good hosts and have somehow managed to keep their general amusement reasonably well contained.

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Preface

Books that seek to cover broad expanses of knowledge are like kitchen appliances that promise to do dozens of different tasks. The truth is that they cannot do each job as well as a specialized implement, and this book is no exception. Each chapter subheading is an entire field of study, a career, and an industry unto itself, and to cover each topic comprehensively would deplete the world's trees (or its electrons). This book is intended to give a useful overview of the food processing and packaging industries, touching on important points and technical concepts, and unfortunately must omit a good amount of detail. Worse, when trying to describe an entire constellation of subjects that are connected together to a relatively common purpose, the end result is something like a map projection – a sphere flattened onto paper, with all the distortions that it implies, and then linearized into a sequence of words, distorting the picture still further. I can hope that the result informs and interests people enough to spend time re-expanding the content into a larger and more complete picture.

This particular book is the result of teaching introductory packaging and food engineering classes, often to students who do not have a deep mathematics background (or have not used it recently). It is intended to give a general framework for teaching such classes, and a reasonable amount of introductory material, since an utterly complete and unified text on these subjects would be both unmanageably large and would not leave room for individual interests.

Isaac Newton is credited with saying, "If I have seen further, it is by standing on the shoulders of giants" when writing to a rival scientist, the hunchbacked Robert Hooke, with whom he both competed and collaborated. That this was originally attributed to Bernard of Chartres in 1130, who was repeating a current sentiment, does not matter, because it reflects a fundamental truth – a broad perspective is only possible when you have the work of many others to refer to. I urge the reader to search for more information on the topics presented because this is a fast-changing field, but I would also hope that the framework presented will hold fast and provide a good navigational chart for finding one's way through the easily published fog of information that is often doubtful in its accuracy and objectivity.

Many hundreds of publications were reviewed during the writing of this book, but a complete bibliography has been intentionally omitted. The citations contained in each chapter's references section have been included because they should provide the reader with additional useful information or data sources, and as many of these as possible are available via the Internet. This brings up the inevitable problem of "link rot" – the changing or elimination of archival Internet material – and is the eternal bane of publishing links on paper. In as many cases as possible, searchable titles or headings have been provided so that the items may be found either under new headings or in archival websites such as www.archive.org that, as of this writing, maintains old postings.

Scott A. Morris
Urbana, Illinois

Acknowledgments

This book would not exist – for better or worse – without the persistent and very patient urging of several people: Mark Barrett of Wiley-Blackwell (now part of John Wiley & Sons), and Mary Ellen O'Shaughnessey of the University of Illinois, both of whom have alternately prodded and cheered over the very long time that this book was not being written, and with the addition of Susan Engelken, who has answered annoying questions and dealt with general nonsense over the last two years when it really was. Thank you. Credit should also go to the Hulme family who have provided a continuing respite from the flatlands and a safe harbor in several storms of different sorts.

I am also most grateful to:

Mr. Timothy Yost, who taught me, years ago, to never fear a blank page of paper when physical sheets of paper sat in mechanical typewriters. The jury is still out on whether the result was a good thing or not.

Mr. William Knapp, who demonstrated just how cool physics was. The fire department does not show up at my classes nearly so often these days, so I must be getting the hang of it.

Mrs. Linda Allen, who put up with a gaggle of pre–Silicon Valley punch-card nerds, just for the fun of it.

Dr. William D. O'Brian Jr. for taking on a moderately annoying new faculty member and intermittently encouraging and castigating him as the situations warranted.

The University of Illinois at Urbana-Champaign for sabbatical leave to begin this book in earnest during the 2008–2009 academic year.

The University of Illinois at Urbana-Champaign libraries' staff, and particularly the staff of the Grainger Engineering Library, for their general patience, assistance, and good humor.

Many of the helpful donors of images for the book.

And an endless array of smart, challenging examples of good scholarship and clear thinking given to me by my own teachers, friends, professors, mentors, students, and a few of my colleagues – you did your best. Anything good here is yours, the bad stuff and omissions are solely mine.

Chapter 1

Basic Elements of Food Processing and Packaging

The Packaging Cycle

Packaging is a globally integrated discipline: It draws on nearly every aspect of science, technology, business, social science, and engineering. For that reason, the greatest difficulty in teaching a subject that encompasses so many fields is trying to pull them all together into a coherent map to follow as the discussion proceeds. Because most students have encountered some kind of cyclic model, whether a metabolic cycle in biology, a water or nitrogen cycle in earth sciences, or the flow of materials in engineering, a "Packaging Cycle" was devised in 1993 as a roadmap for new Package Engineering classes at the University of Illinois. This has served well and will serve as a basic roadmap for the materials in this book. This is simply a materials' life cycle, tracing the flow of materials from raw resources to finished packaging, but it helps pull together concepts from many different sources and disciplines to contribute to the final packaged product. The cycle completes or terminates as the materials are either discarded or, in a closed cycle, reused in recycling and refilling operations.

It is also necessary to include subjects that relate to several of the "steps" in the packaging cycle if one is to have a good grasp of the interrelationship between the packaging materials, machinery, and the actual food products and materials that are contained and preserved within the package. To this end, the next chapter outlines many of the basic engineering concepts used in the book, and there are segments addressing the basics of food processing and food shelf life. The linking of concepts from many distinct disciplines in the sciences and engineering that come together in many food processing operations and facilities is an important part of understanding the relationships in food and package engineering.

Elements of the Packaging Cycle

Although the subsequent chapters in the book deal with these in more detail, a short description of each of the steps in the packaging cycle will help show how the circular reduction of a global system can be mapped out.

Raw Materials

These include raw inputs into the packaging materials stream such as metal ores, wood fiber, oil, and energy.

Food and Package Engineering, First Edition. Scott A. Morris.

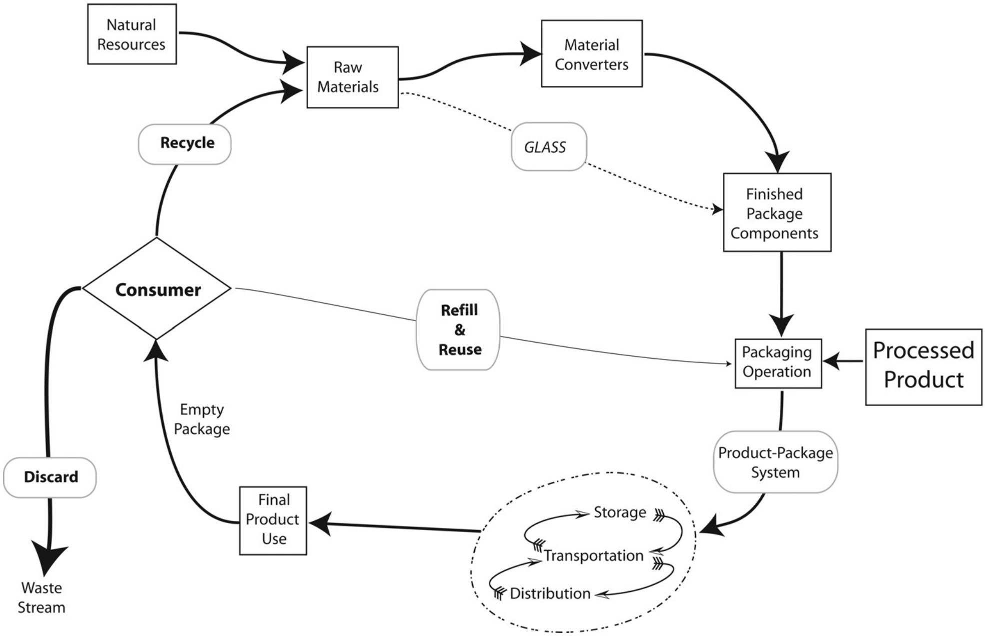


Figure 1.1. The Packaging Cycle

Primary and Secondary Materials Converters

Although the conversion processes are combined in the text, understanding the difference between primary and secondary converters can be useful in understanding materials' sourcing and production problems.

Primary Converters

These are the converters that will take raw materials and convert them into a recognizable single material such as plastic resin pellets, sheets of paper, or rolls of metal sheet.

Secondary Converters

Secondary converters are responsible for taking the materials produced by the primary converters and turning them into finished packages. At this point, the distinction blurs sometimes, because primary converters may be producing finished packages as part of their operation. The most visible example of this is glass manufacturing and molding that is done directly from raw materials to finished containers, primarily because of the enormous capital outlay for production systems and the energy-intensive nature of the material – once molten, it makes little sense to let it cool until fabrication is finished.

Processing, Filling, and Sealing Operations

These operations are where the product is processed, after which the processed product and the package come together to form an interactive system that must remain safe and saleable until used by the consumer. Unfortunately, many people (and more than a few companies) consider this to be the beginning and end of the involvement between packaging and food processing, and may not fully consider the environmental input that the package-product system must endure before it is finally used.

Distribution and Transportation

Distribution, inventory storage and management, and transportation modes and their related hazards are critical considerations in an industrial food production system. They will become even more so as the world's economy continues to integrate, with food, consumer items, and all manner of goods being shipped from one corner of the globe to the other. For the packaging cycle to be properly managed for a product, it is essential to be somewhat conversant with these issues, and particularly the economics and informatics that are involved in managing such huge, dynamic systems.

Final Product Use

Final use is where the package-product system is finally evaluated – the quality of the product and the package's utility may determine the physical and financial success of the product. An inconvenient, dangerous, or spoiled product (or one with insufficient information attached) has little chance of fulfilling the customers' needs and may be dangerous to the consumer, the environment, or both, whereas a splendid product that is economically unfeasible may satisfy the customer but leave the producer somewhat less pleased.

Recycle, Reuse, Refill, or Reduce

This decision, which is usually made by the consumer is also influenced by regulations and the existing market for recycled material, and by whether or not the infrastructure exists to return the empty package into use, either as a raw material or as a refillable container. In the absence of these choices, the package becomes part of the burden on landfills and incinerators that are scarce and expensive in some areas, due to public reaction, regulatory requirements, and the necessity of extensive environmental engineering. Because of the multiple economic incentives in materials use reduction, and better engineering practices, source-reduction strategies have become more common in the design of any number of packaged consumer items and have flattened the per-capita municipal solid waste production in many industrialized countries.

Food Processing

Although this text has a large packaging component, food processing plays an integral part in understanding the relationship of food production and packaging to the overall scope of operations typically seen in post-harvest food production. This text covers many of the engineering fundamentals necessary for the non-engineer, but also has some overviews of the product-processing requirements and shelf-life considerations that may be of interest.

Unlike the packaging material cycle, however, the processing segment is an incomplete cycle because much of it (e.g., the production, harvesting, and storage of agricultural commodities) is well beyond the scope of this book. What is hopefully more useful is the development of

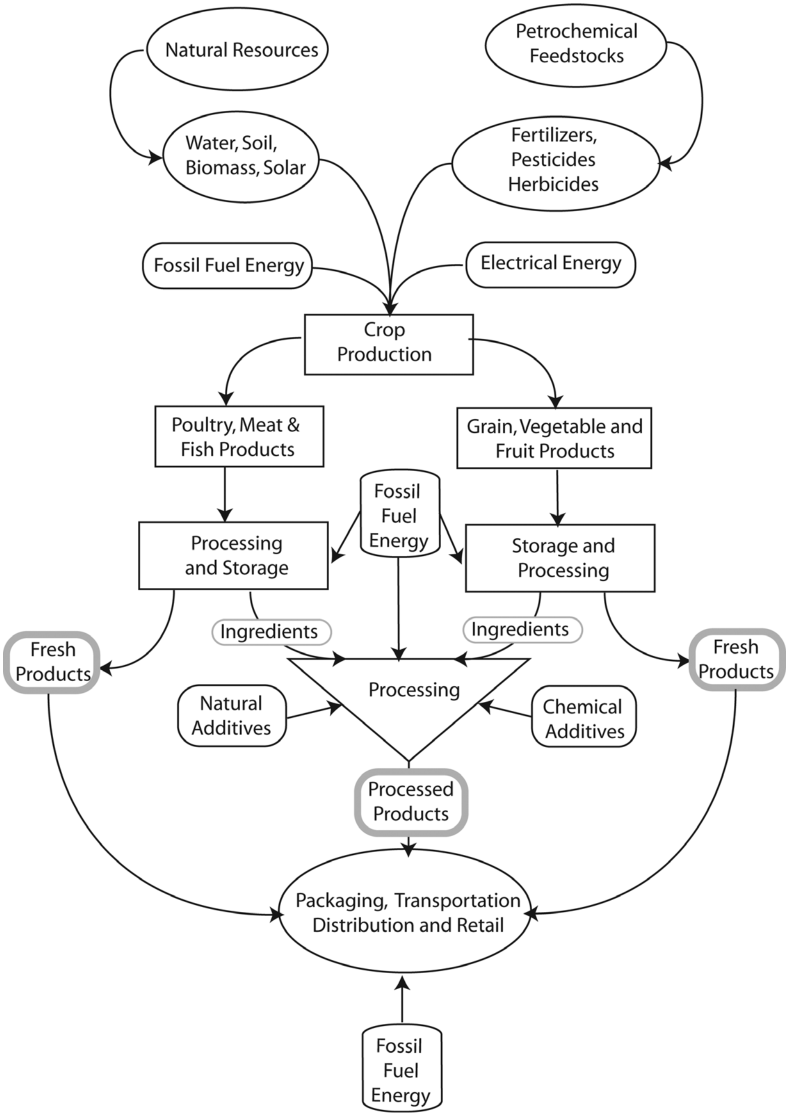


Figure 1.2. Agricultural Production Resource Flowchart

engineering concepts from first principles into basic, useful applications and methods that can provide either the starting point for more complex analysis and design, or the starting point for applied work in a production facility that operated on ingredient-level processes.

The Information Cycle

As materials feed forward from raw materials to manufacturers to consumers (and often recycle back into raw materials), there is a counterflow of information back to retailers, distributors,

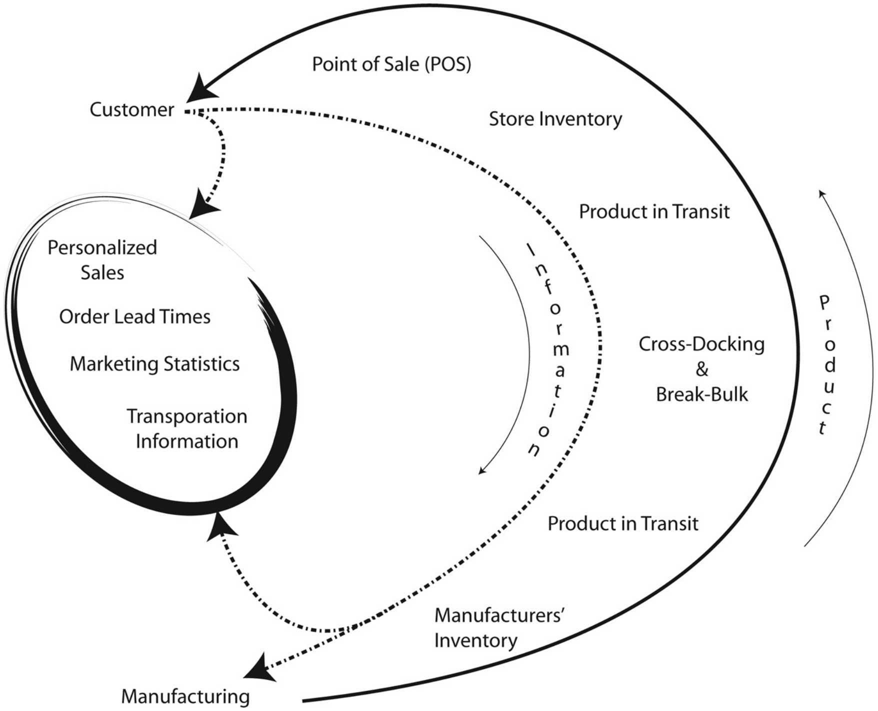


Figure 1.3. The Information Cycle

and manufacturers aided by the development of machine-readable codes that allow automatic tracking of items through the system. This information by itself gives a timely picture of inventory on hand, rates of sale, seasonality, local and regional consumption patterns, and a wealth of other distribution and economic data constantly used as feedback to fine-tune manufacturing, distribution, and retail systems. When integrated with engineering data, this information can also result in improved performance in processing systems and better product safety and shelf life.

In combination with other data taken from records associated with customers, a very accurate demographic picture can be created, which in turn affects marketing campaigns and promotional items advertised in particular markets, and will often directly affect the product mix that a consumer products company will field.

Economics, Marketing, and Packaging

The economics of the food industry may be unfamiliar to people entering the field and occasionally to those people working in the packaging industry that have an interest in entering the food industry. At its heart, the food industry is a marketing-driven, price-conscious converter of raw food materials into finished consumer products that are usually integrated with a large-scale marketing campaign. From this, it is important to remember that the marketing and salesmanship of the products may take precedence over many of the non-safety-related technical improvements in both food product technologies and in package design and manufacture. Much of the food packaging industry's "research" is the development of products to challenge a competitor in the marketplace, expand a successful existing product line, or adopt a process developed by a competing company; reverse-engineering (or "deformulation") of competitors' offerings is a common feature of product development. Thus, the industry has often been very reluctant to consider new production technologies and designs until they are proven, often by a competitor or by a different industry that processes similar materials – for instance, the pet food industry is a primary example of an industry that has been viewed as a prototype arena for the testing of new technologies for human food products.

The wait-and-see approach to investment and adoption of new technologies has led to the food industry – and, by extension, the food packaging industry – being very slow in adopting new technologies in spite of the fact that these may save enormous amounts of money in the long term and may provide more utility and better-quality products to the consumer. For example, retort pouches, which were originally developed in the late 1950s and early 1960s for military applications, are only now becoming available with a significant market presence in a few products after first being proven in pet food sales, in spite of the fact that they offer better product quality and require less energy to construct and process.

Unfortunately, this carries over into research institutions as well, where the nature of scientific publications in food- and packaging-related fields, although prolific in number, have remained remarkably static over the last 50 years, particularly when compared to other fields of life sciences and engineering. As a result, the packaging and food engineers searching for an advanced toolkit to achieve better results and analysis may find themselves frustrated by a lack of applicable research and tools unless they look to other fields first. One of the aims of this book is to introduce some of the advanced tools that have been used for many years in other fields of engineering and that can provide accurate, efficient analysis for design procedures and processes that for many years have been done on a "try it and see" basis.

In distinct contrast to technology developments, items that add marketing appeal have seen extraordinary involvement, from the adaptation of high-speed microembossing processes to produce surface holographic film for consumer food packages, to the test-marketing of implanted circuitry in packages to give voice messages to consumers. Given the extraordinarily competitive nature of food marketing, any feature that can be proven to make a consumer product stand out from a very similar crowd, and thus increase revenues, is likely to be embraced quickly and enthusiastically. In the best of circumstances, a combination of marketing appeal and technical improvement can be combined into product improvements or features that will increase customer satisfaction, expand product sales, and offset any additional cost.

Shortened Product Development Cycles

The increasing volatility of the food marketplace and the changeable and often contradictory nature of marketing-driven nutrition fads have caused the development times for companies to shrink, which has the secondary consequence of reduced time for product shelf-life testing that will be discussed in Chapter 7. Additionally, product development trends have shifted to "concurrent development" methods, where prototype product designers, suppliers, logistics, manufacturing, packaging, and marketing operations are involved early in the process to reduce the amount of repetition involved in refining and changing the system for the final products' production. In traditional, "linear" design models, new prototypes are fully developed and then passed off to manufacturing departments that then develop the means to mass-produce, package, and deliver the product. The "assembly line" nature of this development model means that any changes to the final product requires backtracking completely to the design stage and then downward again, and can lead to enormous delays and lost revenue and market share.

Ideally, a concurrent development model would allow all of these changes to occur simultaneously with product, production, supplier, and distribution input at all stages of the development process. If this goes well, the time wasted on internal procedural protocol can be reduced enormously, and bringing new faces to the table in the central creative process can allow new opportunities to be discovered as well as imparting a good degree of cross-functional understanding and cooperation. A difficulty may arise in that this kind of philosophical change may require a number of internal changes in corporate structure to reduce the "silo mentality" in a particular operation. Operations that are internally territorial and competitive may not be suited for the lateral integration of functions, but some degree of concurrence can usually be achieved.

In addition, ingredient suppliers, packaging materials and component suppliers, and contract packaging operations are increasingly providing ancillary functions that were once part of central research groups, and whole product lines are being assimilated wholesale from start-up companies in a manner similar to the computer software industry. This basic shift in the product development model allows an already risk-averse industry to pick and choose from products that have shown some degree of market success and adaptability, but brings with it the problems of scaling up production from a usually small single production facility to larger, multiple manufacturing operations. For this reason, concept-to-production times are much longer for large companies (as long as 36 months) than for small companies that typically market new concepts within 12 months of concept creation and are similarly responsive in terms of product line extensions and adapting to market changes. Therefore, the advantage of more flexible and responsive manufacturing capacity is the ability to adapt more fully to both rate and type of customer demand, which can allow an increase in market share and may begin to drive product trends if successful enough. To stay responsive to customer needs, methods to shorten concept-to-production times are constantly being sought both in terms of technical tools and in corporate management models.

Cost Analysis – The Bottom Line

Often the question comes down to "the bottom line," and without diverging into a general course on accounting, the bottom line that most people can relate to is simply:

Income − Expenditures = The Bottom Line.

More technically, the bottom line is literally that – the last line on the balance sheet – as simplistically illustrated in Table 1.1.

As can be seen, the Total Assets and the Total Liabilities and Equity must balance on the bottom line, thus increasing the bottom line implies a corresponding increase in the overall financial scale of the company, rather than a simple increase in profitability.

Packaging can affect the bottom line in several ways, and unfortunately the most common approach to increasing the bottom line is to look for costs reduction at the production level, where many of the packaging function decisions take place, without considering the effect on the entire package-product system and the larger product marketing scenario. This can have the final effect of producing substandard products or causing system failure at some point in the life cycle and sabotaging an otherwise successful product. What is often neglected is the consideration of the benefits that other plans of attack may have on the bottom line. This is often the result

Table 1.1. Example of a Corporate Balance Sheet

Morris Declining Assets Inc.
Balance Sheet ($000)

Current Assets			**Current Liabilities**		
Cash	300		Loans Payable	800	
Accounts Recievable	1850		Accounts Payable	1200	
Inventories	1500		Accrued Expenses	400	
			Dividends	600	
Total		**3650**			
			Total		**3000**
			Deferred Taxes		**500**
Investments		**800**	Long Term Debt		**3000**
Property Plant & Equipment			**Shareholder's Equity**		
Land	2000		Common Stock	1500	
Building	2000		Paid-In Capital	500	
Equipment	3000		Retained Earnings	2950	
Total		**7000**	**Total**		**4950**
Total Assets		**11450**	**Total Liabilities**		**11450**

of the "NOMLI" (Not On My Line Item) syndrome resulting from packaging operations being directly charged for the costs of their operations in corporate accounting methods, whereas any benefits that might accrue benefit other operations. The unsurprising results of this are that packaging operations seek to reduce costs as much as possible and may not consider the unintended consequences of customer dissatisfaction or market loss.

If the packaging function is considered at a sufficiently high decision-making level, there are a great number of things that can be done to increase the bottom line or otherwise free up resources within the existing financial structure, both in terms of increasing net income and reducing overall expenditures. Implementing these changes is usually a matter of collecting data about the actual consequences of actions, both good and bad, and understanding their effects on the overall financial well-being of a company.

Current Assets

Increasing sales and accounts receivable by increasing the sales income of a product can increase the assets side of the balance sheet. Achieving this may be as simple as using packaging innovation to promote increased overall market expansion, taking over an increased share of an existing market, or making inroads into an unconsidered market to which similar products have not been applied. Less obvious is the reduction of inventories on hand and their associated costs so that the liberated capital can be applied to other assets on the left side of the balance sheet, such as investments, machinery, or plant facilities – or payroll bonuses.

Inventory management has been lifted wholesale out of the dark ages by the advent of cheap computing and instant communication to the point where very little finished goods inventory is kept on hand in non-seasonal operations. Products are shipped almost immediately upon completion and are not accumulated for any significant period of time anywhere in the distribution chain. The net result of this has been to free the producers from both the "dead assets" of stored inventory and the carrying costs associated with them, thus allowing the emergence of flexible manufacturing as well. This will be considered from both the manufacturers' and the distributors' point of view in later chapters.

Property, Plant, and Equipment

As with inventory, reduced investment in property, plant, and equipment will result in an increased availability of resources elsewhere in the finances of the operation. Reducing the overall cost of an operation either by making the existing operation more efficient, producing more with existing facilities, producing the same product in fewer facilities by extending its shelf life (and therefore increasing its shipping radius, which may reduce the number of separate facilities needed) – and combining separated operations to reduce overall plant expenditures are several ways in which the resources tied up in these long-term asset investments may be extended.

Current Liabilities

Reducing liabilities in the form of reduced costs, investments, and other items that absorb resources is always an attractive strategy. This drives items that are seen as reducible costs such as ingredients, processing, and packaging to be managed as cost-efficiently as possible, consistent with product quality goals. Unfortunately, many of these decisions are made at the levels that leave the operations personnel struggling to maintain production, whether by substituting a cheaper ingredient or material or neglecting a small part of the item's quality, such as an "easy open" feature that becomes ineffective.

Stockholder Equity

Freeing capital from other sources, whether from more efficient production, reduction of liability, or higher sales, can result in an increase of stockholder equity – which ultimately benefits large companies and their shareholders either by providing an incentive for higher stock prices or paying out direct benefits.

Fundamental Packaging Functions

Once the necessary systems and technology are in hand, the basic considerations for package designs must be considered. Although it may be an oversimplification, a good representative list that describes the basic packaging functions is "Protection, Communication, Utilization, and Integration." There are many other considerations, but these four items can provide a good starting checklist for a new package design, or for the consideration of design changes.

Protection

Protection of a product from environmental influences is the most common function that people think of when they consider packaging. The most common type of protection is against contamination of a product by microbes, or protection against the loss of an important component (moisture, for instance) from the product. The other types of protection that a packaging system may provide are less often considered. For instance, protecting consumers from the dangerous contents of a package or protecting the public at large or the environment from the dangerous materials or devices in a package can be a crucial consideration.

A good example of packaging protecting consumers is the often-annoying child-resistant closure on household chemicals, particularly those that are stored under sinks and in areas easily accessible by relentlessly curious children. Although these devices are sometimes hard to open by adults, the number of fatal household poisonings of children from household chemicals and medicines dropped by an estimated 45% between 1974 and 1992 as a result of their use, with a similar drop in non-fatal medical emergencies [1], and from 1974 to 1981, the U.S. Consumer Product Safety Commission (CPSC) estimates of regulated products ingested by children under 5 years of age that prompted emergency room (ER) visits decreased from 48,000 (2.9/1,000 population under 5 years) to 34,000 (2.0/1,000) [2].

Finally, protection of the public and the environment from dangerous materials in a package is seldom considered, yet packaging plays an important role in getting everything from hair bleach and insecticide to nuclear fuel rods safely from manufacturer to its final users.

Communication

The communication role that packaging plays is also important and has become more so as packaging becomes more interactive and able to communicate with other devices using optical and electronic means, as well as communicating with people using printed words and images. Since packages are the “face” of the product that the consumer will see, usually while trying to decide which of several similar items to choose, the marketing impact of packaging has always been of the utmost importance, especially with consumer goods. Visiting a supermarket’s cereal aisle will give a vivid impression of the competition among products, as the gaudy front panels of the boxes vie for attention. Packaging must perform many other communication functions as well simple display dominance. Most products marketed for consumer sales must give an accurate listing of the contents, and for products such as foods, pharmaceuticals, and household items such as cleaners, the packaging must communicate preparation methods, ingredients lists, and proper (or improper) usage of the product. For items intended for more specialized uses, such as surgical implements, emergency equipment, or munitions, the packaging may be critical in selecting the correct items under dangerous or stressful conditions.

The communication function has expanded with the spread and increased capability of computing equipment in all sectors of the retail and distribution networks. The Universal Price Code (UPC), which was originally adopted in the United States in the 1970s was initially developed to allow faster and more accurate checkouts of consumer goods, particularly groceries. The data that is gathered at the point of sale (POS, sometimes called Point of Purchase, or POP) was immediately useful in helping stores manage inventory. As items were scanned at checkout, the level of inventory was appropriately adjusted, and this would allow orders to be placed in time for replenishment. This inventory tracking quickly spread to automated ordering and tracking systems, often for the entire network of stores in a particular chain, with similar networks in place for the manufacturers of goods. Orders can be placed directly with manufacturers on a just-in-time basis, tracked through the entire distribution chain, and arrive on a schedule that allows stores to operate with only the stock on their shelves as inventory. This cascading rise in efficiency allows an extraordinary reduction in inventory held in most sectors (the exception being seasonally produced food items), reducing costs and essentially eliminating the need for warehouses. Those have been replaced by *crossdocking operations*, described more fully in Chapter 9, that take in truckloads of items from a single manufacturer and redistribute them to trucks waiting to go to individual stores or regions for redistribution.

This dynamic distribution scenario ensures that the inventory is constantly moving from the time it leaves the manufacturer until it arrives on the store shelf. In addition to the information transmitted by the package, information gathered at the point of purchase from discount cards, credit cards, and debit cards allows large amounts of very accurate market data to be collected about individual consumer's spending habits. Amusingly, this has led to the occasional embarrassment when manufacturers send inappropriate offers, coupons, and birthday greetings.

Information technology has also been expanded by the development of non-optical information devices such as Radio Frequency Identification (RFID) chips that can be read at a distance without having to uncover a tag or label. These have found limited use on single units of consumer goods because of technical and economic limitations, but are beginning to be included in credit cards, key tags for identification and gas purchases, luggage tags at several airports in the United States, and on large shipments (palletload or shipping container) of products. As these devices increase in memory capacity and utility, the ideal of store checkout by simply walking through a scanner becomes closer to reality, as does the less visible ideal of easier and more accurate product tracking and identification.

Utilization

Packaging is often blamed for a high level of consumer frustration in gaining access to products, but nearly all products require some form of package to be useful, at least in the sense that consumers have come to accept them; many gain some benefit of utility from the package, and there is a broad range of products that could not exist without packaging. The marketplace is full of products that gain their market niche solely from the utility given by the package, from hand-pumped spray cleaners to aerosol cheese spread; most of these items would be much less useful and would be certainly be much less profitable, if they existed at all, without effective packaging. It would be hard to imagine having to store ketchup in some kind of storage tank in the kitchen rather than getting it from a bottle, and more complex items such as aerosol spray paint or asthma inhalers would be very difficult to use without portable, relatively inexpensive packages that replace large-scale spray equipment and medical nebulizers.

Integration

Integration is seldom considered when package designs are proposed – designers are often attempting to convey a sense of style, a marketing message, or to provide a utility function, but there are several types of integration that must be considered. The first of these, and often the most annoying to designers, is the integration into manufacturing systems. A beautiful and useful package that cannot be produced quickly and cheaply will be unlikely to find its way to market for most large-volume consumer items. This often leads to protracted debate between designers and manufacturing engineers, but integrated designs where manufacturing concerns are included early in the design process can help alleviate this.

The second is integration into a product line and its associated media presence – does the package design fit in well with similar items produced by the same company? The electronics and cosmetics industries have made this a substantial priority in design of both packages and often of the products themselves – looking at a store display of shampoo, fingernail polish, or toys will give a good idea of this. Food and consumer products companies, which are often conglomerates of brand lines that are acquired and divested on a nearly continuous basis, may rely on a simple small brand to indicate that their product comes from a larger corporate entity.

This type of integration aids in brand recognition, as well as in repeat purchases by consumers who like the parent company's line of products. This in turn is often influenced by the customers' perception of the products in relation to their particular lifestyle, as well as their own personal preferences, with the designers continuing to come up with increasingly creative packaging to distinguish themselves among a plethora of similar products.

A third type of integration involves the product's physical life cycle – does the package fit in with available materials and production resources, as well as disposal or recycling regulations requirements? This has driven the design of some types of packages as well as a large component of materials selection in many packaging systems. As recycling issues continue to be a large concern in disposal of municipal waste, the design of packages to comply with a multiplicity of regulations and requirements limits the choices of materials and structures and provides a challenge to the technical implementation of package design.

Engineering Design versus Trial and Error

The packaging industry is unique among high-speed, high-volume industries in that there is often very little theoretical consideration of the factors involved in design, particularly as it applies to food package design. Standardized containers such as plastic and glass containers, as well as aluminum and steel cans, may have some stress analysis done on them during the basic design phase, but the vast majority of food packaging, which may be assembled of a variety of stock components, is designed to be appealing to the marketing scheme underway at the moment and often is only incidentally structurally capable of surviving the distribution environment.

This lack of design allows for a very fast introduction time if the design works well, but if complications arise, it then requires many cycles of the "build a prototype and see if it works" philosophy, which consumes a great deal of time and effort (Figure 1.4). Unfortunately, there is

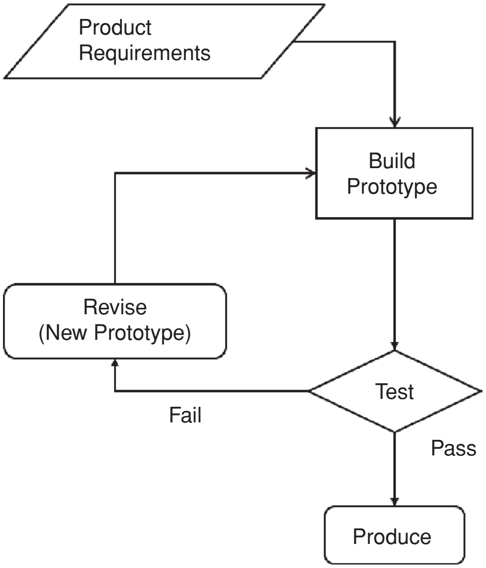


Figure 1.4. Trial-and-Error Design

a lack of specific design analysis tools for many parts of the industry, and there is also often a reluctance to use the ones that do exist for other industries, owing either to lack of experience with them, distrust of the results, or an aversion to investments that produce long-term savings. There is a severe need for both the use of analytical tools in the packaging industry and the understanding of their utility and results as a means of cost saving and efficiency improvement.

Most people, including those who actually work on a prototype-based design system, would hesitate to board an airliner that was developed by building a prototype, crashing it, examining the wreckage, making changes, and then building another prototype until the resulting guesswork finally flew. In fact, most people would not use many devices designed this way, from a car to a can opener, yet a lot of packaging development follows just this method. While shelf-life trials on food products are usually destructive, structural and physical development can be aided with the benefit of method developed (not surprisingly) for other industries.

Moore's Law, which roughly states that computing power doubles every year and a half, means that the cost and speed of computationally based modeling systems becomes ever cheaper. In fact, many of the limitations to the adaptation of these types of design systems are the result of poor software user interfaces that make them difficult and counterintuitive to use, and a poor managerial understanding of the results and benefits of the systems. If things go well with proper training and experience, product and package designers can do effective and even elegant predictive modeling as a design enhancement, as well as a means of shortcutting tedious preliminary trials.

As can be seen from Figure 1.5, the shortened feedback and model construction time in the design cycle system may offer an improvement over a prototype-based design scheme. Countering this is the reality that very often, packaging materials and structures are produced by secondary suppliers and are simply being comparatively evaluated. Even if produced "in house," the fabrication costs are so small and the tests so simple that it may be advantageous

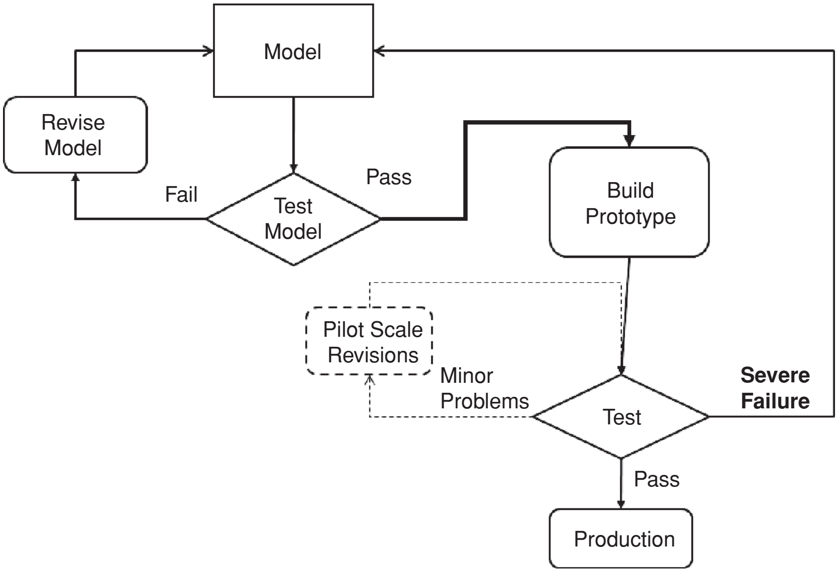


Figure 1.5. Modeling and Analysis Design

to simply continue with a prototype-based system. It may be difficult to find personnel trained in the tools and methods for evaluation and modeling, and the management of these types of operations may be very unfamiliar to an existing system.

The eventual consequences of not being adept in advanced design methods may eventually be that the operation will expand into products that require a higher degree of technical analysis, or that remaining competitive may demand these skills. The decision regarding the design method then is a matter of individual choice that depends on the product requirements, market size and complexity, and need for fast design turnaround. In addition, it may be possible to outsource many of the technical and design skills needed to create a good design cycle, though managing the flow and confidentiality of information can be challenging.

Finally, with a knowledge of the financial, marketing, scientific, and engineering processes that can be applied to better designs and implementation, whatever method and process is chosen, the design challenge is to be creative – developing a new product or package is an opportunity to learn from, rather than to copy, the accumulation of trial-and-error and guesswork of its predecessors and competition. Innovation requires managerial foresight and the dedication of necessary resources to take the risks implicit in change, and this may be the biggest challenge of all.

Additional Resources

1. National Academies Press, *Forging A Poison Prevention and Control System*, Washington, DC: The National Academies Press, 2004, p. 84. http://www.nap.edu/catalog.php?record_id=10971
2. Centers for Disease Control, "Perspectives in Disease Prevention and Health Promotion: Unintentional Poisoning Among Young Children – United States," *CDC Morbidity and Mortality Weekly* 32(9) (March 1983): 117–8. http://www.cdc.gov/mmwr/preview/mmwrhtml/00001263.htm

Chapter 2

Engineering Basics

The Fundamental Concepts of Engineering Analysis

While this text is built around the Packaging Cycle described in Chapter 1, it is necessary to include a section on the fundamental engineering concepts that lie behind the processes and analyses that this requires. Other chapters will refer back to this section as required, but it can be helpful to go through the concepts and calculations that follow in this chapter in order to understand how and why some of the subsequent processes and components operate and interact.

Many people outside of the field find engineering to be an inscrutable heap of equations that is more concerned with mathematical dexterity than with clarifying the nature of the relationship between abstract mathematical modeling and practical applications in the real world. As a result, students are often either completely discouraged or are left with little to do when it comes to the sorts of real problems they will face in their work environment.

This book approaches the concepts of engineering from a slightly different direction, based on experiences instructing students from non-engineering backgrounds on the underlying ideas of engineering, as well as how to learn and reason as many engineers do. To this end, the text attempts to cover basic engineering concepts in this chapter, with more complex and practical types of applications in food processing and packaging operations throughout the rest of the text.

Basics of Engineering

Engineering, which uses a combination of experiment, experience, mathematics, and science to provide working solutions to practical problems, has many of its roots in the belief that one can reason through the physical nature of the world and reduce it to a series of mathematical and physical models to answer the question “What will happen?” and more importantly “How much of it will happen?” These, then, are usually developed outward to find an appropriate quantitative solution to the situation.

With any system of basic engineering analysis, the underlying quantitative concepts – derived from the conservation of mass and energy – are usually simple, although very complex systems, models, and analyses are sometimes derived from it (Equation 2.1).

$$\text{“Stuff” In} - \text{“Stuff” Out} + \text{“Stuff” Generated} = \text{“Stuff” Retained} \tag{2.1}$$

Food and Package Engineering, First Edition. Scott A. Morris.

What quickly becomes apparent is that managing this arithmetic model is simply a matter of bookkeeping, and that using the materials, energy, moisture, chemical compound, work, money, or other quantity that goes into a system and that comes out of it at another point, the amount stored, the amount generated or destroyed can all be accounted for or at least estimated. Additionally, the concept of control volumes allows the choice of artificial boundaries within which one can apply this analysis.

Most simple analyses can be done either with empirical research or estimation models, and is often easily handled with a spreadsheet or hand calculator. Additionally, exchanges can be made, such as matter for heat energy and combustion by-products, and chemical admixtures for quantified final reaction products. Without this basic idea, students confronted with a series of simultaneous equations describing engineering equations often get lost in the arithmetic and never see the conceptual idea behind it, and are often hard-pressed to implement the answer.

Variables – Y Bother?

Students who have had "Story Problem" traumas inflicted on them at some point are terrified of the engineer's typical method of describing a physical reality: "We will call the speed of the airplane flying north 'X', and the speed of the car driving south 'Y'. . ." Although it may seem trivial, most students are usually not allowed the realization that *any* unique, consistent variable for the quantity will do – or none at all. It is perfectly acceptable to write the entire quantity out if it helps with comprehension of the problem (e.g., "The speed of the airplane flying north" and "The speed of the airplane flying south") when doing the final quantitative analysis. After doing one or two practice problems, a sore writing hand will demand the commonsense step of unique single-letter variables of some sort for use in the repetitive steps of writing equation solutions.

This method has been shown to help students who are apprehensive or lacking in recently used mathematics skills to get back up to speed on solution methods. Another helpful step is the practice of explicitly writing down which variables correspond to each quantity. This often helps students sort out relationships and final answers in relation to the real problem at hand once the calculations are completed.

Engineering Analysis

Engineering analysis is often all that people think of when they think of engineering – solving more-or-less abstract problems to try and predict whether a particular design will work or not, sometimes coupled with real-world and prototype testing. As with so many other types of engineering, the underlying idea is often simple, although the analysis and final implementation may be abstract, complex, and difficult.

If there is a canonical method for solving engineering problems, it might look something like this:

(1) Understand What You Are Looking For

Obviously, if one does not know what they are looking for, it will be hard to know when they have finally found it. Students often simply start solving problems and equations at random in a pattern memorized from classroom demonstrations and homework, without considering what the most effective approach will be, or whether they are actually working on the desired part of the problem.

(2) Draw a Diagram

This does not have to be particularly elegant – engineers are notorious for “boxes and arrows” artwork – but providing a visual roadmap for the problem at hand, as well as a place to label and diagram relevant quantities, can simplify large, complex problems and help reduce errors and confusion.

(3) Select and Label Components and Boundaries

By labeling both system boundaries and the components that move across (and within) them, the final analysis will be simpler and more apparent. If engineering is about keeping track of “stuff,” a good layout of what is moving and where it is going can help. A bit of practice at this will pay off both in efficient solution of problems and a better intuitive grasp of the solutions’ meanings. Using a well-diagramed system, desired quantities may often be found simply by inspecting the diagram rather than complex calculation.

Creating a legend for the map and variables may be helpful. For large processing operations, the variables used may be lost in the complexity of the analysis, and having a “Rosetta Stone” to return to can be very useful.

(4) Set Up the Model That Is Going to Be Used

Although most engineering courses use mathematical models to give quantitative results for the performance of a particular engineering system, and this is often extended to complex, interactive computer models in an era of inexpensive computers, it should be remembered that there are often physical models and simulations that may provide a more efficient means to the same end. Building a simple, physical model and experimenting with it may save months of programming and analysis.

(5) Solve the Equations or Otherwise Utilize the Model

This is where a lot of people want to begin, but it is good practice to go through the other steps first, because real-world engineering situations will expand and become more complex very quickly. The previously mentioned diagrams, referring back to the original conditions as well as providing help in interpreting the results, can help eliminate confusion.

Solution of the problems may be accelerated by the clever use of very simple computational tools. Although most of the examples given in many texts will reduce to a system of one, two, or three equations, real-world problems often become much more complex and require the solution of a large set of simultaneous equations. Hand calculation of a system of five equations can be an experience in patience building and paper consumption.

The “Solver” function available in many spreadsheets and calculators, as well as a host of independently programmable solution methods such as the Gauss-Jordan method, can be applied. There are many good texts on linear algebra, its application to engineering, and its computational solutions that may be consulted for these methods.

The “Law of Computational Correctness” has to be followed if a solution is to be reached. The number of available equations must match the number of unknown quantities, thus creating a well-posed problem in order to provide a solution. An insufficient number of equations (for example, three equations for four unknown quantities) is termed an ill-posed problem in that it has many different solutions (it will provide a two-dimensional line as a partial solution). By contrast, a well-posed problem, where the number of equations and unknowns are equal (and first defined by Jaques Hadamard in 1902) – has a unique solution that depends on the data used, and provides stable solutions for different data sets [1].

(6) Check the Solution

It is easy to lose sight of the final application when calculating a solution, and produce an answer that makes no common sense (water flowing uphill because of a sign error, or heat being transferred from a cold to a warm region without benefit of a heat pump). Unfortunately, it is also possible to come up with a valid solution that runs contrary to mistaken commonsense. One of the facets of engineering analysis is that one must sometimes trust counterintuitive results – at least to the extent of a careful real-world test. Judicious checking of solutions and testing of final results will help eliminate the incorrect solutions.

Abbreviations and Units

Unfortunately, engineering and all of its subspecialties has dozens, if not hundreds, of quantities that require abbreviation, so that often the abbreviation used is confusing. For example, does **P** stand for power, pressure, probability, Poise (a derived unit), Phosphorus (an element), or something else? Worse, the Roman alphabet only contains 72 upper- and lower-case characters, and the Greek another 48 characters, so every abstract quantity cannot have its own assigned letter, and there is often very little agreement among texts.

One should be careful to keep track of the notation used in analysis so that terms are not inadvertently interposed. Every attempt has been made in this book to list the meanings of variables either with the equation or very close to it. For the student, it can be useful to add a unique subscript or superscript to alleviate the confusion, and again, creating a table or list of variables for large analyses can be an invaluable aide, particularly where a larger group of people are working on the problem.

It is a mistake to neglect units while conducting engineering analysis. There are several fundamental types of units that will be subsequently discussed, but for those starting out with engineering analysis, the principle of Dimensional Correctness must apply.

Dimensional Correctness

Write the units with each quantity at each step of the equation. In an era of inexpensive and capable calculators that have reduced or eliminated arithmetic mistakes, a majority of the calculation errors seen in engineering homework could have been prevented by including the units at every step of the way and recognizing when the units no longer match in the equation. This is an extremely useful flag for analytical errors. As experience is gained, it may be possible to shortcut this from time to time, but in general, it remains good (if tedious) practice.

The operations applied to a quantity must be applied to the units attached to this quantity. Operations with units follow the laws of algebra. A common error is to perform an operation on a quantity – squaring it, for instance, without performing the same operation on the units attached to that quantity.

The distributive law will apply to units (Equation 2.2):

$$22\,\mathrm{kg}\cdot(12\ \mathrm{m/s}) = \frac{264\,\mathrm{kg}}{\mathrm{m}\cdot\mathrm{s}} \tag{2.2}$$

Exponents are another source of error (Equation 2.3):

$$\sqrt{296\,\mathrm{m}^2/\mathrm{s}^2} = 14\,\mathrm{m/s},\ \text{not}\ 14\ \mathrm{m}^2/\mathrm{s}^2 \tag{2.3}$$

Additionally, it is not possible to perform addition or subtraction between quantities with different units. Thus, $x = 14\ \mathrm{kg} - 10\ \mathrm{kg{\cdot}s}^{-2}$ cannot be reduced to a smaller expression.

Types of Units

Fundamental Units

These are the beginning point for larger systems of units. Typically, this will include length (L), mass (m), temperature (T), electrical current in Amperes (A), moles of matter (m), candelas of illumination intensity (cd), and time (often t, τ, or θ to avoid confusion with other uses of T). In English units systems, force ($\mathrm{lb_f}$) is also a fundamental (and confusing) unit.

Derived Units

Derived units are generated from combinations of fundamental units. Simple examples include velocity (L/θ), power in watts ($\mathrm{m^2{\cdot}kg{\cdot}s^{-3}}$), volts of electric potential ($\mathrm{m^2{\cdot}kg{\cdot}s^{-3}{\cdot}A^{-1}}$), and so on. In 1995, several *supplementary units* such as the radian were incorporated into the general category of derived units.

Archival Units

Although this is not an official category, the world has long been measuring quantities using what was (often, literally) at hand, and in ways that served well at the time and have simply been carried forward into modern applications. For example, the English system of measurements was partially defined in the Magna Carta in order to eliminate the chronic (and socially incendiary) mismeasurement of grain and wine [2], and continues to this day in many countries. Beyond this, measures evolved such as the inch (the length of three grains of barley laid end to end), the yard (which was created to measure cloth and "corrected" to the length of King Henry I's arm), the pood (a 12th-century Russian grain weight unit), and so on.

Unfortunately, some countries have strongly resisted metrification, particularly the United States and the United Kingdom [3], and the confusion can be both annoying and occasionally disastrous; the loss of the U.S. Mars Climate Orbiter in 1999 was the result of the contracting aerospace company using English units and NASA using metric measurements in linked trajectory correction software, and neither doing the proper conversions [4]. Even the SI units system has its archival problems; the French government's expedition to measure the distance from the North Pole to the equator and calibrate the official length of the meter was rife with fraudulent data, altered to provide a close match to prior expectations, because the actual journey was extremely dangerous and statistical handling of data was not well developed [5].

The food and packaging production industry often lags behind many others in adopting standards such as the SI system, with machinery in a single facility having a mixed set of indicators on equipment of different ages, and so the practitioner is well served to have a good conversion table at hand as working installations may have mixed-unit systems in operation.

Conservative Engineering

This concept does not refer to any particular political preference, but describes the underlying philosophy of most types of engineering. The underpinnings of physics and related fields such as engineering are laws of conservation (thus the “conservative” term).

Conservation of Mass

Mass is neither created nor destroyed within the domain (usually the control volume) of the system. This law, first described by Antoine Lavoisier in 1789 (and matched in similar writings by Mikhail Lomonosov in 1748), simply says that mass may change form (as from a solid to a vapor), but will not be lost.

Conservation of Energy

Energy is neither created nor destroyed within the domain of the system. This law, first postulated in 1842 by Julius Mayer, says essentially the same thing about energy as the previous one says about mass. Energy can change form (from mechanical energy to thermal energy, for instance), but will not be lost.

Conservation of Momentum

Momentum system (defined as Mass times Velocity) will remain constant within the domain of a closed system. This is seldom used in this text, although the concept may be useful in dynamic fluid problems.

The first two laws of conservation – mass and energy, and the concept of conversion from one form to another – beg the question of what happens when mass is completely converted to energy, as when hydrogen undergoes fusion in the sun to produce helium and heat energy. This was resolved by Einstein’s postulation that mass and energy are essentially the same ($E = MC^2$), and thus are conserved. For all practical purposes, the amount of energy that results from a mass-energy conversion is vanishingly small due to the enormously high value of the speed of light ($C \approx 3.0 \times 10^8$ m/s). However, in larger-scale considerations it can become an interesting concept. For example, world energy consumption in 2005 was approximately 15 Terawatts, or 1.5×10^{13} Joules/second [6]. From $E = MC^2$, this has a mass equivalence of (Equation 2.4):

$$M = \frac{E}{C^2} = \frac{(1.5 \times 10^{13}\ \mathrm{J/s})}{(3.0 \times 10^8\ \mathrm{m/s})^2} = 1.67 \times 10^{-4} \frac{\left(\frac{\mathrm{J}}{\mathrm{s}}\right)}{\left(\frac{\mathrm{m}^2}{\mathrm{s}^2}\right)} = 1.67 \times 10^{-4} \frac{\left(\frac{\left(\frac{\mathrm{kg} \cdot \mathrm{m}^2}{\mathrm{s}^2}\right)}{\mathrm{s}}\right)}{\left(\frac{\mathrm{m}^2}{\mathrm{s}^2}\right)}$$

$$= 1.67 \times 10^{-4}\ \mathrm{kg/s} \tag{2.4}$$

This emphasizes why the concept of fusion-based energy – providing some means of nearly direct conversion of mass to energy – is so tantalizing considering that direct, efficient conversion of mass to energy could power the world on a microscopic supply of fuel (roughly 14.4 kg of mass per day), though getting rid of the waste heat might pose other problems. The efficient

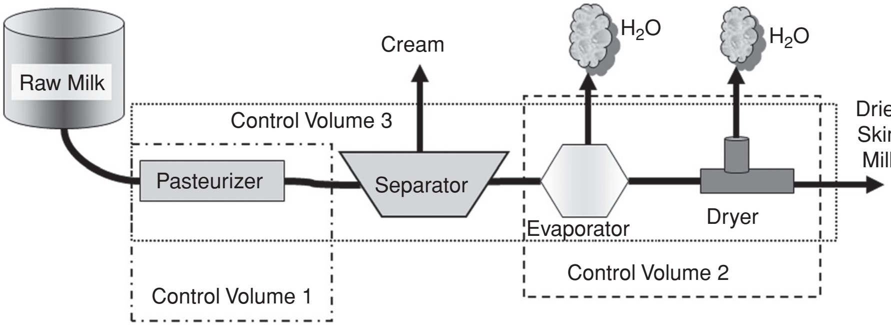


Figure 2.1. Illustration of Control Volumes in Milk Processing

engineering conversion of energy to mass is also conceptually possible, but is confined to high-energy particle accelerator experiments and atomic interactions with gamma rays so far.

Control Volumes

Control volumes are a philosophical convention that has been developed from the process of breaking natural processes down to their most simple parts and studying them in the most isolated manner possible. A control volume (or control area, or control time span) as shown in Figure 2.1 is a convenient set of borders (often completely theoretical) drawn around a particular physical process to facilitate the bookkeeping of which "stuff" is moving in, moving out, or being left behind. More simply, it is a theoretical boundary or system of boundaries that one can use to observe and measure what comes in, what goes out (often into other parts of the process), and what remains. Because overlapping boundaries can be chosen, balances of "stuff" can be done on a particular operation in order to provide more information on other parts where direct information may be lacking. This is the underlying structure of many types of technical analysis from engineering to economics, although it is often difficult to discern from the literature that often omits the diagrams and simply lists equations. Careful choice of control volume(s) can make an enormous difference in the ease of analysis.

System Types

Different types of systems in engineering problems may require different types of systems to be devised, depending on which kinds of "stuff" will cross the boundaries and what sort of theoretical limitations are necessary.

Isolated Systems do not allow the exchange of matter or energy.

Closed Systems, often seen in unit operation problems, do not allow matter to cross the boundary, but heat, mass, work, and volume may all change.

Adiabatic Systems, commonly seen in heat transfer and thermodynamics problems, do not allow heat energy to cross the system boundary.

Open Systems allow heat, work, matter, and other forms of mass and energy to cross the boundary.

Diathermic Systems, which are implicit in many heat-transfer problems, allow *only* heat to cross the boundary of the system.

System States

Steady State

Steady-state operation of a process assumes that the relevant factors are operating at a constant time rate. Thus, a fluid flow system is at steady state if the flow is well established, in its final configuration, and is not increasing or decreasing, and steady-state heat transfer has equilibrated all temperatures and heat flow rates. Nearly all of the examples given in the book are steady-state examples.

Unsteady State

Unsteady-state systems are usually considered to be in transition from one steady state to another, such as in the start-up or shutdown of a particular operation, or a change in its operation rate. The calculation of the relevant factors at any particular time in these unsteady periods can be calculated, although it is usually much more complicated and may require extensive computer approximation of the solution of the relevant differential equations. Approximations of the solution of many unsteady-state problems can be made by "discretizing" the operation – developing a model, usually using a spreadsheet or dedicated program that breaks the unsteady-state operation into very small time steps and aggregates them into an approximate solution of small steady-state parts. This type of stepwise integration, if done carefully, can give a good working solution to a very complex operational problem and is the basis for many computer-based system simulation-and-optimization software packages.

Transient State

Transients are often considered to be momentary perturbations from a steady-state operation, such as a flow surge or voltage spike. The reactions of a system to these short-term dynamic changes can be complex and, although fascinating, are beyond the scope of this text.

Continuous Flow Systems and Batch Systems

The basis for the analysis of a batch system is usually intuitively obvious. Quantities are measured and calculated on a per-batch basis, usually broken down into useful basis units, and the analytical results are returned on a per-batch basis as well. One may reduce this to more fundamental units (kilograms of product, for instance), but the assumption is that the process will start, operate, and then stop, with time-related factors being minimized beyond those reactions occurring within the batch itself.

Continuous flow systems are typically less obvious to work with, but the simple trick of choosing a specific time interval or mass of a particular item (one kilogram of dry solids, for example) to use as a basis will make the solution similar to that of batch processes. Thus, a steady-state process can be analyzed using the chosen time basis, but it must be remembered that the results will be related to the same time basis. It is a common error to forget these units in the final result.

Mass Balances

Beginning with the law of the conservation of mass, mass balances become a fairly simple matter in concept. They can become exceedingly complex when a large number of steps or a large number of compounds are exchanged or otherwise modified, but the underlying idea remains the same: Within the confines of the control volume, the total mass remains the same. Thus, if sugar, yeast, and water are fermented to form ethanol, yeast, and carbon dioxide, the total mass of these resultant components will be equal to the starting mass. All that remains is accurate accounting of the materials in the control volume.

It is often very useful to track a component that is unchanging in the process (dry air or dry solids, for example) in order to give a constant basis of calculation for those ingredients that are added, subtracted, or changed in some way.

Example: For a product that is only dry solids and moisture, and is composed of 10% dry solids (DS) by weight, what is the final product yield if it is dried to 25% moisture content, and how much moisture is removed in the process (Equation 2.5)?

$$\begin{aligned}
\text{Basis of Analysis:}\ & 1\ \text{kg of raw product} \\
1\ \text{kg raw product} \cdot (0.10\ \text{kg DS/kg raw product}) &= 0.10\ \text{kg DS}, \\
\text{Moisture Content} &= 1\ \text{kg raw product} - 0.10\ \text{kg DS} \\
& \therefore 0.90\ \text{kg moisture/kg raw product} \\
& \downarrow \\
\text{Final Moisture Content} &= 25\%\ \text{moisture/kg final product}, \\
& 75\%\ \text{dry DS/kg final product} \\
& \downarrow \\
\text{Final Product Yield} &= \frac{0.10\ \text{kg DS}}{0.75\ \text{kg DS/kg final product}} \\
&= 0.133\ \text{kg Final Product/kg raw product} \\
\text{Final Product Moisture Content} &= 0.133\ \text{kg Final Product} - 0.10\ \text{kg DS} \\
&= 0.033\ \text{kg Moisture} \\
\text{Moisture Removed} &= \text{final moisture content} - \text{initial moisture content} \\
&= \frac{0.033\ \text{kg moisture}}{\text{kg of raw product}} - \frac{0.90\ \text{kg moisture}}{\text{kg of raw product}} \\
&= \frac{0.867\ \text{kg moisture}}{\text{kg of raw product}} \qquad (2.5)
\end{aligned}$$

A common error in mass balance analysis is to leave out the consideration of particular components in the rush to arrive at a solution. In a fermentation process, for example, a small amount of water is taken up in the hydrolysis of starch, which can lead to calculation errors in the final yield. Another common error results from semantic slips such as the confusion of *dry solids*, which are a theoretical quantity and contain no moisture whatsoever, and *dried product*, which will have lower, but significant, moisture content. Writing these out and assigning them distinctly different variables can reduce the errors considerably.

Tracking and Calculating Component and Total Mass Balances

An advantage to tracking both individual components and the total mass is that it can give an additional source of balance equations for creating a well-posed system of equations for use in determining unknown variables. For instance, the separate components as well as the total mass can be used as separate equations to solve the system of equations. Beyond this, it may be useful to track the solids total and its subcomponents, as well as fluids total and its subcomponents, to generate additional equations for analysis.

Because the analysis resembles a spreadsheet so closely to begin with, adaptation to automatic calculation for process design and process variation analysis is a relatively straightforward matter. Most process-monitoring software, although more internally complicated by its calculations of real time date from production equipment, will display data in a similar fashion.

Blending and Separation Processes

For processes that blend or separate ingredients, it is often most useful to determine the component that will go through the process without being changed (often a solvent or dry solid material) and use that as a mass-based tracking aid in the analysis or basis of calculation. Thus, pure water or dry solids may wind up being useful in the calculation of the amount of a compound carried along with that material during processing. When blending occurs, the volume of the final mix may not be the sum of the initial compounds' volumes (dissolving salt into water will illustrate this), and thus analyses must be done on a mass rather than a volume basis.

Multistage Processes

Multistage processes almost always require multipart analyses and involve multiple and often overlapping systems boundaries. A good diagram, as previously described, can be immensely helpful with this. As systems grow to enormous proportions, it may be nearly impossible to consider the entirety of the operation in a single step, and further subdivisions may have to be made. The analysis of very-large-scale operations is the subject of an entire field of study, and the fortunate beneficiary of the development of relatively simple and intuitive computer simulation models.

Recycle Streams

Recycle streams are a common feature of many processing operations, and represent the return of materials into the process that would otherwise go to waste. It is a commonsense step to reuse reclaimed water or other process materials, but the analysis will then depend on creating proper subsystem boundaries to track the flow of materials back to the start of the process, as well as the forward flow of materials into the final product. Careful labeling or other means of tracking the exact content of both the forward and recycle streams is important because many of these are the output from some type of extraction or reclamation step and will not have the same component balance as the final product.

Energy Balances and Thermodynamics

Energy balances become a bit more complicated, because energy cannot be directly measured, but must be observed indirectly by the effect that it has on a material. The basic concepts involved in energy balances are usually expressed in the laws of thermodynamics, usually credited to Isaac Newton:

The First Law of Thermodynamics

The total sum of mass and energy in a closed (conservative) system will remain constant. From this, one can say that the sum total of all types of mass and energies will remain constant, although they may change from one form to another (oxidizing mass to create heat energy, for example).

Second Law of Thermodynamics

The quality of energy will degrade, that is, energy will always degenerate into something more random (very often heat), and you cannot return to the same state of energy without loss. Thus, energy will only spontaneously move from a region of high energy to a region of low energy and not the reverse.

Third Law of Thermodynamics

Entropy – the tendency toward disorder in a system – will reach a constant state as temperature decreases.

Process Types

Thermodynamic processes may take one of a number of different paths, depending on which variables are considered to be held constant. It is important to realize that in many instances, the processes that are listed are convenient for the sake of simple mathematical analysis, but are harder to match to real-world phenomena, many of which occur with no constraints on any particular set of variables.

When considering the types of systems, and the processes operating in those systems, it is useful to make a distinction between several types of systems.

Steady State

Steady-state processes occur without a change in the internal energy of the system. These are often used to manage energy transfer between items within the system boundaries.

Adiabatic

Adiabatic processes occur without heat exchange, as previously described, although the temperature or volume may change, as will be illustrated in the section on gas volume and enthalpy.

Isothermal

Isothermal processes operate at a constant temperature, although internal energy may change, as with a phase change in a material such as ice melting to water.

Isobaric

Isobaric processes operate at a constant pressure, though volume or temperature often change.

Isochoric

Isochoric processes operate at a constant volume, though pressure or temperature change.

Isentropic

Isentropic processes operate at a constant entropy value. This will be used in the section on vapor-compression refrigeration.

Isenthalpic

Isenthalpic processes, often confused with isentropic processes, occur at a constant value of enthalpy. A good example of this is the vapor-to-gas expansion through a throttling valve or orifice in vapor-compression refrigeration that occurs at a fixed enthalpy value.

Energy balances finally reduce to the concept that the total energy of a system will change as a function of the net amount of energy entering and leaving a particular system, and the energy may take any number of interconvertable forms giving Equation 2.6:

$$\text{Net energy change} = \text{energy gained across boundaries} - \text{energy lost across boundaries} \quad (2.6)$$

For any system, then, the energy exchange can be rewritten as Equation 2.7:

$$\text{Energy into system} = \text{Energy out of system} + \text{Energy retained by system} \quad (2.7)$$

And as a broad conceptual model, this will explain how most devices operate. For example, an automobile engine's energy balance would be Energy in = Energy Out + Energy Retained, as shown in Table 2.1:

Table 2.1. Types of Energy in Energy Balances

Energy In	=	Energy Out	+	Energy Retained
Chemical Energy Electrical Current		Mechanical Energy Heat Fluid Flow Sound Light		Electrical Charge in Battery Residual Heat

Energy Terms

Force

Force is defined as an action that will cause a body with mass to accelerate, rotate, or deform a mass. Typically, it is given in Newtons (N) ($1\ \text{N} = 1\ \text{m}\cdot\text{kg}\cdot\text{s}^{-2}$), or pounds of force ($\text{lb}_\text{f}$)

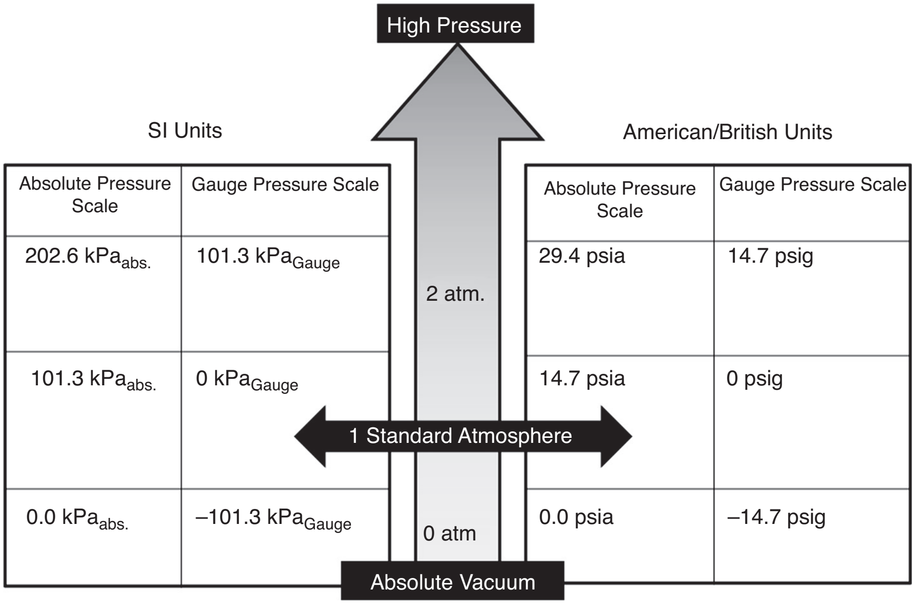


Figure 2.2. Chart of Pressure and Vacuum Terms and Levels

($1\ lb_f = 1$ lb mass · 1 g, where g is the acceleration of gravity). Note that pounds of force and pounds of mass are properties used in American and English units, and cause a great deal of confusion, particularly when working with fluids problems. SI units systems are generally a great deal more useful, and if it is necessary to analyze a system using the American or English units during operation, it is usually more efficient and less confusing to use SI units to do the analysis and simply convert the final result using a conversion table.

Pressure

Pressure is a term used to describe force distributed over an area, and will be given in Pascal (Newton/meter^2) or pounds of force per square inch (psi). Since Pascals are typically very small amounts of pressure, it is more common to use kPa or MPa when working with everyday pressures in the SI system.

Gauge Pressure

Gauge pressure refers to the relative pressure above 1 atmosphere, as shown in Figure 2.2, and is derived from practical uses utilizing an installed pressure gauge that reads “zero pressure” when the system is in an “unpressurized” state, at ambient pressure.

Absolute Pressure

Absolute pressure refers to pressure above absolute vacuum, and is often used in gas chemistry, thermodynamics of gasses, and low-pressure operations such as flavor extraction and steam operations because the reactions of the substances involved require reference to an absolute vacuum. Conversion between gauge pressure and absolute pressure is simply accounting for the 1 atmosphere difference:

Gauge Pressure + 1 Standard Atmosphere = Absolute Pressure

Vacuum

For those not used to working with vacuum quantities, the concept of negative pressure is usually confusing at first. Vacuum is usually taken to be the amount of pressure below 1 standard atmosphere, and – confusingly – is reported in positive units:

Absolute Pressure = (1 atmosphere) − (Amount of Vacuum).

Thus, 50 kPa of vacuum (which is actually −50 kPa of gauge pressure) is equivalent to 101.3 kPa − 50 kPa = 51.3 kPa absolute pressure. Visualizing it from an actual measurement device (shown in Figure 2.3) may clarify the concept.

Work

Work is the amount of force (F) applied over a net distance (d); $W = F \cdot d$. The "net distance" requirement comes from the integral version of work analysis and can usually be neglected in simple cases. Strictly speaking, if force is applied to an object that then moves but returns to its original starting point having covered no net distance, no work has been done. The units will typically be in $(\mathrm{m} \cdot \mathrm{kg} \cdot \mathrm{s}^{-2)} \cdot \mathrm{m} = \mathrm{m}^2 \cdot \mathrm{kg} \cdot \mathrm{s}^{-2}$ or Joules.

Power

Power is the time rate of doing work; $P = W/t$. Thus the units will typically be in $(\mathrm{m}^2 \cdot \mathrm{kg} \cdot \mathrm{s}^{-2})(\mathrm{s}^{-1}) = \mathrm{m}^2 \cdot \mathrm{kg} \cdot \mathrm{s}^{-3}$ or Watts (1 Watt = 1 Joule/second). Power is another area where SI and English units may intermix. During the development of steam engines, a measure of the output of a mechanical engine was developed to compare engines to that of the usual motive power used for mine pumps of the time (a draft horse), and engines are still listed in horsepower (hp) in many places (1 hp = 745.7 W), although kilowatts (kW) of mechanical output are beginning to be listed in most manufacturer's data.

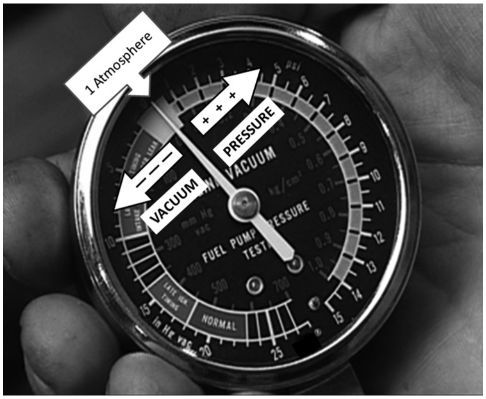


Figure 2.3. A Combination Pressure and Vacuum Gauge

Table 2.2. Heats of Combustion for Selected Common Fuels

Fuel	MJ/kg	BTU/lb
Hydrogen	141.9	61,000
Propane	50.0	21,000
Natural Gas	54.0	23,000
Butane	49.4	21,000
Gasoline	47.0	20,000
Diesel Fuel	45.0	19,500
Ethanol	30.0	12,000
#2 Heating Oil	47.4	20,400
Wood	15.0	6,000
Anthracite Coal	27.0	14,000
Bagasse	17.0	8,800

Thermal Energy

The most common source of thermal energy is the direct combustion of fuels that are nearly always hydrocarbon based. The heat values of these types of fuels are listed in Table 2.2, and most have similar heats of combustion, although ethanol is quite low and hydrogen is quite high.

The forest products and food-processing industries have often used non-traditional sources of fuel for heating where processing by-products can be utilized in biomass furnaces burning processing sawdust, waste, or waste oils. The overall heat production of a particular burner type can be described as Equation 2.8:

$$\text{Heat Produced} = (\text{Heat of Combustion})^*(\text{Mass Flow Rate of Fuel})^*(\text{Combustion efficiency})$$

$$\text{kJ/s} = (\text{kJ/kg})^*(\text{kg/s})^*(\varepsilon) \tag{2.8}$$

Burner efficiencies can vary widely, with some types of triple-flue burners exceeding 95% efficiency and mixed-biomass or waste burners, particularly older ones without direct air injection or fluidized bed combustors, being much lower.

Other sources of thermal energy in food processing and packaging include electrical resistance heating, described in the next section, and heat reclaimed from other plant processes, such as the reheating stages in HTST processing, or, on rare occasions, waste heat from nearby industry such as metal foundries. Solar heat, heat pumps, geothermal sources, and other "alternative" energy sources are used when feasible but are often restricted to specific geographic location or environmental conditions.

Energy and Work Sign Conventions

The general adoption of several *sign conventions* – agreed use of mathematical +/− signs to signify the direction of energy, usually heat flow and work – allows the tracking of energy conversion to work, and the reverse.

Table 2.3. Sign Conventions of Heat and Work in Thermodynamics

	Enters System	Leaves System
Heat (q)	+	−
Work (W)	−	+

Using this convention has two distinct benefits. It allows the concept of heat conversion to work to be illustrated – in a steam engine, for example – because heat in and work out are both positive. More usefully, it allows the determination of the net values of a system that may be so complex that the final result is not intuitively clear.

Mechanical, Electrical, and Other Types of Non-thermal Energy

Many sources for food processing operations concern themselves with thermal processes, but it is important to remember, particularly in a machinery-intensive operation such as food processing and packaging, that there are many other types of energy use that must be accounted for. Although the early industrial age saw a great deal of use of water or wind power to directly operate milling and pumping operations, these sources of power are now almost exclusively run through electrical generators first, and then reutilized via electric motors in order to increase distribution and incorporate versatility by interfacing with electrical power grids. Mechanical energy that was once generated in a central steam engine and transmitted via a central driveshaft to belts and pulleys throughout a factory is now generated by much smaller electrical motors on an as-needed basis, although live steam is still supplied from boilers for thermal processes and compressed air may be used for actuators and conveyors. Motors of all types range widely in size, from very small electro-servomotors and actuators to megawatt hydraulic units used for large industrial machinery and diesel-electric propulsion drives in ships and trains.

Fluid Power

Compressed air, vacuum, and hydraulics are other sources of mechanical energy utilization, although these usually originate in large electric or diesel-powered pumps and compressors. Compressed air and hydraulics offer the ability to operate in wet or hazardous conditions, with compressed air providing simple and inexpensive machine actuators and hydraulics providing the potential for enormous power transmission due to the relatively incompressible nature of the operating fluid. Because of energy losses in distributing the respective fluids, these methods may be less energy-efficient than other means, but compensate by offering durability and simplicity of installation in complex devices.

The basic types of piston linear actuators used in pneumatic and hydraulic systems produce a force that is proportional to the surface area of the piston face and the applied pressure (Equation 2.9):

$$F = P_{\text{fluid}} \cdot A_{\text{piston}} \tag{2.9}$$

F : Force, N
P: Fluid Pressure, Pa, (N/m^2)
A: Area of piston face that fluid exerts pressure on, m^2

Pneumatic and hydraulic motors convert fluid flow into rotary mechanical motion using turbines, vanes, gears, or pistons. Although somewhat inefficient, *Swash Plate* hydraulic motors that utilize variable-displacement linear pistons against an osculating disc can provide enormous starting torque and variable speed use for employment in heavy construction and fabrication machinery.

Electrical Energy

Electrical energy is a primary source of mechanical power in many processing and packaging operations. It is used to generate mechanical power, light, heat, and is widely – indeed, almost uniquely – used to transmit information because it moves almost instantaneously over large distances. It is used as a very efficient means of centralizing power generation because the high-voltage electrical distribution networks typically lose very little energy, and electricity can be easily converted into other types of energy such as light or mechanical power.

Simple electrical circuits such as resistance heaters and filament lights can be analyzed by using Ohm's Law (Equation 2.10):

$$\begin{aligned} P &= IE = \frac{E^2}{R} \\ I &= \frac{E}{R} \\ E &= IR \\ P &= I^2R \end{aligned} \tag{2.10}$$

P: Power, Watts, W
I: Current, Amperes, A
E: Potential, Volts, V

From the first equation, one can see why fuses and circuit breakers exist. If a short circuit occurs at a constant voltage, lowering the resistance to nearly zero, the current will increase to nearly infinity, causing fires or other damage to the other wiring in the circuit.

It should be stated that for more complex inductive circuits such as many types of motor-starting circuits and nearly all electronic devices, the generalized Ohm's Law must include impedance (Z) terms as well as complex (frequency-specific) terms that will not be considered in this text.

Because electrical energy can be switched on and off instantaneously, and can be used to generate heat in highly localized areas, the packaging industry uses electrical resistance heating to operate heat sealers to fuse plastic surfaces together. Electrical resistance heating can be used to power large-scale industrial processes – arc furnaces depend on it – but in a broader context, it is not the most efficient means of generating heat in many cases because the original source of the electrical energy is fuel combustion, and a substantial inefficiency is inherent in the generation, transmission, and subsequent reconversion of electricity into heat.

Forms of Mechanical Energy

Mechanical energy can take an enormous variety of forms, as previously described, ranging from fluid motion to acoustic energy as well as friction and deformation of materials. A complete analysis of the source or disposition of mechanical energy typically will not account for many of these terms, and this text will only examine a few that are immediately relevant.

Potential Energy (PE)

Potential energy is usually defined as the energy that is stored, usually by raising a mass above a datum level by a particular amount (Equation 2.11):

$$PE = \mathrm{m} \cdot \mathrm{g} \cdot \mathrm{h} \tag{2.11}$$

PE: Potential Energy, $\frac{\mathrm{kg} \cdot \mathrm{m}^2}{\mathrm{s}^2}$
m: mass, kg
g: acceleration of gravity, m/s^2
h: height above datum, m

Potential energy may also include energy stored in an extended elastic spring, an electric battery or other chemical or nuclear reaction, or in a compressed gas, which will facilitate the consideration of the trade-offs between potential energies and the kinetic energy that may be producing them. For example, the kinetic energy expended by a mechanical device to operate a compressor provides potential energy in the form of compressed air that can be used at a later date.

Kinetic Energy (KE)

Kinetic energy is the energy of movement, which, in addition to the obvious movement of mass discussed here, can include thermal energy – considered in the heat transfer section of this chapter – acoustic energy, and electrical energy in an active circuit.

A simple, steady-state system may be written as Equation 2.12:

$$\begin{aligned} \mathrm{KE} &= 1/2\,\mathrm{mV}^2 \\ \mathrm{KE} &= \text{Kinetic Energy, } \frac{\mathrm{kg} \cdot \mathrm{m}^2}{\mathrm{s}^2} \\ m &= \text{mass, kg} \\ V &= \text{velocity, } \mathrm{m}^2/\mathrm{s}^2 \end{aligned} \tag{2.12}$$

From the first law of the conservation of energy, then, it is possible to see how, in a closed system, one may track the changes between mechanical energy, velocity, pressure, and many other energy forms.

A classic example of the trade-off between kinetic and potential energy is an amusement park roller coaster (Figure 2.4). Cars are mechanically hauled to the top of a tall ramp, where the potential energy is at its maximum while kinetic energy is nearly zero from the slow movement of the cars. As the car accelerates down the ramp, potential energy (height) is exchanged for kinetic energy (velocity) until at the very bottom of the ramp, the cars are moving at their maximum velocity at minimum height. The inertia of the system again carries the cars to their highest available point, trading kinetic for potential energy and back again, until wind resistance and rolling friction cause the ever-decreasing system of exchanges to come to ground level.

Thermal Energy and Temperature

The fundamental units of thermal energy often relate to temperature, and these are often indexed to either an absolute temperature (Kelvin [°K] and Rankine [°R]) or their respective relative measurements (Celsius [°C] and Fahrenheit [°F]). Absolute temperature is often used in the

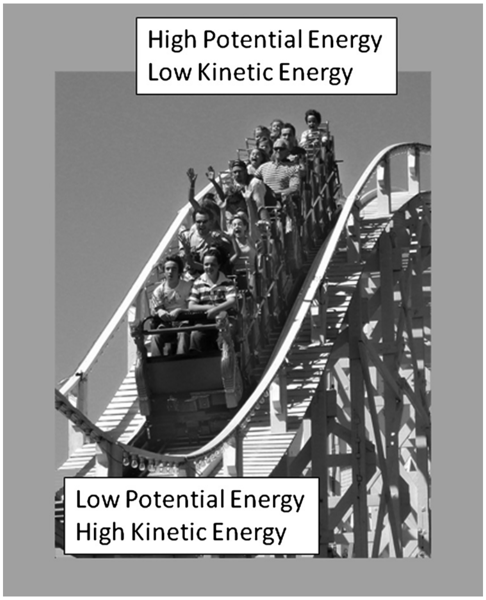


Figure 2.4. Roller Coaster Illustration of Potential and Kinetic Energy
Source: Wikimedia Commons. Source: Stevage. Used under Creative Commons License

understanding of basic chemical and thermodynamics, whereas the relative measurements are often used for more practical purposes. Both of these are simple conversions (Equation 2.13):

$$\begin{aligned} &{}^{\circ}\mathrm{F} = {}^{\circ}\mathrm{R} + 460 \\ &{}^{\circ}\mathrm{C} = {}^{\circ}\mathrm{K} + 272 \end{aligned} \tag{2.13}$$

For temperature *change* problems, such as those in heat transfer, it is useful to remember that the chosen units (within a specific units system) do not matter (Equation 2.14):

$$\Delta T^{\circ}\mathrm{K} = \Delta T^{\circ}\mathrm{C}$$

since

$$\begin{aligned} T_2{}^{\circ}\mathrm{C} - T_1{}^{\circ}\mathrm{C} &= T_2({}^{\circ}\mathrm{K} + 272) - T_1({}^{\circ}\mathrm{K} + 272) \\ &= T_2{}^{\circ}\mathrm{K}(+272) - (T_1({}^{\circ}\mathrm{K} + 272)) \\ &= T_2{}^{\circ}\mathrm{K} - T_1{}^{\circ}\mathrm{K} + (+272 + {}^{-}272) \\ &= T_2{}^{\circ}\mathrm{K} - T_1{}^{\circ}\mathrm{K} \end{aligned}$$

similarly,

$$\Delta T^{\circ}\mathrm{R} = \Delta T^{\circ}\mathrm{F}$$

but, of course,

$$\begin{aligned} &\Delta T^{\circ}\mathrm{R} \neq \Delta T^{\circ}\mathrm{C} \\ &\Delta T^{\circ}\mathrm{K} \neq \Delta T^{\circ}\mathrm{F} \end{aligned} \tag{2.14}$$

Heat energy is particularly difficult to deal with because it may affect a material in two different ways. The obvious way that increasing or decreasing the heat energy of a material

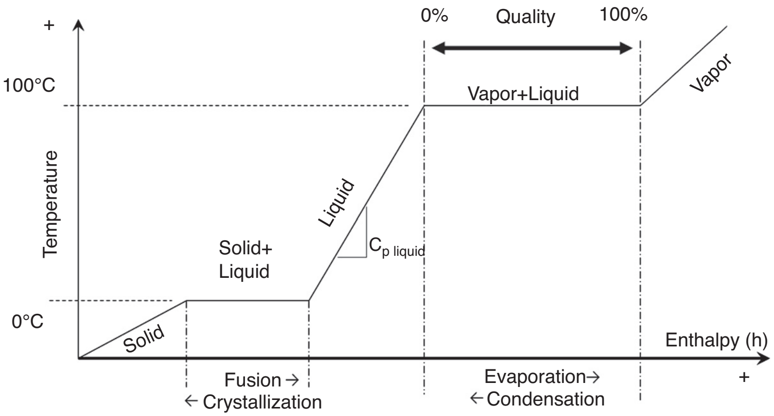


Figure 2.5. Relationship of Phase, Temperature, Enthalpy, and Specific Heat Content for Water at Sea Level

will change it is in a change of temperature, but there is also the matter of phase changes – the freezing, thawing, boiling, and condensing that most materials will exhibit. To account for the overall thermal energy contained in matter, a general term, enthalpy, is used. The best example of how enthalpy may be used is to observe it correlated to temperature in water, where the concept was originally considered (Figure 2.5).

Note that there are two distinct changes that occur as a result of the changing internal energy in a system: the change of phase and the change of temperature. These were first described by Dr. Joseph Black, a professor of medicine at the University of Glasgow, Scotland, after 1756, as he was attempting to determine the most efficient way to distill scotch whiskey that had become enormously popular in the booming British international trade economy. Dr. Black noticed that a mass of water would absorb heat but not change temperature when it was changing phase from ice to water, and that the absorption of the same amount of heat in a single-phase system (water only) would cause a change in temperature. He referred to the change of temperature as *sensible heat* because one could measure (sense) it as a change in temperature, and to the change of phase as *latent heat* because no temperature change could be measured and thus the heat was going to some other result – that of the phase change.

This was the beginning of the quantitative understanding of the intrinsic energy contained in matter, and had enormous future implications. One of Black's colleagues, James Watt, an instrument maker who was hired by the University of Glasgow in the 1750s to repair astronomical instruments, adapted several of the principles to improving the existing Newcomen steam engines that were used to pump water from mines, and produced one of the first relatively compact and efficient sources of steam power – the Watt steam engine – providing an engine to drive the nascent Industrial Revolution. Black and Watt collaborated further to gain an important understanding of the nature of heats of evaporation and condensation of water, and, by extension, those properties in other compounds. The final result was a general consideration of energy in a system, termed enthalpy, and generally defined as (Equation 2.15):

$$h = U + pV \tag{2.15}$$

h: Enthalpy, joules, J
U: Internal Energy, J
p: pressure, Pa
V: volume, m^3

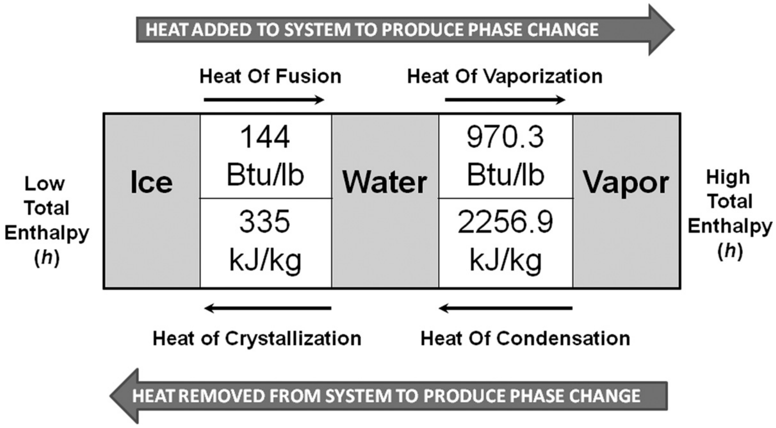


Figure 2.6. Latent Heats of Phase Changes In Water

From this relationship, it can be readily demonstrated that enthalpy can vary as a function of variations in pressure, volume, or internal energy. For many of the discussions in this text, pressure and volume will be considered to be constant while the internal energy term, U, will change. Enthalpy is usually measured relative to temperature and pressure absolutes for use in chemistry and physics, but a large amount of the data is referenced to more useful measures such as the freezing point of water.

The change of enthalpy content of the water in any form can be observed as either a change of phase or a change of temperature, and one can calculate the amount of energy that goes into or out of the material to change it as required. Although most people are comfortable with the notion that adding heat will cause the changes that one observes when moving to an increased state of enthalpy, since this is what boiling water or thawing ice entails, what is not intuitively obvious in this is that when moving to a state of lower enthalpy, heat is removed from the system, either by spontaneous rejection of heat or by extracting it with a cooling device such as a refrigerator. The practical implications demand that, when doing process designs, many freezing processes in the food industry have to consider the heats of crystallization and the effect of materials in the path of that heat as it leaves the product, as shown in Figure 2.6.

The phenomenon of heat being released on crystallization is occasionally utilized in orchards to prevent fruit from freezing by spraying it with water during cold snaps, and by liquid chemical heat packs that evolve heat by crystallizing saturated solutions, particularly sodium acetate.

Pressure, Phase, and Criticality

The phase that a particular compound exhibits under specified circumstances is dependent on the surrounding pressure, temperature, and the vapor pressure of the material itself. Although the relationship between phase, pressures, and temperature is well handled by the Clausius-Clapeyron equations, a good rule of thumb for practical applications is shown in Table 2.4.

This is useful when determining the phase of liquid-vapor changes both in steam utilization and refrigeration, although the latter is well handled by refrigeration charts. An additional use for this principle is when gasses are compressed above their thermodynamic critical point until they become a *supercritical fluid*, whereupon they have the ability to both diffuse through solids and to act as a solvent. This allows processes such as the removal of caffeine from coffee to be conducted

Table 2.4. The Relationship of Phase and Pressure

Vapor Pressure of Material & Surrounding Pressure	Material State
Vapor Pressure ≥ Surrounding Pressure	Material in vapor state
Vapor Pressure < Surrounding Pressure	Material in liquid or solid state

without toxic organic solvents. Although this process requires substantial pressure vessels to operate, the lack of residual solvents in the final product makes it appealing for more and more types of solvent operations in foods, pharmaceutical, and some types of industrial operations.

Specific Heat

The ratio of temperature change to heat input (enthalpy change) per unit mass is called specific heat capacity, which is usually shortened to specific heat. Heat capacity, which is a mass-independent term, is occasionally (and incorrectly) used as well. Specific heat values may be determined at either a constant pressure (C_p) or constant volume (C_v). Because the two are very similar for solids and liquids at the relatively low pressures and temperatures used in food processing operations, C_p is most often used and the difference between the two is seldom considered in food and other relatively low-energy systems. In calculations that are beyond the scope of this text, involving the large flows of superheated vapors or gasses such as turbine design and large-scale chemical refining, these differences become quite significant, but for most food-processing operations, the difference is negligible and C_p will be used.

Specific Heats of Complex Food Compounds

Although this text begins its discussion of specific heat values with simple compounds such as water, most food-processing operations involve compounds that have a complex and sometimes nonlinear specific heat range that is most often experimentally determined through calorimetry or some other method. Nonlinearities in heterogeneous foods may be the result of phase changes within the compounds – the crystallization or fusion of lipids, desorption of water, or some other chemical reactions. If specific data are not available for the estimation of specific heat capacities of particular food materials – these are often tabulated in published literature and handbooks and a few of these are provided in the chapter appendix – then estimation equations are available that will give a reasonable approximation of the heat needed to affect a particular temperature change [7].

The Siebel equations [8] gave a very simple first estimate of specific heat based on moisture content (Equation 2.16):

$$C_p = .04F + .02S + M \tag{2.16}$$

$$C_p\text{: specific heat, } \frac{\text{Btu}}{\text{lb}_m \cdot {}^\circ\text{F}}$$

M: water mass fraction
S: solids (non − fat) fraction
F: fat fraction

However, they only give good correlation for high-moisture, low-fat foods.

Subsequent approximations such as those by Heldman and Singh (Equation 2.17) account for a larger number of components in order to provide a more accurate estimation [9]:

$$C_\mathrm{p} = 1.424w_\mathrm{c} + 1.549w_\mathrm{p} + 1.675w_\mathrm{f} + 0.837w_a + 4.187w_\mathrm{m} \tag{2.17}$$

C_p: specific heat, $\frac{\mathrm{kJ}}{\mathrm{kg}\cdot{}^\circ\mathrm{C}}$
w_c: mass fraction of carbohydrates
w_p: the mass fraction of proteins
w_f: is the mass fraction of fats
w_a: is the mass fraction of ash
w_m: is the mass fraction of moisture

These allow a larger number of variables to accommodate more diverse materials more accurately. These approximations are usually based on the fundamental composition of the food materials (fat, protein, carbohydrates, moisture, ash, etc.) and are the result of analyzing a good deal of published data and generating a statistical approximation for the specific heat values within the relevant ranges of temperature and composition. There have been a large number of subsequent studies published regarding these types of estimations, many of which are difficult to use without a spreadsheet, but that will give a good, close correlation depending on the accuracy of formulation or material component analysis [10].

Heat Flow and Specific Heat

Heat added or rejected in temperature changes can be calculated as a factor of the temperature change, mass of compound, and specific heat (Equation 2.18):

$$q = M \cdot C_\mathrm{p} \cdot \Delta T \tag{2.18}$$

q: heat necessary for temperature change, J
M: mass of component, kg
C_p: specific heat of compound, $\frac{\mathrm{J}}{\mathrm{kg}\cdot{}^\circ\mathrm{K}}$
ΔT: process temperature change, °K or °C usually $(T_\mathrm{final} - T_\mathrm{initial})$

Note that this only accounts for the materials changing temperature; if the material changes phase, the relevant energy associated with that phase change must be accounted for. For mass-flow systems, where there is a time rate of mass exchange, the heat flow can be calculated on the same time basis.

Specific heat is determined by rewriting the equation as (Equation 2.19):

$$C_\mathrm{p} = \frac{q}{M \cdot \Delta T} \tag{2.19}$$

Here, the amount of heat energy required to affect a given temperature change can be experimentally determined.

Latent Heat

Latent heats are often called heats of fusion, crystallization, vaporization, and condensation as shown in Figure 2.6, depending on the process that is actually being described and its direction. These quantities are fixed for standard pressure conditions, and for most applications may be treated as constants. Changes in surrounding pressure will affect the heats of vaporization and condensation of liquids and of fusion and crystallization of solids, and should be considered in applications involving high- or low-pressure operations. The values for latent heats of compounds are usually available in engineering handbooks or in published literature. Note that the value for latent heat will only account for the heat flow to change the phase of the material – any temperature changes must be accounted for using specific heats or an equivalent method.

Heat Flow

The overall heat flow is given as (Equation 2.20):

$$q = \Sigma \left\{ MC_{\mathrm{p}} \Delta T \right\} + \Sigma \left\{ \Delta \text{ latent heat} \right\} \tag{2.20}$$

So, for a simple water system, the amount of heat required to change ice at −10°C to water vapor at +120°C is (Equation 2.21):

$$\begin{array}{l}
\text{Sensible heat energy to raise temperature of ice from } -10^\circ\text{C to } 0^\circ\text{C)} \\
+ \text{(Latent heat energy [heat of fusion] to change ice to water at } 0^\circ\text{C)} \\
+ \text{(Sensible heat energy to raise the temperature of the liquid water from } 0^\circ\text{C to } 100^\circ\text{C)} \\
+ \text{(Latent heat energy} - \text{heat of vaporization} - \text{to change liquid water to vapor} \\
\quad \text{at } 100^\circ\text{C)} \\
\underline{+ \text{(Sensible heat energy to superheat vapor from } 100^\circ\text{C to } 120^\circ\text{C)}} \\
\qquad\qquad\qquad \text{Total Heat Energy Required}
\end{array} \tag{2.21}$$

The amount of energy given off when the process is reversed is the same. Because of the conventions used in thermodynamics, the sign will indicate whether heat is absorbed (+) or given off (−). Of course, this kind of calculation can be both tedious and error-prone, particularly when working under non-standard conditions, so tabulated values of the relevant heat energies and other coefficients have been devised to ease the use of this information.

Liquid/Vapor Tables (Steam Tables)

Because it may be most efficient to burn fuels directly on-site to produce heat, and because steam transmission is a robust means of thermal energy transfer, a great deal of the energy for processing in the food industry is taken from steam supplies. Thus, a working knowledge of the energy available from steam is necessary. Steam tables, as well as thermodynamic tables for many types of refrigerants and gasses, are supplied in many engineering handbooks and are available online as well as in program form for use in many types of computing devices. Typically, these will contain heat energy values for specific states of matter, with temperature and pressure being the most common. For the purposes of this book, we can assume that the energy changes in the process are path-independent, and thus all that is necessary is to know the state of the system at the beginning and at the end of the process. An abbreviated steam table is in the chapter appendix, though it should be mentioned that for actual engineering applications, a more detailed table should be consulted.

Because of the conservation of energy in the system being considered, the usual method of use is to determine the total energy content of the material at the end of the process and the total at its beginning, and then determine the difference (Equation 2.22):

$$\begin{aligned}\text{Energy Requirement} &= (\text{Final Enthalpy Value}) - (\text{Initial Enthalpy Value})\\ &= h_{\text{final}} - h_{\text{initial}}\end{aligned} \tag{2.22}$$

h: enthalpy, J/kg

This is quite simple so long as the materials remain in a single phase, but it is often difficult to determine the phase of the material unless one knows the environmental conditions in which the materials exist.

Vaporization and Condensation

To account for the heat movement in liquids vaporizing or condensing, remember that a liquid vaporizes only when the vapor pressure of the liquid equals or exceeds that of the surrounding pressure. For example:

> The absolute vapor pressure of water at 100°C is approximately 14.696 PSI or 101.3 kPa, or 1 atmosphere. At sea level, then, water will make the transition to vapor when it reaches 100°C. At 20,000 feet, the surrounding pressure of the air is approximately 46% of that at sea level, equivalent to 46.52 kPa, indicating that water will boil – the vapor pressure of the liquid exceeding the surrounding pressure – at approximately 79°C, absorbing heat as it does so.

Thus, by reducing the surrounding pressure, a liquid may be made to boil at very low temperatures, and conversely by increasing the pressure, vapor may be converted to liquid even though their measured temperature is much higher than the liquid's "normal" boiling point – the basis of refrigeration processes described later in this chapter.

This has practical applications in many areas, including low-temperature evaporation in the food industry as well as the use of pressurized radiators in automobiles that allow the coolant to run at elevated temperatures without boiling. This principle is also used in "puffing" cereals where grain kernels (typically, rice or wheat) are saturated with superheated water in a closed chamber, then the pressure chamber is opened, the endosperm of the grain expands with the steam, and the moisture is usually carried away as vapor, as well as in extrusion processes where superheated water expands as the extrudate exits the pressurized extrusion barrel via the extrusion die to make a puffed product. The same principle highlights the hazard associated with removing a radiator cap from an overheated car, or removing the cap from a glass jar of food that has been heated above the boiling point in a microwave oven. In these cases, releasing the sealed cap will allow the pressure surrounding the liquids to drop to atmospheric pressure all at once, at which point the liquids boil explosively, often causing severe burns.

Quality of Steam

Because there is a large span of energy values that are available as water (or other materials) makes the transition from pure saturated liquid to pure saturated vapor, it is necessary to calculate the *quality* or useable energy content in the liquid-vapor mix. Conceptually, this means that a mass of steam that is primarily composed of saturated liquid droplets is likely to produce less energy of condensation than the same mass of steam that is completely saturated vapor and therefore has a higher enthalpy value. This is not an intuitively obvious quantity, but can be measured using steam calorimeters that are specialized devices used to measure the energy contained in a mass of steam. Large steam operations may utilize *wet steam separators* to remove water droplets via centrifugation or other means to increase the energy content of the plant steam (Equation 2.23):

$$\text{Steam Quality} = (1 - x)(h_{\text{sl}}) + (x)(h_{\text{sv}}) \tag{2.23}$$

x: steam quality, the ratio of saturated vapor to saturated liquid, kg/kg or %
h_{sl}: enthalpy of saturated liquid, J/kg
h_{sv}: enthalpy of saturated vapor, J/kg

Based on the same analysis, the thermal quality of other mixtures, such as ice and water, can be done using a simple mass balance, but it is seldom used.

Other Liquid-Vapor Systems

While this book relies primarily on water-steam systems for illustration, there are similar systems for any number of other compounds ranging from simple gasses such as helium or carbon dioxide and liquids such as ethanol to elements that one does not commonly associate with vapor state, such as aluminum, which boils at 2,467°C and is used to coat plastic films.

Properties of Ideal Gasses and Vapors

Most simple gasses that do not change phase can be described by the ideal gas equation (Equation 2.24):

$$PV = nRT \tag{2.24}$$

P: absolute pressure, N/m^3
V: volume, m^3
n: number of moles of gas
R: gas constant, $R = 8.314 \dfrac{\text{J}}{{}^\circ\text{K} \times \text{mol}}$ although many other systems of units may be used.
T: absolute temperature, °K

This can be used to describe the change in volume, temperature, pressure, or number of moles of gas involved in a particular process. One of the more useful tools that can be applied to problems involving the ideal gas law is a table of values for R, provided in the chapter appendix, the ideal gas constant that incorporates as many of the units that one is using at the time. When gas mixtures are used, the ideal gas law can be modified to accommodate Dalton's law of partial pressures (Equation 2.25):

$$P_x V = n_x RT$$

and by extension,

$$P V_x = n_x RT \tag{2.25}$$

x: fraction of particular gas species
P_x: partial pressure of gas species
V_x: volume fraction of gas species

Another useful modification of the ideal gas law for calculations where many of the constants (volume, pressure, or temperature) are held constant is (Equation 2.26):

$$PV = nRT$$

Holding $n,\ V,\ R$ constant:

$$\frac{P_{\text{final}}}{P_{\text{initial}}} = \frac{T_{\text{final}}}{T_{\text{inital}}}$$

Holding n, P, R constant:

$$\frac{V_{\text{final}}}{V_{\text{inital}}} = \frac{T_{\text{final}}}{T_{\text{inital}}}$$

Holding n, R, T constant:

$$\frac{P_{\text{final}}}{P_{\text{inital}}} = \frac{V_{\text{inital}}}{V_{\text{final}}} \tag{2.26}$$

Mechanics of Materials

All materials have similar characteristics that may be described in simple situations by a number of relatively simple descriptive equations.

Solid Mechanics

Although the nature of solid mechanics – important to basic human endeavors such as building construction since prehistoric times – has been investigated for millennia, the first mathematical underpinnings were provided by Robert Hooke in 1678, who proposed the simple elastic equation (Equation 2.27):

$$\sigma = E\varepsilon \tag{2.27}$$

σ: stress, (force per unit area), Pa, psi, $\text{Lb}_\text{f}/\text{ft}^2$
E: elastic modulus ("Young's Modulus"), Pa, $\text{Lb}_\text{f}/\text{ft}^2$
ε: strain, dimensionless; (length/length or %)

Stress

Stress in its most simple terms is the amount of force that an object is subjected to divided by the area over which it is applied. Thus, a strip of material with a sectional area of 1 cm^2 or $1.0 \times 10^{-4}\ \text{m}^2$ that is subjected to a force of 1 N will have a stress of 1 N/($1.0 \times 10^{-4}\ \text{m}^2$) = 10,000 Pa = 10 kPa.

Strain

Strain is the distance that a material deforms, usually as a result of applied stress. It is most often expressed as a percentage, calculated as the final length divided by the original length. Thus, if the material was originally 10 cm long, and after the application of stress was 12 cm long, the strain would be 12/10 or 120%.

Elastic Modulus

Sometimes called Young's Modulus, after Thomas Young who established it in the early 1800s, the elastic modulus is the numerical relationship between stress and strain. It is convenient to think of this in terms of a spring or rubber band that will stretch some known distance upon the application of a force. The elastic modulus is simply calculated as stress divided by strain (Equation 2.28):

$$E = \frac{\sigma}{\varepsilon} \tag{2.28}$$

Note that for the viscoelastic materials described in this chapter, this number will usually decrease over time – a property called *creep* or *cold flow*, as the material deforms farther and farther under applied stress, and which requires time-based terms to describe.

Deformation of Solids

One of the simpler ways of describing the behavior of solid materials under stress is to place them under tension and describe their changing modes of deformation and failure as more stress applied. Because the linear-elastic behavior of solids (Figure 2.7) has already been described, subsequent additional stress and strain will often include one or more of the following features.

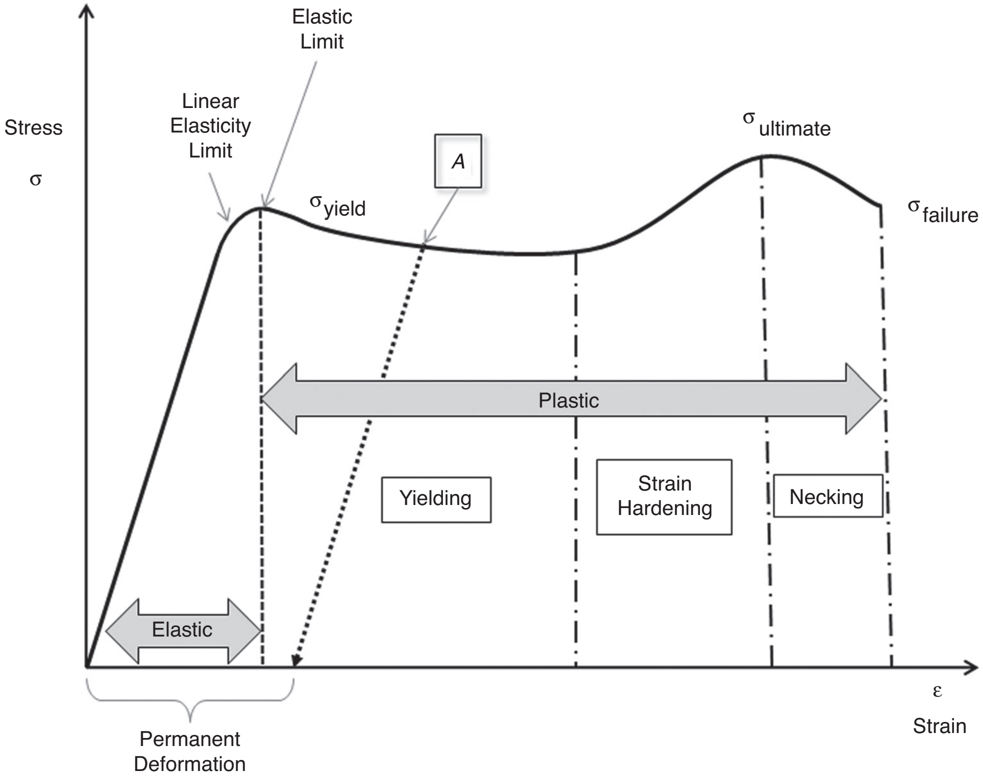


Figure 2.7. Stress-Strain Diagram for Material Under Tensile Load

Limit of Linear Elasticity

Just beyond the limit of linear elasticity, the material still behaves in a completely elastic manner, returning to original shape after the force is removed, but the linear relationship between stress and strain no longer holds. Most often, it becomes a curvelinear relationship that indicates that the material's molecular structure is distorting in unusual ways and is approaching the point at which elastic recovery is not possible.

Elastic Limit/Yield Point

The elastic limit, often different from the limit of linear elasticity, is the point at which the material will no longer behave in a strictly elastic manner, returning completely to its original dimensions. In a brittle material, this is often the failure point as well, but in a ductile material, the material may continue to deform before failing, but part of the deformation will be permanent.

Plastic Deformation

A material that exceeds the elastic limit without breaking will begin to exhibit plastic deformation that then continues until the material fails. For an extremely ductile material, there may be several hundred percent strain in the plastic deformation portion of the stress-strain curve, whereas for brittle materials such as glass and hardened steel, there may be little or none. Plastic deformation has a large number of immediate applications in metalworking and paper, as well as in what we commonly term plastics, because the mechanism of forming the material, either folding it or molding it into the useable shape of a bottle cap or an automobile fender, depends on plastic deformation of the material. Materials that are plastically deformed will store elastic energy as well, and will "spring back" slightly on release of applied force, but also exhibit useable permanent deformation as shown at point **A** on the stress-strain diagram (Figure 2.7).

Failure Point

Also called the *rupture point* or *breaking point*, this is where the materials fail completely by breaking or tearing. The failure stress is taken to be the stress that is applied when this occurs. Note that the failure stress may not be the same as the ultimate stress, and may occur after substantial deformation.

Ultimate Stress

This is the maximum stress that a material exhibits at any point under load. This may occur in any one of several points in the stress-strain curve, depending on the material. In a very brittle material such as glass, the ultimate stress, yield point, and failure stress may be very closely associated (Figure 2.8). In a highly ductile material, the ultimate stress may occur near the yield point or it may occur during plastic deformation. Some materials that exhibit cold-drawing behavior will show an extremely high ultimate stress at the failure point due to the material's molecular structure undergoing reorientation.

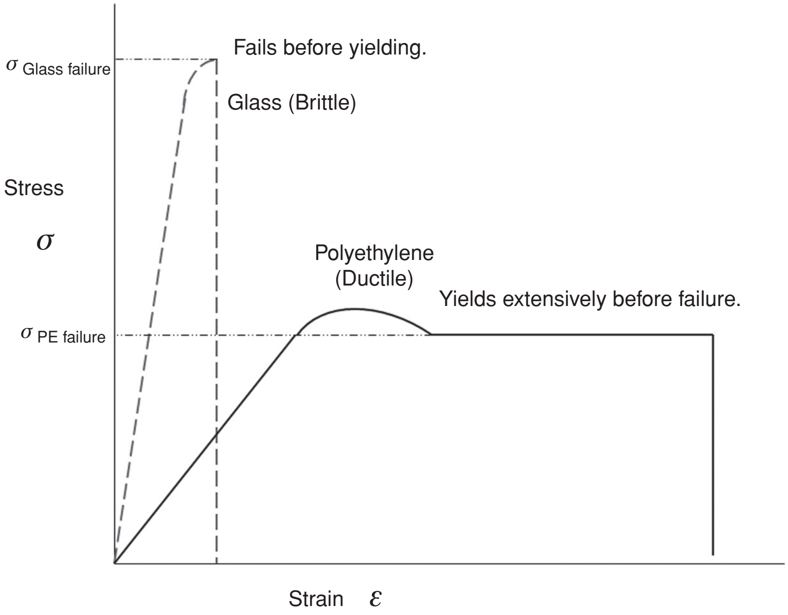


Figure 2.8. Stress-Strain Diagram Comparison of Brittle and Ductile Materials

Stress Concentration and Failure in Brittle Materials

Stress concentration and brittle fracture in elastic materials may be estimated using the Griffith Equation (Equation 2.29) (Figure 2.9) [11]:

$$\sigma_{\text{elliptical crack tip}} = \sigma_{\text{applied}} \left(1 + 2\sqrt{\frac{l/2}{\rho}}\right) \tag{2.29}$$

l: crack length, m
ρ: crack tip radius, m
σ_{applied}: applied stress, Pa

Note that the Griffith Equation shows the substantial effect of either a deep crack or a very small crack tip can have in concentrating stress past the failure point in a brittle material. Thus, small scratches or defects can have a great effect on brittle materials such as glass and tempered steel.

Although a thorough treatment of failure mechanics is beyond the scope of this book, a simple version may be given for brittle materials that promote or inhibit crack propagation as follows:

Initiation

Failure begins at some small weakness or stress concentration point in the material. A small flaw, scratch, or dent may cause this.

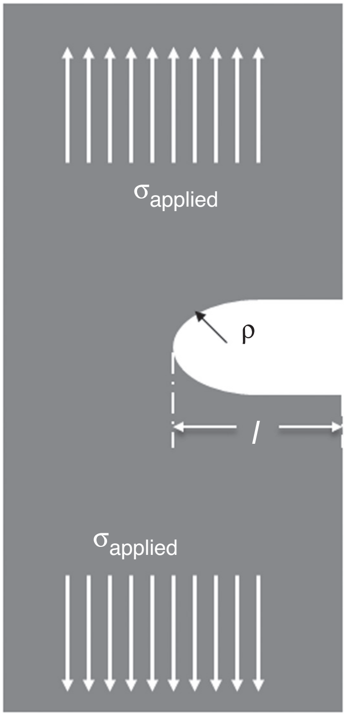


Figure 2.9. Diagram of Griffiths Brittle Failure Model

Propagation

Failure of the material will continue because the stress is still being concentrated along the progressing tip of the failure zone.

Termination

The failure zone continues to propagate until it is stopped. Typically, this occurs when the original stress is relieved, when the failure zone runs out of material to travel through and the piece breaks, or when it encounters an obstruction as shown in Figure 2.10a.

A crack in a piece of brittle material such as the aluminum skin of an airplane can be stopped by drilling a hole at the tip of the crack. This distributes the stress over a wide area, causing the crack growth to stop as shown in Figure 2.10b. The last means of termination results in several interesting phenomena in nature where this principle is used to add strength to materials that might be considered quite fragile otherwise. Materials can be fabricated that have *failure interrupters* in them that will exhibit strength characteristics that are quite different than the base materials from which they are fabricated. Mollusk shells are made of material that is essentially soft chalk, but is produced in such a way that it is made of microscopic overlapping plates. This structure stops any crack that may have started from progressing through the material, rendering the material very strong. In man-made structures, the interruption of failure points is often used to advantage. One of the positive features of engineered composite materials is that fractures seldom have an uninterrupted path to travel, inevitably encountering a discontinuity at a fiber

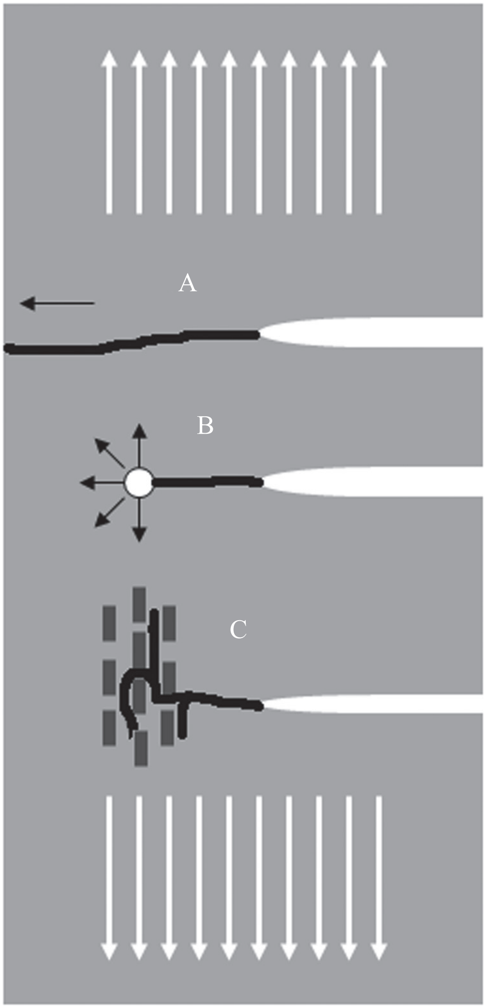


Figure 2.10. Diagram of Failure and Crack Interruptors

bond or other surface and not allowing the crack to progress easily, thereby making the material tougher, as shown in Figure 2.10c.

Failure in Ductile Materials

Ductile materials fail in more complex ways, but in general it is the result of tearing or dissassociation of the structure along the boundaries of some micro- or macromolecular boundary or defect, and is accompanied by the large-scale deformation that its name would imply. In general, the material will exhibit necking, then void formation, then convergence into a final large-scale crack, and finally failure. During this process, a great deal of energy is absorbed in the microfracturing, tearing, and deformation of the material, so ductile materials are often used for their toughness – their ability to absorb a great deal of energy while deforming – rather than their high failure strength. Automobile bumpers, sporting goods, and the like are usually made of high-impact polymers that will absorb a tremendous amount of energy before breaking.

Types of Materials

Elastic

Elastic materials store deformation energy as dimensional deflection. An elastic material will deform upon the application of stress and then return to its original dimensions when the stress is removed. Rubber bands and many harder metals such as steel are good examples of elastic materials, as is glass.

Viscous

Viscous materials dissipate deformation energy as flow. A viscous material will flow when stress is applied, and when the stress is removed, flow stops and the material will not return to its original dimensions; thus it does not store energy in the same manner as an elastic solid. Most fluids are viscous materials, as well as some biological and engineering materials.

Viscoelastic

Viscoelastic materials exhibit properties of both viscous and elastic materials, with the elastic properties predominating. Many biological and plastic materials are viscoelastic to some degree. Plastic materials and particularly those plastic materials used in the packaging industry often are viscoelastic. Viscoelastic materials are time-dependent, in that they will change over time after load application. Most often, viscoelastic materials will exhibit a property termed creep or cold flow, distorting under sustained load and dissipating load energy slowly over time as the structure becomes more and more distorted. Since these are no longer linear elastic materials, a time-dependent constitutive equation is necessary to describe them, the simplest being that in Equation 2.30:

$$\tau = E(t)\varepsilon \tag{2.30}$$

τ: stress, (force per unit area), Pa, psi, $\mathrm{Lb_f/ft^2}$
$E(t)$: time-dependent modulus, Pa, $\mathrm{Lb_f/ft^2}$
t: time, s
ε: strain, dimensionless; (length/length or %)

where E(t) is considered to decrease over time as a function of the particular material involved to account for the continued deformation of the material under a constant load, or to account for the decreasing force contained in the material under a constant deformation. More complex models exist, and time-dependent materials are an entire branch of theoretical mechanics and materials science, but this will illustrate the basic concept.

Elastoviscous

Similarly, these exhibit properties of both viscous and elastic materials, where the viscous properties dominate the system's behavior. These are similar to viscoelastic materials, but most often used for gels and biological fluids.

Anelastic

This is a broader term for the previous two terms that simply defines the relationship between stress and strain as being a complicated, time-dependent function. Because research into elastoviscous, viscoelastic, and other time-dependent materials leads to a plethora of similar terms for similar materials exhibiting similar phenomena, this is an attempt to simplify the terminology. This should not be confused with *inelastic*, meaning “having no elastic properties” – something that rarely, if ever, occurs in real materials.

Rate-Dependent

This is a type of material that has an elastic modulus or other characteristic that is dependent on the rate of load application. A true elastic material will be rate-independent, exhibiting the same elastic modulus regardless of the rate of load application. Rate-dependent materials, on the other hand, will exhibit a differing elastic modulus depending on the rate at which the load is applied. Additionally, materials may exhibit failure points, plasticity, and load characteristics dependent on the load application rate. Some very good examples of this are time-dependent materials such as plastics, as well as rubber compounds and the natural cellulosic polymers that make up paper.

Fluid Flow Systems

For fluid systems, it is first necessary to develop an understanding of the nature of fluid systems as used by engineers. Fluids, which include both liquids and gasses, may be thought of as either *compressible* or *incompressible*, depending on whether they change density with pressure. Although it is commonly thought that liquids are incompressible while gasses may be readily compressed, this is not absolutely true. Sound waves are readily propagated through water or other fluids by compression and rarefaction – a truly incompressible fluid would not transmit sound at all. However, in useful analyses, the assumptions that liquids are generally incompressible and gasses are compressible are used. There are some significant deviations from this, particularly in the food industry that routinely handles materials that are foamed or otherwise have gasses trapped in a liquid matrix. Hydraulics systems engineers also must contend with the fact that hydraulic fluid in heavy machinery will entrain a good deal of air when being used and will become “spongy”, able to compress somewhat, reducing the effectiveness of many hydraulically driven implements.

For fluid flow to occur, there must be the application of force (usually in the form of a pressure differential), and unlike solids, which will deform under the application of force, this will result in a time rate of flow.

Thus, much as stress produces strain in a solid and vice versa, shear force produces shear flow in fluids and vice versa. Additionally, a differential in flow velocities will create shear force, with viscosity, the corresponding resistance to shearing (and therefore flow), corresponding to a solid material’s resistance to deformation. A rough correspondence between solid mechanics and fluid mechanics is shown in Equation 2.31:

Solids (2.31)

$$\sigma = E\varepsilon$$

σ: stress, (force per unit area)
E: elastic modulus (“Young’s Modulus”)
ε: strain

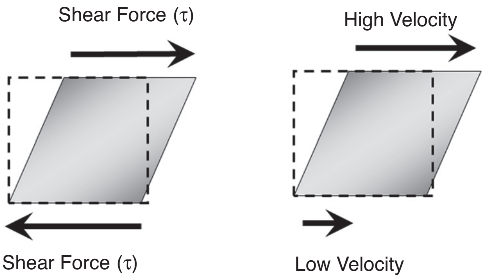


Figure 2.11. Diagram of Shear Deformation in Fluids

Fluids

$$\tau = \mu \dot{\gamma} = \mu \frac{\mathrm{d}V}{\mathrm{d}x}$$

τ: shear stress, Pa
μ: viscosity, Poise, 1 Poise = 1 Pa · s = 1 kg · $\mathrm{m}^{-1} \cdot \mathrm{s}^{-1}$
$\dot{\gamma}$: velocity gradient, $\frac{\mathrm{d}V}{\mathrm{d}x}$, s^{-1}

Flow will continue so long as the force is applied and, unlike elastic solids, will not return energy once the force is removed. Fluid flow energy is usually dissipated as turbulence, friction, and eventually heat energy.

Flow Regimes

Fully developed flow may be thought of as either *laminar* or *turbulent*. Laminar flow indicates that the flow of the material does not change lateral position as it progresses along a reference axis, and thus a particle of material that is at a certain position in the cross section of the fluid flow will not change that position as the fluid makes its way down the flow channel or pipe. Because of this, laminar flow does not exhibit the same heat and mass transfer capacity as turbulent flow. The flow profile of a laminar flow regime is usually parabolic, with the maximum velocity in the center of the pipe being approximately twice that of the average velocity, although this will change with viscosity. Turbulent flow, on the other hand, indicates a great deal of mixing, and any material will change position in all three axes as it is transported. Because of this, the peak velocity at any point is statistically uncertain but can be approximated as 1.2 times the average flow velocity of the fluid for Newtonian fluids.

Reynolds Number

The Reynolds number is a dimensionless number that is used to determine the fluid flow regime as shown in Equation 2.32:

$$\mathrm{Re} = \frac{\rho V x}{\mu} \tag{2.32}$$

ρ: fluid density, $\mathrm{kg/m^3}$
V: fluid velocity, m/s

x: characteristic length dimension usually pipe diameter (D) or distance from leading edge in fluid flow, m
μ: viscosity, Poise, 1 Poise $= 1\ \text{Pa} \cdot \text{s} = 1\ \text{kg} \cdot \text{m}^{-1} \cdot \text{s}^{-1}$

For flow in pipes with diameter D,

$$\text{Re} = \frac{\rho V D}{\mu}$$

$\text{Re} < 2{,}100$,	laminar flow – poor mixing, parabolic flow profile
$2{,}100 < \text{Re} < 4{,}000$	transitional flow – not used in this text
$4{,}000 < \text{Re}$	turbulent flow – good mixing, flow profile variable

Developed Flow in Pipes, Tubes, and Ducts

As fluids enter a piping or channel system, they will exhibit momentary turbulence and instability as the fluid inertia continues to disrupt the fluid flow regime for some time, resulting in *undeveloped flow*. For developed flow to occur, the fluid must travel a distance approximated by the Entrance Length Number (*El*) (Equation 2.33) [12]:

$$L_{\text{fd}} = \text{El}^{*} D \tag{2.33}$$

L_{fd} : length of flow to fully developed velocity profile, m
D : pipe diameter, m
El : entrance length number, dimensionless
$\text{El}_{\text{turbulent}} = 4.4\,(\text{Re})^{.167}$
$\text{El}_{\text{laminar}} = 0.06\,(\text{Re})$

Energy Equation

For the handling of fluid products, the energy requirements of a fluid flow system may be expressed as (Equation 2.34):

$$W_{\text{s}} = \Delta\text{KE} + \Delta\text{PE} + \Delta P/\rho + E_{\text{f}} \tag{2.34}$$

W_{s} is the energy required to drive the process, in m^2/s^2. This value is positive if energy is put into the system (such as with a pump) and negative if energy is being extracted (as with a hydroelectric turbine). The power (in Watts) required to drive the process may be obtained by multiplying W_{s} in m^2/s^2 by the mass flow rate in kg/s; ($\text{m}^2/\text{s}^2{*}\text{kg/s} = \text{kg}{*}\text{m}^2/\text{s}^3 = (\text{kg}{*}\text{m}^2/\text{s}^2)/\text{s} - \text{J/s} = \text{Watts}$)

ΔKE is the change in kinetic energy in the system, also in m^2/s^2, $\Delta\text{KE} = \frac{1}{2}\, m(V_{\text{final}} - V_{\text{initial}})^2$.

ΔPE is the change in potential energy in m^2/s^2, usually related to a change in height (h) of the fluid. This is most often calculated as $\text{mg}(h_{\text{final}} - h_{\text{initial}})$.

$\Delta P/\rho$ is the change in system energy due to pressure changes in m^2/s^2. $\Delta P/\rho = (V_{\text{final}} - V_{\text{initial}})/\rho$. The quantity ΔP is divided by density, ρ, to create dimensional consistency with the other terms.

E_f is energy losses due to friction in the system in m^2/s^2. Most often this is calculated using the Fanning Friction Equation and estimations given in Equation 2.35 [13]. There is also a similar Darcy-Weisbach friction factor that is often used by civil and mechanical engineers, and whose value is four times that of the Fanning Friction Factor – the two should not be confused.

$$E_f = \frac{2fV^2L_{total}}{D} \tag{2.35}$$

f: Fanning friction factor, Dimensionless
V: Average fluid velocity, m/s
L_{total}: Total pipe length, including sum of equivalent pipe lengths, m
D: Actual pipe inside diameter, m (may be different than published pipe size designation)

Estimation Equations for the Fanning friction factor (f):

For Laminar Flow:		
$\mathrm{Re} < 2300$	Moody:	$f = 16/\mathrm{Re}$
For Turbulent Flow:		
$10^4 < \mathrm{Re} < 10^7$	Filonenko:	$f = (1.58\ln(\mathrm{Re}) - 3.28)^{-2.0}$
$3000 < \mathrm{Re} < 10^5$	Blasius:	$f = 0.079\,\mathrm{Re}^{-2.5}$
$6000 < \mathrm{Re} < 2.0 \times 10^5$	McAdams:	$f = 0.046\,\mathrm{Re}^{-0.2}$
$2000 < \mathrm{Re} < 10^5$	Koo:	$f = 0.0014 + 0.125\,\mathrm{Re}^{-0.32}$

Source for Estimation Equations: "Charmeau, A. et al. (2009) "Ultrahigh Specific Impulse Nuclear Thermal Propulsion", DOE Award Number DE-FG07-05ID14699, Final Report. p.166.
Available from: DOE Office of Scientific and Technical Information: http://www.osti.gov/bridge/purl.cover.jsp;jsessionid=718A80A47AACC05C5D7C0C8A4B9E3C90?purl=/950459-XggUh7/

Note that fluid viscosity plays a role in both the Reynolds number and the Fanning friction equation, making it the dominant factor in many food-related fluids with high viscosities, and thus most of the power that is often needed in a pumping system is used to overcome fluid friction (Figure 2.12) rather than any great distance, height, or pressure:

Pipe Equivalent Lengths

Equivalent lengths (L_{eq}) is a method used to simplify the accounting for friction and pressure loss through piping systems that have fittings, valves, diameter changes, and other deviations from flow in simple, straight pipes. Using the equivalent length formula shown in Equation 2.36:

$$L_{eq} = L'/D \tag{2.36}$$

L_{eq}: equivalent length of pipe used in friction calculation, m
D: actual inside diameter of pipe, m
L': length equivalence factor specific to the particular fitting or bend, dimensionless

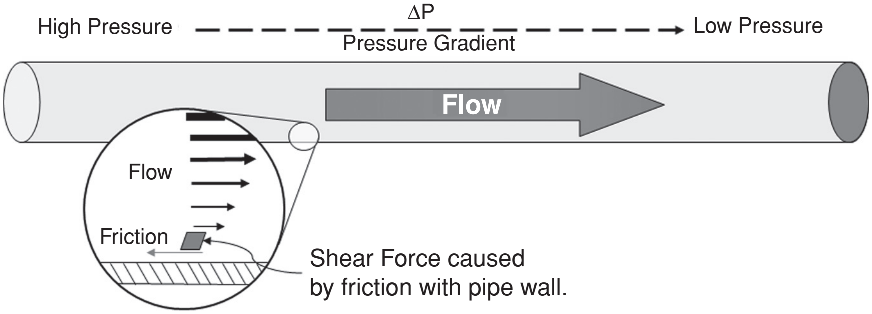


Figure 2.12. Diagram of Fluid Shear in Pipe Flow

in the friction equation, the equivalent straight-pipe lengths may be found and added to the overall length of straight pipes in the friction equation. Some simple L' values are shown in Table 2.5, but in practical use, these are tabulated in engineering handbooks or may be supplied by the fitting or equipment manufacturer.

Pump Efficiencies

Like most mechanical devices, fluid pumps are subject to inefficiencies due to impeller design, leakage, turbulence, and other design factors. When using the energy equation for any practical purpose, one must realize that the energy equation will only give the theoretical value for power in the fluid. This will not be the amount of power that must be applied to an inefficient pump or being produced by an inefficient fluid-flow turbine, so inefficiencies must be considered. Most pumps or turbines have an efficiency rating, either supplied by the manufacturer or that can be generalized from handbooks that may be used to calculate the actual power involved (Equation 2.37):

$$\begin{aligned} &\text{Pumped system } (W_s \text{ negative}): && \text{Actual power required} = W_s/\varepsilon \\ &\text{Turbine system } (W_s \text{ positive}): && \text{Actual power produced} = W_s{}^*\varepsilon \end{aligned} \tag{2.37}$$

Table 2.5. L′/D Values for Common Fittings and Bends

Item	Description	L′/D
Globe Valve	Fully Open	340
Ball Check Valve	Fully Open	150
90° Standard Angle		30
45° Standard Angle		16
Tee Fitting	Flow through “run”	20
Tee Fitting	Flow through “branch”	60
Return Bend (“U”) Fitting		50

Source: Department of Defense (2004), “United Facilities Criteria (UFC); Exterior Mechanical Utility Distribution.” UFC 3-430-09N. http://www.wbdg.org/ccb/DOD/UFC/ufc_3_430_09.pdf

While students usually try to memorize this (and then often misapply it), it is more useful to remember that any power-handling device will lose energy in the exchange, so whether it is the fluid flow providing power to a turbine or a pump providing power to move the fluid, the energy transmitted through the device will always be less than that supplied to it.

Pressure and Safety in Fluid Systems

The energy equation may be used to determine the pressure at any point in a piping network, but particular care must be taken with high-pressure systems where rupture of pipes, seals, or equipment housings may create a safety hazard. Additionally, if the pressure of a fluid drops below its vapor pressure, the phenomenon of *cavitation* will occur – low-pressure bubbles of vapor rapidly forming and collapsing, usually on a localized basis. This can impede pump efficiency and, if the collapse of the bubbles is energetic enough, will create acoustic shock waves that will chip material from the pump impellers and housings. This will shorten the life of the equipment and cause problems with stray metal in the product.

Misuse of Energy Equation Fluid Flow Models

It is tempting to use the energy equation models to attempt to calculate the flow requirements for all types of situations, but it should be remembered that the application of equations to estimate the operation of a system based on relatively low viscosity Newtonian fluids will probably not work well when applied to very thick, viscous fluids often used in the food industry. Many of these materials are gels and viscous solids and barely flow under high pressure in a regime termed *plug flow*, where slugs of material are pushed intact through the system with very little deformation. Rheological determination of the flow properties can assist in determining the proper type of modeling equation, or whether the flow can be modeled on a fluids basis. There have been instances of process engineers attempting to use the energy equation to calculate flow parameters with obviously inappropriate materials, with catastrophic equipment failure such as pump seal and explosive pipe rupture as a result.

Rheology

Rheology is the study of the flow and deformation of matter. Very often this is utilized in the study of the nature of flow of fluids and fluid-like materials. Although water, hydrogen gas, and corn syrup may not appear to have many features in common, the basic concepts of rheology apply to all of them. Because many food products are made up of complex fluid mixtures, often with unusual characteristics, rheology becomes an important consideration in food engineering.

Viscosity

Viscosity is a measure of a fluid materials resistance to flow, and for many common systems is related back to the flow behavior of water under standard conditions. There are several common types of fluids, all of which are distinguished by viscosity characteristics.

Newtonian fluids have constant viscosity that will only vary with temperature, and are described by the simple, linear relationship between shear force and shear rate, as shown in

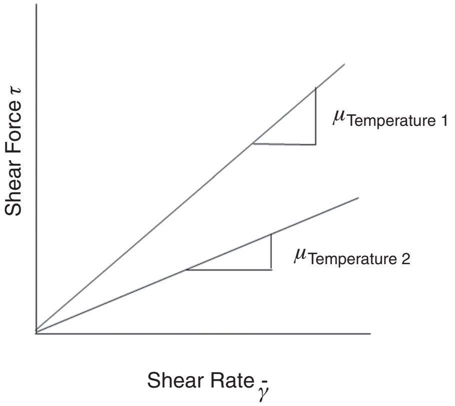


Figure 2.13. Relationship of Shear Force and shear Rate in Newtonian Fluids

Figure 2.13 and described by Equation 2.38:

$$\tau = \mu \dot{\gamma} \tag{2.38}$$

τ: shear stress in the fluid, Pa
$\dot{\gamma}$: shear rate of fluid flow, s^{-1}
μ: viscosity, $\mathrm{Pa \cdot s}$

Power Law fluids are related by a similar equation that accommodates the non-linearity in the stress-shear rate relationships (Equation 2.39):

$$\tau = k\dot{\gamma}^n \tag{2.39}$$

k: consistency index, dimensionless
n: flow behavior index, dimensionless

The experimentally determined *consistency index* and *flow behavior index* replace the viscosity term and will give an indication of the non-linear response to changing shear stress in the fluid. The simplest case is where the flow behavior is completely linear – a Newtonian fluid – and thus $k = \mu$ and $n = 1$.

Adding an initial stress that must be overcome to start the fluid flow, which is a common feature in rheologic fluids – most annoyingly, ketchup and salad dressing in glass bottles – and these fluid types become *Bingham fluids*, thus Equation 2.40 gives:

$$\tau = \tau_0 + k\dot{\gamma}^n \tag{2.40}$$

τ_0: inital shear stress to initiate flow, Pa

For practical purposes, there are several equations that allow flow analysis to be done using the equations available for generalized Newtonian fluid flow, but with the appropriate calculation adjustments for the Reynolds number and other factors. In effect, this will allow the analysis of a simple flow system that is under steady-state conditions given the appropriate fluid parameters.

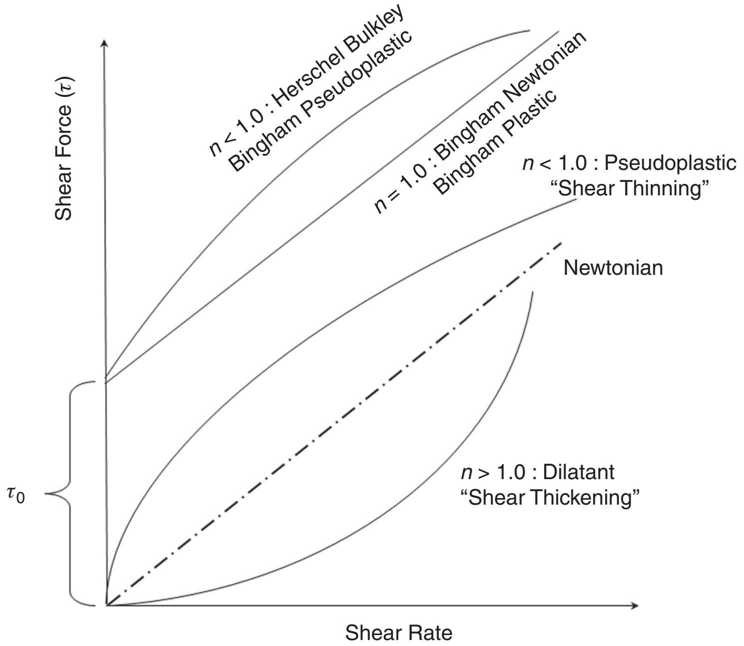


Figure 2.14. Relationship of Shear Force and Shear Rate in Power Law Fluids

Viscoelastic Materials

Viscoelastic (and elastoviscous) materials both store energy as an elastic solid and dissipate energy over time as a fluid; their describing equations are more complex and must manage to describe the stress-strain relationship as a function that includes time as well.

In practical use, several other models beyond the simple time-dependent one given in Equation 2.41 have been proposed to describe simple viscoelastic types of materials. These are usually modeled by engineers after two simple devices: a spring and a dashpot. A spring is simply a piece of material that can store and instantly return elastic energy, and a dashpot is a simple piston-and-orifice device that dissipates force through viscous fluid flow over time.

A practical combination of spring and dashpot can be found in screen door closers that force the door closed slowly by combining spring force and fluid flow to provide slow, steady closing force, or in automobile suspensions that combine a shock absorber (dashpot) and spring to provide isolation from shock and vibration caused by driving over rough surfaces. This latter principle becomes important in shock and vibration isolation for packaged products, and will be discussed in Chapter 9.

"Static" Properties of Viscoelastic Materials

Combining the spring and dashpot components in different sequences gives a means of visualizing and quantifying the relationship between force and response in the materials. In essence, they are very similar in the sense that they will show a short-term response that mimics a simple elastic solid, and over a longer period of time will exhibit continued deformation over time that either will reach an extreme value and stop or will continue until the material fails.

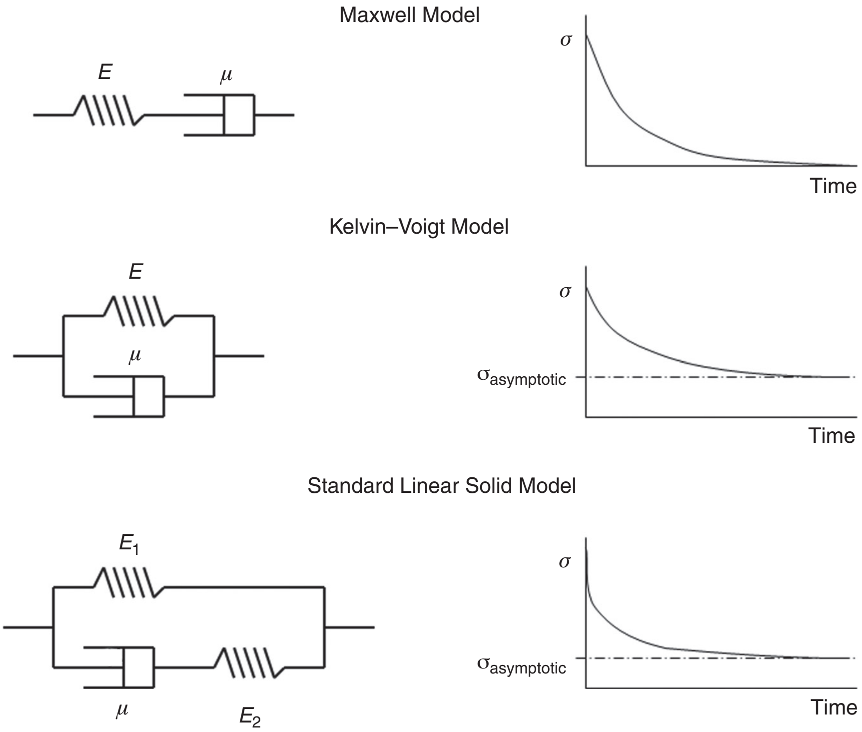


Figure 2.15. Viscelastic Models and Their Behavior Under Sustained Stress

The three most common viscoelastic models are the Maxwell, Kelvin-Voigt, and the standard linear solid model, which are shown, along with their time response to a constant stress loading, in Figure 2.15; their respective constitutive equations are shown in Equation 2.41.

Maxwell Model:

$$\frac{\mathrm{d}\varepsilon}{\mathrm{d}t} = \frac{\sigma}{\mu} + \frac{1}{E}\left(\frac{\mathrm{d}\sigma}{\mathrm{d}t}\right)$$

Kelvin-Voigt Model:

$$\sigma(t) = E\varepsilon(t) + \mu\left(\frac{\mathrm{d}\varepsilon(t)}{\mathrm{d}t}\right)$$

Standard Linear Solid Model:

$$\frac{\mathrm{d}\varepsilon}{\mathrm{d}t} = \frac{\dfrac{E_2}{\mu}\left(\dfrac{\mu}{E_2}\dfrac{\mathrm{d}\sigma}{\mathrm{d}t} + \sigma - E_1\varepsilon\right)}{E_1 + E_2} \tag{2.41}$$

E_n: elastic modulus of spring element n
μ: viscosity coefficient for dashpot

The Maxwell model is the only model that allows stress to be completely dissipated and the material to extend indefinitely mimicking a viscoelastic fluid or very soft polymer, whereas in the Kelvin-Voigt model, the stress will reach an asymptotic value ($\sigma_{\text{asymtotic}}$) and stop. The standard linear solid model adds initial, instantaneous elastic stress removal to the Kelvin-Voigt model, which is a moderately good representation of many polyolefins and packaging plastics. Further, the constitutive equations allow further analysis of material response to vibration and unusual loading schemes.

The practical implications of this are extremely important in the design of packaging structures because they are often required to sustain loads for periods ranging from weeks to years. A hanging pouch of viscoelastic material that exhibits a large and continuing degree of deformation over time will sag and perhaps fall from a display, and a pressurized soft drink bottle would expand into a nearly cylindrical balloon, making them both unstable and unappealing, whereas polymers that have predictable degrees of initial deformation may be properly engineered to fit specific applications.

Dynamic Properties of Viscoelastic Materials

Viscoelastic materials' combination of solid and fluid properties makes them unique in their response to cyclical input. Simple undamped springs will exhibit either an amplifying or damping effect depending on the relationship of the natural frequency of the system to its forcing frequency. Fluid response is somewhat more complex because it responds to the velocity of fluid flow rather than a simple measure of force. Because of this, fluid systems tend to provide a phase shift in their response, considering that the peak velocity often occurs at minimal deflections in the fluid system – the midpoints between extremes.

The combination of viscous and elastic properties may be utilized to "tune out" specific frequencies, reducing the amount of vibration transmitted. This concept is often used in a general form in the design of many package cushions, but is often carefully implemented into specially engineered couplings designed to reduce vibration from motorcycle and automobile engines, and in delicate aerospace installations. This will be discussed further in Chapter 9, in the section dealing with transportation damage and cushioning.

Heat Transfer

Heat transfer is critically important in many types of processing operations that depend on thermal processes for sterilization or pasteurization, as well as in many types of packaging-manufacturing systems. As with the other conservative engineering models, the underlying assumption is that there is a control volume, and that the energy entering, leaving, or remaining within the volume must be accounted for. Although there are many types of energy transfer, as previously described, heat transfer is typically broken into three main modes of energy transfer: radiation, conduction and convection. All of these rely on a variation of the generalized heat transfer equation (Equation 2.42):

$$q = UA(\Delta T_{\text{ht}}) \tag{2.42}$$

q: amount of heat transferred, W, $\dfrac{\text{kg} \cdot \text{m}^2}{\text{s}^3}$

ΔT_{ht}: heat transfer temperature difference $^\circ$K

A: heat transfer area, m^2

U: heat transfer coefficient, $\dfrac{\text{W}}{\text{m}^{2\circ}\text{K}}$

Radiation Heat Transfer

Radiation heat transfer is the only one of the three main modes that does not require an intermediate material such as a solid or liquid through which the heat is transferred. Instead, it relies on electromagnetic energy transfer, usually in wavelengths near the infrared spectra. Other types of radiation, using higher frequencies, rely on the receiving materials or structures to convert the energy such as light or microwave energy to lower-frequency forms such as heat.

Radiative heat transfer is dependent on several factors, including the differences in energy of the surfaces emitting and absorbing the energy (quantified as similar *emissivity* and *absorption* coefficients, respectively), the absolute temperatures of the surfaces, and a constant known as the Stefan-Boltzmann constant. Thus, the radiation heat transfer value can be quantified for a surface radiating heat to a very large area as (Equation 2.43):

$$q = \sigma A_1 \varepsilon_1 \left(T_1^4 - T_2^4\right) \tag{2.43}$$

q: the overall heat transfer from emitter, W
$\sigma = (5.6703\ 10^{-8}\ \mathrm{W/m^2K^4})$; the Stefan-Boltzmann Constant
A is the area of the emitting surface, m^3
ε_1 is the emissivity of the emitting surface, dimensionless
T_1 is the absolute temperature of the emitting surface, $^\circ$K
T_2 is the absolute temperature of the cooler surroundings, $^\circ$K

A partial table of emissivity reveals why radiative and absorbing surfaces are often painted black when a great deal of heat exchange is desired, and why touching a dark surface such as the hood of a black car on a sunny day can be a painful experience. The emissivity values (ε) of several example surfaces are given in Table 2.6.

Conduction Heat Transfer

Unlike radiation, conduction requires an intermediate material to transfer the heat into or out of a material. It is distinguished from convective heat transfer because the conducting materials usually do not move. Heat conduction depends on several factors: the temperature difference across a particular material, the nature of the material's ability to convey heat, and the surface area involved. Fourier's Law, named after Joseph Fourier, the French mathematician and physicist who first postulated it, can be used to describe the one-dimensional (linear) heat flow through a solid body as (Equation 2.44):

$$q = -k\mathbf{A}\frac{\partial \mathbf{T}}{\partial \mathbf{x}} \approx -k\mathbf{A}\frac{\Delta \mathbf{T}}{\Delta \mathbf{x}} \tag{2.44}$$

q: overall heat transfer, W
A: heat transfer area, m^2
k: thermal conductivity, $\dfrac{\mathrm{W}}{^\circ\mathrm{C}\cdot\mathrm{m}}, \dfrac{\mathrm{W}}{^\circ\mathrm{K}\cdot\mathrm{m}}$
$\dfrac{\partial \mathbf{T}}{\partial \mathbf{x}}$: generalized temperature differential, $^\circ$C/m, $^\circ$K/m
$\dfrac{\Delta \mathbf{T}}{\Delta \mathbf{x}}$: steady-state temperature difference $\Delta\mathbf{T}$ through distance $\Delta\mathbf{x}$, $^\circ$C/m, $^\circ$K/m

(Note that the negative term ensures that the heat flow will move from hot to cold region)

Table 2.6. Table of Selected Emissivity (ε) Values

Material	ε
Carbon Black	0.95-0.99
Steel, Polished	0.7
Ice & Snow	0.94-0.99
Black Paint	0.96
Bread (average)	0.9
Wood	0.85
Soil	0.38
Aluminum Paint	0.30
Aluminum Foil	0.06-0.09
Silver, Polished	.01

Sources: S. Grabowski, M. Trigui, M. Marcotte, and F. Castaigne (2006). "Heat Transfer Coefficients on Cakes Baked in a Tunnel Type Industrial Oven," *Journal of Food Science* 64(4), 688–94.
N. Hamdami, J.-Y. Monteau, and Alain Le Bailb (2004). "Heat and Mass Transfer in Par-Baked Bread during Freezing," *Food Research International* 37(5), 477–88.
MODIS UCSB Emissivity Library. http://g.icess.ucsb.edu/modis/EMIS/html/em.html
N. P. Zogzas, M. K. Krokida, P. A. Michailidis, and Z. B. Maroulis (2002). "Literature Data of Heat Transfer Coefficients in Food Processing," *International Journal of Food Properties* 5(2), 391–417.

For a composite surface such as that shown in Figure 2.16, which is a common feature in insulated structures ranging from food packages to picnic coolers to house walls, the overall equation becomes (Equation 2.45) based on the assumption of constant heat flow through the composite section of material:

for n layers with individual thicknesses: $\Delta X_{1,2,3\ldots n}$ and thermal conductivities: $k_{1,2,3\ldots n}$

$$q = -A\left[\frac{\Delta T_{\text{overall}}}{\left(\frac{\Delta X_1}{k_1}\right)+\left(\frac{\Delta X_2}{k_2}\right)+\cdots+\left(\frac{\Delta X_n}{k_n}\right)}\right] \tag{2.45}$$

A: heat transfer area, m^2
$\Delta T_{\text{overall}}$: temperature difference throughout entire composite structure, $^\circ$C, $^\circ$K

Calculation of steady-state heat conduction is a fairly straightforward exercise once the material thicknesses and thermal conductivities are known. Thermal conductivities of some materials are given in Table 2.7.

Convection Heat Transfer

The third major means of heat transfer, convective heat transfer is the most commonly experienced in everyday life. Heat is convected into or out of our body continuously to maintain body temperature and to remove heat generated by our body's metabolic processes. For convection to occur, it is necessary to have a moving fluid to exchange heat. Convective heat transfer therefore becomes the most complex to calculate because it requires an understanding of fluid flow and

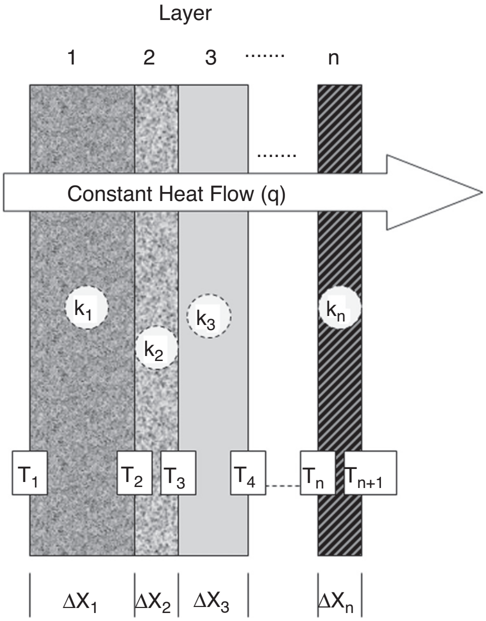


Figure 2.16. Composite Heat Conduction Diagram

the bulk properties of materials to arrive at a quantitative estimation of how much heat will be exchanged under a given set of conditions. In addition to this, for many of the estimation systems, knowledge of whether the system is a *forced* or *natural* convection system is necessary, because the amount of heat exchanged is often different by several orders of magnitude.

Considering that we have already defined fluids in terms of compressible and incompressible rather than liquid or gas, we have a set of equations that will predict fluid flow for both liquids

Table 2.7. Thermal Conductivities of Common Materials

Thermal Conductivities (W/(m°K))	
Aluminum	205–250
Steel	36–54
Stainless Steel	16.3
Glass	0.8–1.4
Packaging Plastics	0.04–0.52
Foods	0.6–0.7
Water	0.5–0.6
Ice	1.6–2.2
Snow	0.05–0.25
EPS Foam	0.03
Urethane Foam	0.021
Fiberglass	0.04
Silica Aerogel	0.003–0.03

Source: “Thermal Conductivity of Some Common Materials.”
http://www.engineeringtoolbox.com/thermal-conductivity-d_429.html

and gasses. For convective heat transfer, we also have to have an understanding of what is causing the fluid movement – convection – to understand the amount of heat energy that will be transferred.

Natural convection, sometimes called free convection, is driven by the change in bulk density of the fluid. As the fluid is heated, it will expand, and will decrease in density, causing it to rise to a region of similar density. As it cools, its density will increase and it will sink. In many heating systems, as well as in nature, these two events will be coupled, causing a repeating cycle of heating and cooling of the same material, often forming *convection cells*, regions where the hot material flows upward in a column then settles in a region outside of the upwelling fluid. Clouds are the most common example of this, although it can be observed on the surface of a pot of boiling water. Natural convection is often exploited to manufacture relatively inexpensive heat exchangers with few or no moving parts that are used in solar collectors, hot water heaters, and geothermal heating systems. Because fluid velocity is determined solely by bulk density changes, it is not immediately apparent what the Reynolds number is, and so it is often hard to discriminate between the laminar or turbulent flows. This is usually determined as a result of other empirical formulas.

Forced convection, on the other hand, relies on an external source of power for the fluid movement and is usually orders of magnitude more effective in transferring heat than natural convection. Although natural convection effects still exist in a forced-convection system, they are usually overwhelmed by the action of the pump or fan, and are most often neglected in simple calculations. In a forced-convection system, fluid velocity can be measured or calculated and a Reynolds number determined.

The overall heat transfer in a convective system is given by (Equation 2.46):

$$q = hA(T_\mathrm{f} - T_\mathrm{s}) \tag{2.46}$$

q: overall convective heat transfer, W/m^2
h: convective heat transfer coefficient, $\dfrac{\mathrm{W}}{\mathrm{m}^2 \cdot {}^\circ\mathrm{C}}, \dfrac{\mathrm{W}}{\mathrm{m}^2 \cdot {}^\circ\mathrm{K}}$
A: heat transfer area, m^2
T_f: fluid temperature, °C, °K
T_s: surface temperature, °C, °K

Determination of the Convective Heat Transfer Coefficient

Determination of the convective heat transfer coefficient is the most arduous part of calculating a value for convective heat transfer. Although tabulated estimations exist, the determination of this value may require any number of different types of analyses. Because of the complexity of these calculations, a series of simple empirical equations based on the type of flow and other parameters have been designed to calculate the Nusselt number (Equation 2.47):

$$\mathrm{Nu} = \frac{h \cdot L}{k} \tag{2.47}$$

h: the convective heat transfer coefficient, $\dfrac{\mathrm{W}}{\mathrm{m}^2 \cdot {}^\circ\mathrm{C}}, \dfrac{\mathrm{W}}{\mathrm{m}^2 \cdot {}^\circ\mathrm{K}}$

L: characteristic length of system, m

k: Fluid thermal conductivity, $\dfrac{\mathrm{W}}{\mathrm{m} \cdot {}^\circ\mathrm{C}}, \dfrac{\mathrm{W}}{\mathrm{m} \cdot {}^\circ\mathrm{K}}$

For pipes, $L = D$

$$\mathrm{Nu} = \frac{h \cdot D}{k}$$

By rearranging terms:

$$h = \frac{\mathrm{Nu} \cdot k}{d}$$

Determining the Nusselt number in practical applications requires that the nature of the flow regime, fluid type, and type of convection be known, as well as perhaps several other factors to determine which equation to apply. These have been derived by dimensional analysis and empirical studies, and are therefore useful only within the limited conditions set forth in the equation set. However, once the estimation of the Nusselt number is made, Equation 2.47 may be combined with the known values for diameter and fluid thermal conductivity to give an immediate estimate of the value of the heat transfer coefficient (h).

Estimation of The Nusselt Number

Estimation of the Nusselt number is a large part of heat transfer analysis, and there are a number of empirical formulas available for different materials and flow regimes. A very limited list of generally applicable models will help understand the method of analysis, but specific applications may require consulting a more specialized heat transfer reference.

Nusselt Number for Turbulent Flow

The simplest estimation calculation for fully developed turbulent flow in smooth tubes that considers the effects of temperature on the fluid viscosity was proposed by Sieder and Tate (Equation 2.48) [14]:

$$\mathrm{Nu} = 0.027\mathrm{Re}^{0.8}\,\mathrm{Pr}^{0.33}\left(\frac{\mu_{\mathrm{bulk}}}{\mu_{\mathrm{wall}}}\right)^{0.14} \tag{2.48}$$

Pr: Prandtl Number, dimensionless

$$\mathrm{Pr} = \frac{C_{\mathrm{p}} \cdot \mu_{\mathrm{bulk}}}{k}$$

μ_{bulk}: bulk viscosity of fluid, Pa · s

μ_{wall}: viscosity of fluid at heated or cooled surface, Pa · s

C_{p}: specific heat of fluid, J/(kg K)

k: thermal conductivity of fluid, W/(m K) and is valid for

$$0.7 \leq \mathrm{Pr} \leq 16{,}700$$

$$\mathrm{Re} \geq 10{,}000$$

$$\frac{L}{D} > 10$$

For laminar heat transfer in tubes, another estimation equation is available (Equation 2.49):

$$\mathrm{Nu} = 1.86(\mathrm{Re}\cdot\mathrm{Pr})^{0.33}\left(\frac{D}{L}\right)^{0.33}\left(\frac{\mu_{\text{bulk}}}{\mu_{\text{wall}}}\right)^{0.14} \tag{2.49}$$

D: tube diameter, m
L: tube length, m and is valid for

$$\mathrm{Re}\cdot\mathrm{Pr}\cdot\frac{D}{L} > 10$$

Formation of Laminar Sublayers

Because of the three-dimensional nature of real-world applications, Reynolds numbers description of fluid flow applies in all directions of fluid flow. For a flat heat exchanger plate or the surface of a tubular heat exchanger, a region just near the surface may develop laminar flow, even in flow regimes that are generally turbulent. This will interfere with heat transfer, because the laminar fluid flow will transfer heat only by conduction due to the lack of mixing. If this phenomenon is obstructive enough, the flow or heat exchanger will have to be modified to correct the problem, and the application may require scraped-surface heat exchangers or unusual surface profiles to overcome this limitation. These are a common feature in food processing applications with high viscosity fluids.

Heat Exchangers

Heat exchangers are a means of transferring heat from one medium to another, and typically involve at least one fluid component. These exchangers may take many diverse forms in nature and engineering from jackrabbits' ears that have evolved to help lose body heat in the desert to the extraordinary energy transfer systems that are designed into nuclear power plants. In food processing, heat exchangers run the gamut from a simple cooking pot to complex, multistage systems for aseptic processing.

Direct-contact heat exchangers will mix the heating medium (typically, hot water or "culinary steam" that does not add taste to the product) with the product, and the more common, indirect heat exchangers will separate the heating or cooling medium from a product by means of a series of tubes, plates, or other surfaces that are typically made of a thermally conductive material such as stainless steel.

Because of the diverse nature of food products, the heat exchangers that have been developed to process them are similarly diverse, but they all share the requirements of being thermally efficient, cost-effective, durable, and sanitary. Low-viscosity fluids that easily develop turbulent flow can be processed in single or multipass tubular or plate heat exchangers, whereas more viscous products may have to have shaped tubes or even mechanically driven scraped-surface heat exchangers to achieve proper mixing.

Shell and Tube Heat Exchangers

As their name implies, the simplest of shell and tube heat exchangers may be a simple pipe that is jacketed with heating or cooling media. In practice, these will usually involve many parallel tubes, perhaps folded or otherwise arranged to increase efficiency. Energy balances between product and media may be calculated using an energy balance with the addition of the use of the log mean temperature differential, considering that no distinct temperature difference exists to work with. Additionally, the direction of flow of product relative to heating or cooling media is important because the maintenance of high temperature differences with countercurrent flow exchangers will provide a more efficient heat-transfer system than a concurrent one.

Heat Exchanger Calculations

The rate of heat transfer through a heat exchanger is similar to the one previously given by the general conduction equation (Equation 2.50):

$$q = UA(\Delta T_{\mathrm{ht}}) \tag{2.50}$$

q: Heat Transferred, kJ

U: Heat Transfer Coefficient, $\dfrac{\mathrm{kJ}}{\mathrm{m}^2 \cdot {}^\circ\mathrm{C}}$

A: heat transfer area, m^2

ΔT_{ht}: heat transfer temperature gradient, °C

From this, it is obvious that higher rates of temperature differential will allow the use of a smaller (and thus less expensive) heat exchanger for a given value of U and a fixed need for q. To this end, several different strategies have been adopted, either by using a counterflow heat exchanger (Figure 2.18) that maintains a higher temperature differential between the inlets and outlets of both product and heating or cooling media, as well as the construction of heat exchangers that utilize multiple surfaces (so called *multitube* or *multipass* heat exchangers) to improve the value of U. Automobile radiators that must remove the waste heat from internal combustion engines are typically single-pass, multitube heat exchangers that rely on thin, flat tubes with attached thin fins of copper or aluminum to help transfer heat from the engine coolant into the airstream caused by vehicle movement and fan operation. As more and more tubes and passes accumulate, the overall effectiveness of the heat exchanger is hampered by the changing temperature of the heating or cooling media as it passes through the exchanger's many stages. This is accommodated by incorporating a correction factor F into the overall heat transfer equation (Equation 2.51) that is either taken from a standard heat exchanger configuration or is supplied by the manufacturer based on experimental evaluation.

$$q = \mathrm{F}(\mathrm{UA}\Delta T) \tag{2.51}$$

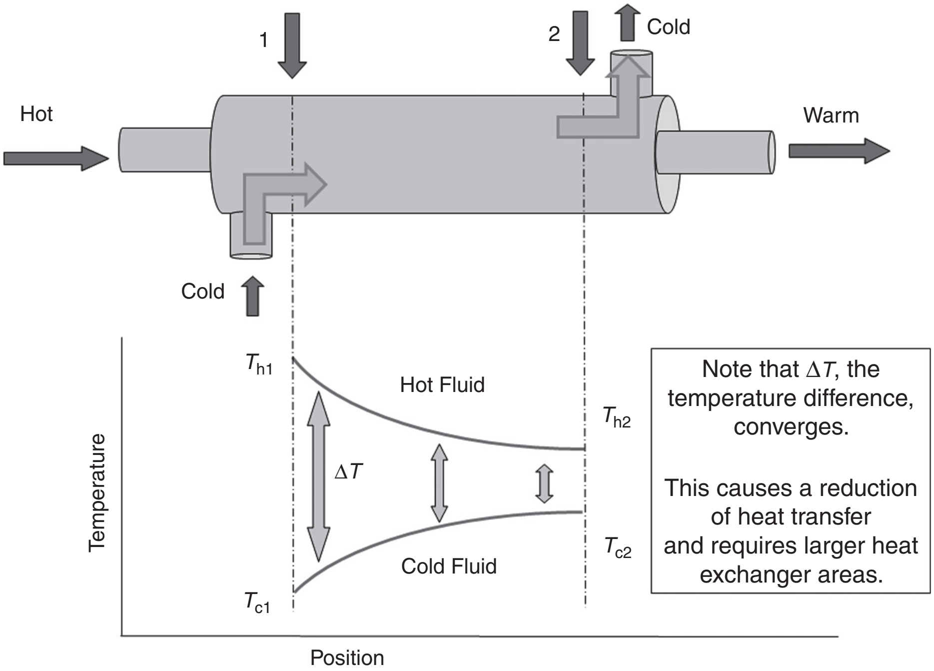
F: Correction factor, dimensionless

where F may range from 0.6 to 1.0 in typical applications and can be found either in manufacturer's test results or in standard handbooks.

Log Mean Temperature Differential

For many types of heat conduction, it is not intuitively obvious what the temperature differential should be. In this case, the log mean temperature difference provides a slightly more accurate estimation of heat exchanger performance (Equation 2.52):

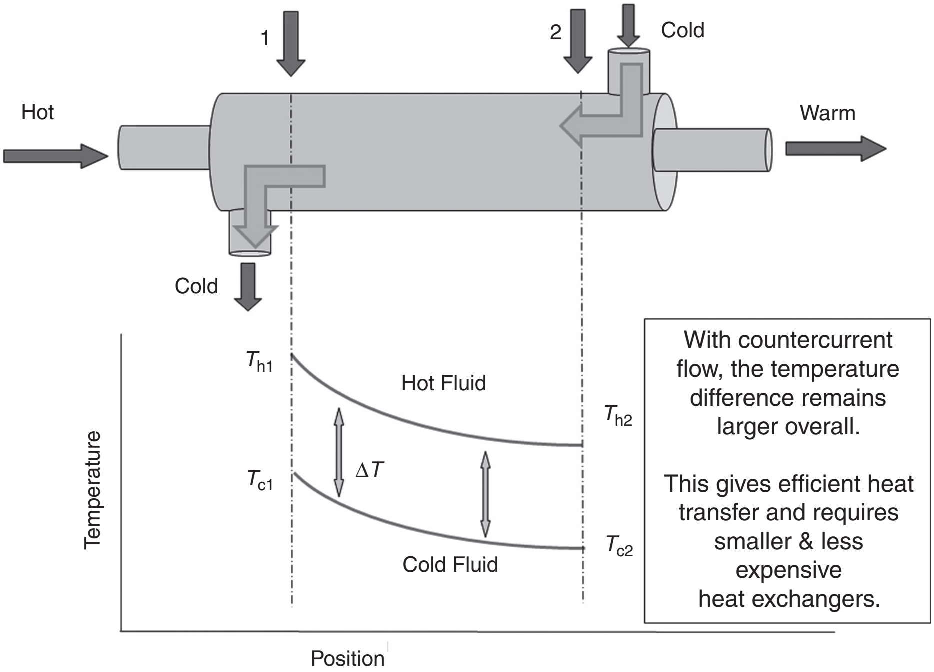
$$\Delta T_{\mathrm{ht\ log\ mean}} = \left(\frac{(T_{\mathrm{h}_2} - T_{\mathrm{c}_2}) - (T_{\mathrm{h}_1} - T_{\mathrm{c}_1})}{\ln\left[\dfrac{(T_{\mathrm{h}_2} - T_{\mathrm{c}_2})}{(T_{\mathrm{h}_1} - T_{\mathrm{c}_1})}\right]} \right) \tag{2.52}$$



Note that ΔT, the temperature difference, converges.

This causes a reduction of heat transfer and requires larger heat exchanger areas.

Figure 2.17. Concurrent Flow Shell and Tube Heat Exchanger



With countercurrent flow, the temperature difference remains larger overall.

This gives efficient heat transfer and requires smaller & less expensive heat exchangers.

Figure 2.18. Concurrent Flow Shell and Tube Heat Exchanger

where ΔT_1 and ΔT_2 are taken at inlet and outlet points of many heat exchangers as shown in Figures 2.16 and 2.17, and thus the overall heat transfer can be expressed as (Equation 2.53):

$$q = U \cdot A \cdot \left(\frac{(T_{\mathrm{h}_2} - T_{\mathrm{c}_2}) - (T_{\mathrm{h}_1} - T_{\mathrm{c}_1})}{\ln\left[\dfrac{(T_{\mathrm{h}_2} - T_{\mathrm{c}_2})}{(T_{\mathrm{h}_1} - T_{\mathrm{c}_1})}\right]} \right) = U \cdot A \cdot \Delta T_{\mathrm{ht\ log\ mean}} \tag{2.53}$$

Other Types of Heat Exchangers

Jacketed kettles are often used for batch processing in small to medium-sized operations and rely on having large kettles with the inner surface mated to coils or a hollow jacket to transfer heat into or out of the product. Similar methods are used in the brewing industry to remove the heats of fermentation, although these may be as simple as a closed fermenter with a film of water flowing over its outer surface. Immersion coil heat exchangers work in similar fashion except that they rely on a simple coil of tubing that is immersed in the product to transfer heat. These have the advantage of being extremely simple, but may be hard to clean properly with certain types of products, or if product has been cooked onto the surface. Scraped-surface heat exchangers are used for very viscous liquids and rely on mechanical scrapers to remove the film of heated or cooled product from the outer heat transfer surface. Ice cream freezers are a common example of this type of heat transfer device, with the added feature that the scraping assembly (called a *dasher*) is used to incorporate necessary air (called *over run* because it expands the total product volume) into the ingredient mix as it freezes.

Plate-type heat exchangers utilize large hollow plates with product and heat-transfer fluid in alternate chambers to provide a very large surface area and efficient heat transfer. Most plate systems are constructed with gasketed subassemblies held together in a large press structure so that they can be completely disassembled to clean the product surfaces after operation. These are particularly common in dairy operations.

Alternative Food Processing Technologies

The preceding sections described some of the classic modes of conducting thermal heat into or out of a product, and while these predominate in industry because of the ease of use and relatively low cost and high reliability of installed equipment, there are other processing methods that are being used on either an experimental or limited basis that provide thermal processing without using the three basic methods previously described.

Ohmic Heating

Ohmic heating has been a viable processing method for many years – the first implementations were conducted during the nineteenth century – and although the process parameters are now well described, the basic concept remains the same: a current applied to a resistive material will generate internal heat in a material according to Ohm's law. The advantage to this type of processing is that the heat is generated within the product itself and is therefore not subject to the problems with time lag inherent in conductive heating of thick sections of material.

Although this seems like an appealingly simple and effective means of processing materials, it depends on a moderate balance of conductivity and resistance. If the material has too little resistance, the heat generation will be very low, and if the material has too much resistance, it will require enormous current flow to operate properly. Further, the current flow in a product will be along a path of least resistance, so for heterogeneous materials, the heating may occur in a single phase or ingredient while the rest of the material remains underheated. A good example of this might be a meat-containing stew where the conductive saline broth would provide a good current path (and therefore poor heat generation) whereas the resistive meat and vegetable solids would only be heated indirectly, leaving them underprocessed. Finally, using electricity directly, with the previously described thermodynamic losses, is often more expensive than generating heat directly from some other fuel source. So, for these types of products to be processed by Ohmic heating, the factors of economics, effectiveness, and efficiency have to converge. A homogenous, somewhat resistive moist product that resists efficient processing by other means, often as a result of poor thermal conductivity, is an ideal target product for this type of processing operation, and because of its ability to process product in a continuous fashion, it may be ideal for certain types of in-line pasteurization and sterilization processes, and particularly those coupled to aseptic packaging lines. The pet food industry has been successfully experimenting with Ohmic heating for some time for use with its moist and semimoist products.

High-Pressure Processing

High-pressure processing, which relies on extremely high pressures, often combined with a time or flow protocol, has also been around since the nineteenth century, and substantial commercial sterility for processed fruits was reported as early as 1914 [15]. The phenomenon has remained a curiosity for some time because of the difficulty of producing a cost-effective means of treating products at the extremely high pressures necessary. Recent interest has been the result of the availability of high-pressure technologies that were produced for other processes such as continuous-flow devices for the high-pressure stripping of paint from ships, or batch systems originally produced as hot and cold autoclaves for the densifying, compacting, and curing of composite and ceramic material structures, such as powder-casting.

One of the attractions of high-pressure processing is that it is a *cold* process; although some heat is generated as compression occurs, this is relatively small when compared to typical thermal processing techniques and can aid in the preservation of flavors and colors in delicate products. As one might expect, there are *textural changes* that may occur as a result of the enormous distortion of the materials in the press-cell wall, and fiber rupture may cause an undesired homogenization process or lead to undesired organoleptic changes.

Complete microbial inactivation in high-pressure processes may be problematic as well; most current applications are used to extend the shelf life of refrigerated foods rather than provide shelf stability. This is due to the highly variable pressure sensitivity of different organisms, and the durability of bacterial spores. Spore-forming bacteria such as *C. botulinum* and *Bacillus cereus* have demonstrated tremendous resistance to pressure, and several types of non-sporeforming bacteria that have been studied are highly resistant to high pressure processing – for example, *E. coli* O157:H7 required 700 MPa, and *S. aureus* 700 MPa to achieve a 5 log-cycle reduction in population [16]. The final result of this is that other co-factors such as pH, salinity, or partial thermal processing may be included in the final processing regime to achieve the desired result. High-pressure processing is currently best utilized as a pasteurization device for liquid products and some meats and fruit or vegetable purees. Slow throughput times and incomplete inactivation of some organisms has continued to be a problem in the manufacture of shelf-stable foods using high pressure as the sole means of commercial sterilization.

An additional hurdle to the use of high-pressure processing is the high cost of installed equipment and the comparatively slow cycle rate for batch processes, although it is interesting to note that on at least one occasion, companies that have installed processing equipment for their own use have found that there is sufficient demand to warrant the installation of additional equipment for use in contract packaging operations.

Microwave Heating and Processing Principles

Microwave ovens and thermal processing, invented as a result of the intensive development of accurate microwave aerial radar during World War II, have revolutionized the way that food is prepared in most of the developed world, with sales in developing countries with workable electric power distribution systems soaring as well. Microwave heating was discovered by Percy Spencer, who developed magnetron manufacturing methods for Raytheon during World War II, and who reportedly noticed that a candy bar in his pocket melted as he stood in front of an operating magnetron system, though he must be considered lucky given the cataract hazards from microwave energy [17]. To understand the mechanisms that packages and food use to convert microwave energy into heat in the oven cavity, it is first necessary to have a description of the general mode of operation of ovens' conversion of electric power into a useful electromagnetic field (EMF) within the oven cavity.

The internal circuitry of a household microwave oven takes household current (typically, 100–240 VAC at 50–60 Hz, depending on location), amplifies the voltage, and passes it through a cavity magnetron. The flow of electrons causes the cavity to emit a high-power electromagnetic field (EMF) at one of two approved frequencies (usually 2,450 MHz, although 915 MHz systems exist for commercial processing). The physics of this are somewhat complex, but the process of creating a powerful, single-frequency EMF from electric current is roughly analogous to the way a whistle creates a loud, single-frequency tone from a turbulent stream of air. Energy conversion efficiency is good, in the range of 60–70%, and frequency control is sufficient so this remains the universal method of microwave generation for home ovens.

From the magnetron, the EMF is channeled through a waveguide duct to the oven cavity, often passing through a *stirrer*, a rotating, multifaceted reflector that alters the beam dispersion into the oven cavity so that standing nodes and antinodes – which can cause hot and cold spots in the cooking foods – are avoided. Nodes are regions where overlapping waves reinforce, causing high-energy areas, and antinodes are regions where overlapping waves cancel one another out, causing low-energy areas. Most new ovens have rotating platforms built in to further distribute energy application to the food product to avoid hot and cold regions in the product. It is also possible to use a microwave EMF field to generate high-temperature plasma fields, but there is currently no commercial implementation of this for home food preparation.

Heating Mechanisms

There are two major heating mechanisms that are possible in a microwave oven: dipole rotation and ionic polarization. In dipole rotation, the polar molecules will try to "follow" the oscillating electric field, generating heat. Water, fats, and other very polar substances tend to heat more quickly than dry, non-polar ones. Given the broad range of polar compounds in foods, this is the predominant heating mechanism. Ionic polarization is most often a secondary effect and generates heat as shifting electric field accelerates ions, which generates heat when collisions occur on molecular level, as shown in Figure 2.19.

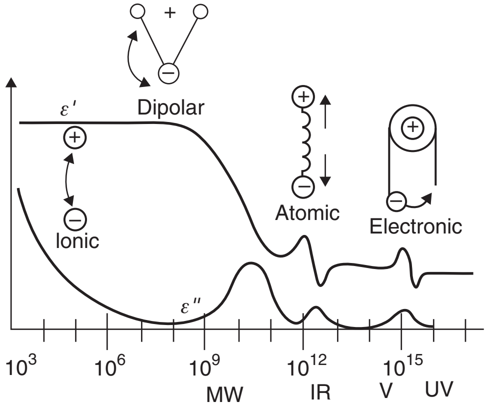


Figure 2.19. Dielectric Response of Materials
Source: Dr. Kenneth A. Mauritz, Used with Permission

Power Density, Heat, and the Dielectric Properties of Materials

Power density per unit volume can be given by Equation 2.54:

$$p = \omega \cdot \varepsilon'' \cdot \varepsilon_0 \cdot E^2 \tag{2.54}$$

$\omega = (2\pi f)$: the angular frequency, rad/s
f: frequency, Hz
ε'': the imaginary component of the complex permittivity equation: $\varepsilon = \varepsilon'\omega + i\varepsilon''\omega$
ε': the real component of the complex permittivity equation (not used in power calculation)
ε_0: the free space permittivity
E: electric field strength

Generally, permittivity or the dielectric constant (ε'), is a measure of how a particular material will allow an electric field to penetrate, with low-dielectric materials typically being considered conductors (neglecting frequency effects) and high-dielectric materials being considered insulators. Copper wire has a very low dielectric constant, and is therefore a good conductor, whereas the polymer insulation on wire has a high constant and is used as an insulating cover. The complex permittivity component is generally termed the dielectric loss factor (ε'') and is generally used as a measure of a material's ability to dissipate electrical energy as heat. Materials that have a high loss factor are termed *lossy* materials and are the basis for microwave susceptors to convert microwave energy into heat in food packaging, as well as many other applications including stealth antiradar coatings.

The loss tangent – the ratio of resistance to reactance – gives an idea of how well an electric field will penetrate and heat a material, and can give a rough estimate of its utility for thermal conversion. A high loss tangent will heat food well but not transmit energy to the interior of a large food mass, leaving it uncooked in the middle, whereas a low loss tangent may transmit energy through a material but may not heat well. Given that the loss tangents are a function of individual materials' properties such as phase and temperature, as previously discussed, only generalized predictions can be made about the ability of foods, which generally have non-linear loss characteristics and are anisotropic, to heat well in microwave fields. Most of the utilization has been based on empirical observation rather than a deep analysis of the mechanisms of action in food compounds.

Lossiness is therefore a desirable property in a material that is being heated in an EMF field because highly lossy materials heat more quickly and convert energy more efficiently when an EMF is applied. Conversely, a product that is extremely lossy will exhibit a high temperature gradient through the materials' section because most of the energy will be converted at or near the surface, leaving the core material unheated. The lossiness of a material, and particularly complex, non-linear materials such as foods, is a function of the geometry, temperature, and chemistry of material as well as several secondary factors. Composition factors include the moisture, solids, fats, and salts content as well as the temperature, and particularly phase of the material as well as the state of water in the product.

Lossiness changes dramatically during phase changes, with ice and other crystalline materials being orders-of-magnitude less lossy than liquid water, and cold liquid water being less lossy than warm water. This effect is enhanced even further with the addition of salts, sugars, and other compounds. Other compounds tend to increase their lossiness with temperature increases as well, leading to *runaway heating*, where hot areas heat faster and faster with increasing conversion efficiency, whereas cold or frozen ones change very little. This can cause the product to burn or even ignite in some areas while remaining frozen in others, and was one of the complaints with early-model ovens that lacked stirrers or turntables, because standing nodes and antinodes amplify the effect even further. A great deal of microwave oven design is concerned with power settings that pulse power on and off, allowing heat transfer and equilibration to occur, and with rotating turntables and *stirrers* – slowly rotating reflectors, typically in the roof of the oven, that try to even out the power distribution problems caused by node and antinode formation, and to prevent runaway heating.

An additional concern with home microwave heating is that microwave heating does not create surface browning effects that we have learned to expect while using conventional ovens that transfer heat to food products by conduction and radiation, which creates high surface temperatures. In an effort to counteract this, many food manufacturers have included microwave *susceptors* – patches or components that have a lossy coating or lamination – to provide direct thermal heating of a product, which are covered in Chapter 4.

Microwave Processing

As an industrial process, microwave heating suffers from high energy and equipment costs, safety concerns, and relatively poor conversion efficiency. Its primary use is in larger kitchens and commissaries, as well as commercial installations tempering frozen foods, efficiently bringing them to just below the freezing point for immediate use or further processing.

Refrigeration

Although vapor-compression refrigeration predominates in both domestic and commercial installations, there are many types of processes that may be used to cool or freeze materials, from the simple use of water ice, dry ice, or liquid nitrogen phase-change cooling to sophisticated solid-state methods such as Peltier effect cooling modules. For vapor-compression refrigeration, working against the second law of thermodynamics and moving energy from a high energy (hot) area to a low energy (cool) one requires the addition of a substantial amount of energy, usually in the form of electricity or mechanical energy to drive refrigeration compressors. Most large-scale vapor-compression refrigeration processes rely on a simple chain of processes, all of which have been previously discussed:

1. A liquid refrigerant will absorb heat via a heat exchanger (the *evaporator*) during a change to a vapor state, whether the change is driven by adding heat or by changing pressure.
2. Vaporized refrigerant can then be condensed back to a liquid state by raising its pressure, usually by utilizing a mechanical compressor. When it does this, it will release (*reject*) the heat of condensation through a separate heat exchanger (the *condenser*) in another location.
3. By using a closed loop of refrigerant flow, a liquid refrigerant can be used to cool one location by vaporization in a heat exchanger, then transfer that heat energy as increased enthalpy in the vapor to another location, rejecting the heat via another heat exchanger after being recompressed to a liquid, thus creating a *heat pump*.

This provides a means of making heat flow from a region of low energy to a region of high energy – preferably in separate locations. This is not done without cost – remember that the second law of thermodynamics only addresses what energy flow will *spontaneously* occur. Heat pumps require a huge energy input to overcome this and may require additional energy input in the range of 10–40% of the heat energy transferred simply to operate the heat pump system.

To describe a classic vapor-compression refrigeration cycle, four steps are commonly used. The first of these is the flow of the refrigerant through a device called an *expansion valve*. In large refrigeration systems, this can be a complex device, but in home refrigerators and air conditioners, it may be nothing more than a constriction in a tube end, or a machined orifice. This allows a pressure drop as the liquid expands through the orifice, much like an aerosol spray, and is considered to be an isenthalpic process (no change in enthalpy at that particular point). After the refrigerant flows through the expansion valve, it is in a low-pressure region between the valve and the suction (low pressure) side of the refrigeration compressor, and is carried through a heat exchanger on the "cold side" of the refrigerator. The liquid refrigerant will change phase into a saturated vapor, and it absorbs the heat of vaporization in the process, removing heat from the cold side via a heat exchanger (an evaporator, introduced earlier) and cooling the air or material in contact with the evaporator. As it does so, the enthalpy of the material increases with the absorption of the heat energy, and the vaporized refrigerant is drawn into the compressor. For most simple refrigeration systems, it is assumed that the compression of the refrigerant occurs under isentropic conditions – the entropy of the system does not change – and this fact may be used to predict the pathway of the energy state of the refrigerant as it increases in pressure. In practical terms, the refrigerant is brought to a pressure higher than its equilibrium vapor pressure and returns to a liquid state while traveling through a heat exchanger called a condenser. When this phase change occurs, the heat of condensation is removed from the refrigerant via the condenser into the air or cooling water, leaving a relatively cool liquid refrigerant that once again flows through the expansion valve, repeating the process cycle. This is shown schematically in Figure 2.20 and the processes are shown on a Mollier curve chart in Figure 2.21. Mollier charts are provided in the chapter appendix.

Note that the energy rejected in the condenser is the sum of both the heat absorbed during the evaporation of the refrigerant and the heat added to the mixture by the work of compressing it. For many installations, particularly in large food-processing plants, the refrigeration cycle may look somewhat different than the idealized cycle shown here. In many installations, multistage compression is used to lower the cost and increase the effectiveness of the compressor. Additionally, the refrigerant may be allowed to cool past the saturated liquid state to increase the refrigeration capacity of the installation, as well as being allowed to evaporate slightly into the superheat range to both increase capacity and to avoid incompressible liquid refrigerant from damaging the compressor mechanism.

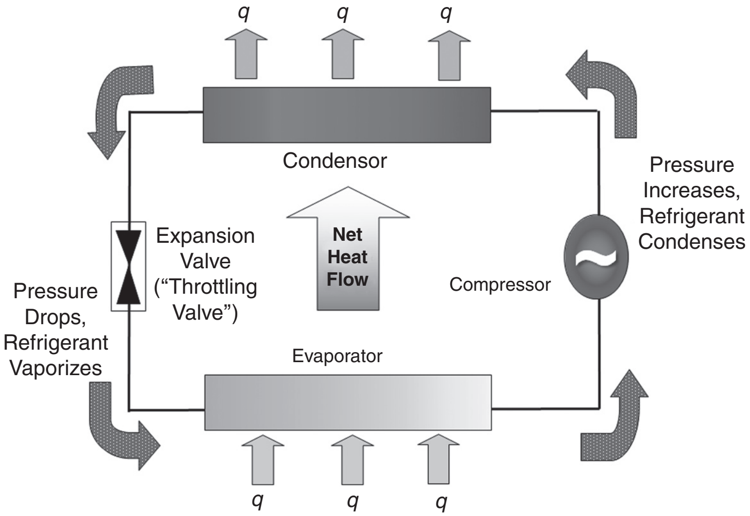


Figure 2.20. Diagram of Vapor-Compression Refrigeration Cycle

Calculation of Refrigeration Parameters

Three basic parameters are needed to calculate the heats that occur in a simple single-stage refrigeration cycle. The terminology for these is not standardized in engineering texts, so different notation may be used in different references. Thus, the generalized refrigeration equation is given in Equation 2.55:

$$\dot{q}\text{: is the heat flow, } \left(\text{W}, \frac{\text{j}}{\text{s}}\right) \tag{2.55}$$

Thus, at any stage in the refrigeration process,

$$\dot{q} = \dot{m}_r(h_{\text{final}} - h_{\text{initial}})$$

$\dot{m}_{\text{r}}$: refrigerant mass flow rate, $\left(\frac{\text{kg}}{\text{s}}\right)$

h_{L}: the enthalpy of the liquid refrigerant at the point that it is finished condensing and begins to moves through the expansion valve, kJ/kg

h_{cv}: the enthalpy of the liquid refrigerant at the point that represents the end of the evaporation and the beginning of compression, kJ/kg

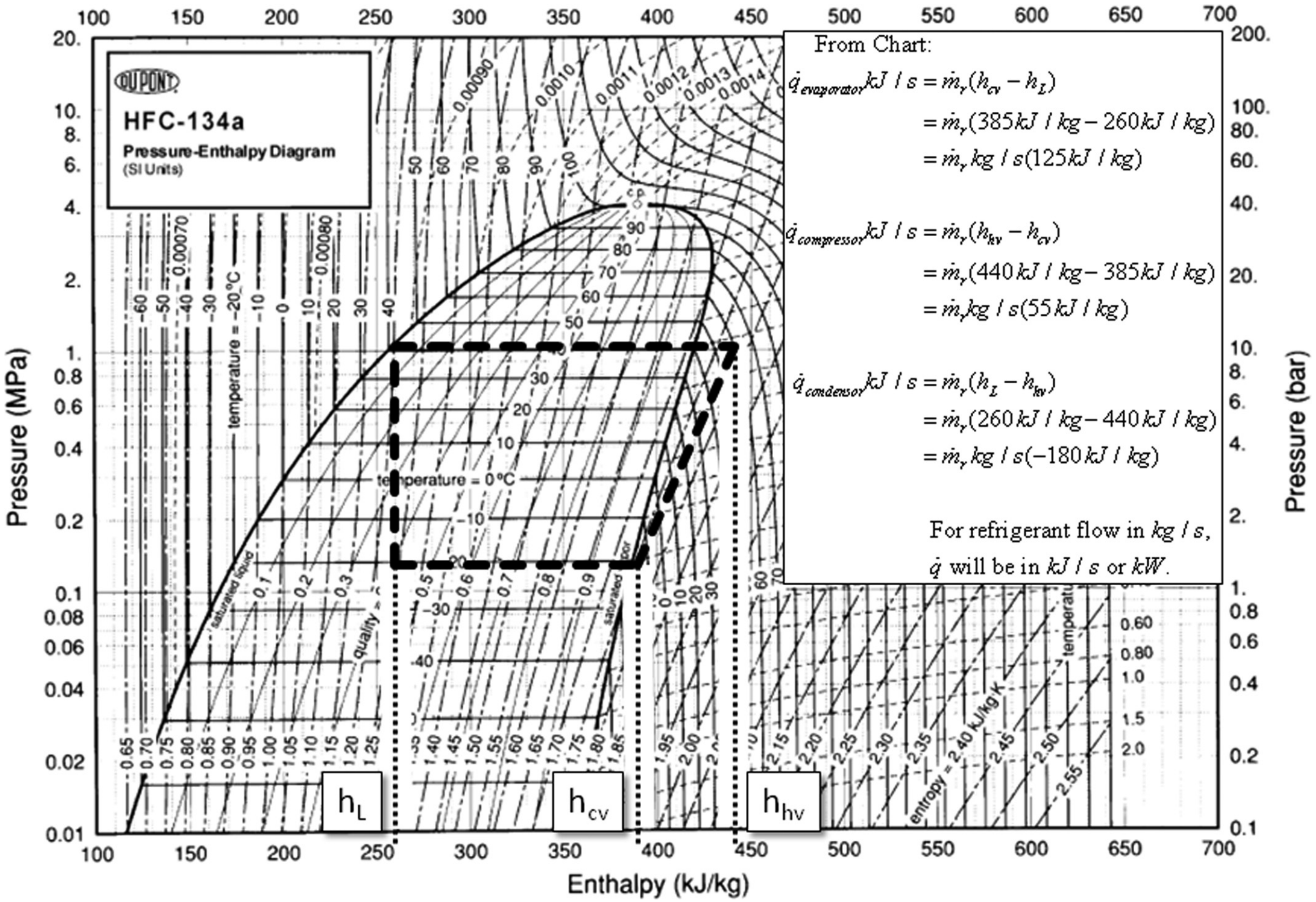
h_{hv}: is the enthalpy value when the refrigerant has been compressed but has not yet begun to reject heat or change phase in the condensor, kJ/kg

This is considered to be the highest enthalpy state of the refrigerant.

Heat of Evaporation and Cooling Capacity

$$\dot{q}_{\text{evaporator}} = \dot{m}_{\text{r}}\,(h_{\text{cv}} - h_{\text{L}}) \tag{2.56}$$

$\dot{q}_{\text{evaporator}}$ = "Heat of Evaporation" or "Cooling Capacity", J/s or W



From Chart:

$$\dot{q}_{evaporator} kJ/s = \dot{m}_r(h_{cv} - h_L)$$
$$= \dot{m}_r(385 kJ/kg - 260 kJ/kg)$$
$$= \dot{m}_r kg/s(125 kJ/kg)$$

$$\dot{q}_{compressor} kJ/s = \dot{m}_r(h_{hv} - h_{cv})$$
$$= \dot{m}_r(440 kJ/kg - 385 kJ/kg)$$
$$= \dot{m}_r kg/s(55 kJ/kg)$$

$$\dot{q}_{condensor} kJ/s = \dot{m}_r(h_L - h_{hv})$$
$$= \dot{m}_r(260 kJ/kg - 440 kJ/kg)$$
$$= \dot{m}_r kg/s(-180 kJ/kg)$$

For refrigerant flow in kg/s, $\dot{q}$ will be in kJ/s or kW.

Figure 2.21. Diagram of Vapor-Compression Refrigeration Cycle Stages on Mollier Chart of R-134a
Source: DuPont, with Permission for Underlying Graph

The *heat of evaporation* (Equation 2.56) is the energy that will be absorbed during evaporation of the refrigerant and usually is equated with the cooling capacity, or *cooling load*. In conservative system, this heat must come from outside the refrigerant, and therefore will cause cooling (energy removal) of the material near the evaporator.

Cooling capacity is the ability of the system to absorb heat and in vapor-compression systems is usually taken to be the total Heat of Evaporation. In much the same fashion as early steam engines being rated in horsepower to demonstrate the effectiveness of their use compared to the horses they replaced, North American refrigeration systems have been rated in terms of *tons* of capacity to compare them to the amount of melting ice that would be needed to absorb an equivalent amount of heat energy. A ton of refrigeration capacity is defined as the equivalent heat energy of 2,000 lbs. of ice melting in 24 hours. In more practical terms, this is equivalent to 12,000 Btu/h or 12,660.5 kJ/h or 3.517 kW.

Heat of Compression

$$\dot{q}_{\text{compressor}} = \dot{m}_{\text{r}}\,(h_{\text{hv}} - h_{\text{cv}})$$

$$\dot{q}_{\text{compressor}} = \text{“Heat of Compression”, J/s or W} \tag{2.57}$$

This is the theoretical value for the amount of heat that is added to the refrigerant during compression (Equation 2.57). In a conservative system, this must be the work done by the compressor on the refrigerant and can be used to predict the power requirements of the refrigeration system. It should be noted that, like all fluid flow systems, the efficiency (ε) of the pump will be less than 100%, and thus the actual power requirements of the compressor may be much higher (Equation 2.58):

$$\text{Actual compressor power required} = \dot{q}_{\text{actual}} = \dot{q}_{\text{compressor}}/\varepsilon \tag{2.58}$$

For vapor-compression refrigeration, there is no equivalent turbine power-output state in these simple systems, although such systems can be run as closed-cycle heat engines, producing power.

Heat of Condensation

$$\dot{q}_{\text{condensor}} = \dot{m}_{\text{r}}\,(h_{\text{L}} - h_{\text{hv}})$$
$$\dot{q}_{\text{condensor}} = \text{“Heat of Condensation” or “Rejected Heat”, J/s or W} \tag{2.59}$$

The *heat of condensation* (Equation 2.59) is the heat that is given off during the condensation of the refrigerant (in most systems, this is a negative number, indicating heat rejection from the system). It is the sum of the heat absorbed during evaporation and the heat added during compression. In vapor-compression refrigeration systems, therefore, the condenser must usually be much larger than the evaporator to give off the increased heat that is contained in the fluid, and of course this must be done at another location, whether the outside of an insulated refrigerator or the outside of a building, to effectively move heat from the evaporator to the condenser. In large industrial refrigeration or office air-conditioning systems, the heat of condensation may be taken up by water flow that is then cooled via a cooling tower or natural water source such as a stream. Problems with refrigeration systems' loss of performance often can be traced to either mechanical problems (compressor malfunction or refrigerant leakage) or the system's inability to reject heat properly. In industrial systems, solar heat load on exposed condensers can cause significant problems, and home refrigerators may run constantly because of lack of air circulation, or dust and pet hair accumulation in the condenser heat exchanger.

Coefficient of Performance (COP)

$$\mathrm{COP} = \frac{\dot{q}_{\mathrm{evaporator}}}{\dot{q}_{\mathrm{compressor}}} = \frac{\dot{m}_{\mathrm{r}}\,(h_{\mathrm{cv}} - h_{\mathrm{L}})}{\dot{m}_{\mathrm{r}}\,(h_{\mathrm{hv}} - h_{\mathrm{cv}})} = \frac{(h_{\mathrm{cv}} - h_{\mathrm{L}})}{(h_{\mathrm{hv}} - h_{\mathrm{cv}})} \tag{2.60}$$

The Coefficient of Performance (Equation 2.60) gives a simple ratio of how much heat is removed by the evaporator in comparison to the energy required to drive the system. For many types of refrigeration systems such as a home refrigerator or a window air conditioner, the COP is usually somewhere between 2.0 and 5.0. This is illustrative of the extraordinary energy expenditures that are required by refrigerators and air conditioners (often the most energy-intensive devices in a home) that require high generating capacity in cities in the summer. Essentially this says that for every 2–5 watts of heat that are transported from the inside of the refrigerator to the outside (or from the inside of a home to the outside air), 1 watt of electrical energy is required. Thus, the refrigeration industry is constantly searching for more efficient ways of providing refrigeration and cooling capacity, which has resulted in the design of both new refrigeration methods, described later on in this section, and ultra-insulated home refrigerators that offer significant efficiency improvements.

Refrigerant Types

The general types of refrigerants include those that absorb latent heat, sensible heat, and those that use liquefiable agents or refrigerating media. Ice and chemical cooling are common methods used in some applications such as fishing vessels and "quick cool" medical devices. Most home vapor compression refrigerators use 1,1,1-trifluoroethane (R-134a) or purified isobutane (R-600a), which, although flammable, is present in such small quantities as to not be deemed a hazard in the event of leaks. Ammonia (R-717) is often used in large-scale industrial freezer systems, but is confined primarily to non-domestic applications (including food-processing plants) because of toxicity and flammability issues. There are literally hundreds of materials suitable for use as refrigerants, many of which are blends of hydrofluorocarbons, but any material that will provide the proper phase changes and will flow at low temperatures may be used as a refrigerant. Many of these are rejected because of either extraordinarily high pressure changes required for the necessary phase change to occur, and the attendant expensive pumping systems to drive it, or because of toxicity, corrosion, flammability, or environmental problems. Even water can be used as a refrigerant – in theory. In reality, it requires a great deal of pressure to change phase and freezes solid at temperatures well above the desired evaporator temperatures of most refrigeration systems.

Compressor Types

From a simplistic thermodynamic viewpoint, refrigeration is simply a heat engine run in reverse – apply mechanical power, and heat flow will occur. Compressors are simply devices that will cause both the refrigerant flow and a rise in pressure, and, in the case of many portable refrigeration units used in trucking and rail shipment, are coupled directly to an engine such as a small-displacement diesel for power. Compressor design is similar to other types of pumps, with reciprocating piston or helical rotary screw (similar to Roots-type compressors) being the most commonly used in industrial refrigeration, as well as rotary, scroll, and centrifugal pumps used in other applications. Home refrigerators and air conditioners typically use a piston- or vane-type compressor that is hermetically sealed in a canister and cooled by the flow of refrigerant [18].

Other Refrigeration Systems

Absorption Refrigerators

These are simple devices commonly found in recreational vehicles and remote applications such as rural medical clinics because they can be powered by a simple flame or other heat source. The most common version of these uses the evaporation of ammonia in the presence of hydrogen to provide the cooling effect, with the gaseous ammonia then being absorbed by water. The water-ammonia mixture is then heated in another stage to re-separate the ammonia from the water, and the ammonia is condensed with gaseous hydrogen in a heat exchanger and rejects heat from the system to complete the cycle.

Peltier Effect Cooling

Jean-Charles Peltier observed that application of a current flow in dissimilar metals will create a heat flow – a reversal of the Seebeck Effect that is responsible for the application of thermocouples that generate a current in dissimilar metals on the application of heat flow. A Peltier module, then, is simply a junction of dissimilar metals or semiconductors that will generate a net heat flow when current flow is applied, resulting in one side of the module being chilled while the extracted heat plus heat of operation is emitted on the other side. Although very sturdy and small, these modules are not terribly efficient and are most often used in specialized electronics-cooling applications and consumer applications such as car beverage coolers.

Vortex Coolers

Vortex coolers operate by generating a centrifugal flow of air, essentially separating air on a density basis (although the exact physics are still a subject of some debate), and producing a stream of both hot and cold air. They are not thermodynamically efficient, but are very useful in systems that have an abundant supply of compressed air, such as locomotives. A similar cooling method is the Air Cycle Machine used in aircraft installations, which cools hot air from the primary stages of the engine's compressors, conditions it via heat exchangers and water separators, and then uses it for cabin ventilation and climate control.

Chemical Chillers

Often the basis for marketing self-cooling or self-freezing packaged foods, chemicals chillers rely on a binary mixture of chemicals that create an endothermic (heat-absorbing) reaction. Typically these include reacting water with ammonium nitrate, ammonium chloride, potassium chloride, or other materials such as ethanoic acid and sodium carbonate. The most common use of these is for chiller packs used in first-aid applications, and the methods have not yet been proven economically feasible in most consumer food packaging applications.

Stirling Cycle Refrigeration

Stirling cycle refrigeration typically uses an oscillating piston, sometimes suspended in a sealed *free-piston* system and magnetically driven to increase efficiency, to achieve vapor compression and circulation through an internal heat exchanger. Although currently not common except in specialty applications such as liquid nitrogen production, these promise an increase in efficiency as demonstrated by a higher COP when compared to standard vapor-compression refrigeration systems, although their higher manufactured cost has slowed their commercial and domestic acceptance.

Magnetic and Acoustic Refrigeration

These methods, still largely under development, rely on very different principles. The first uses magnetic action on paramagnetic salts to induce a magnetocaloric effect. This shifts the entropy of the refrigerant and produces heat absorption and rejection depending on the orientation or randomness of magnetic dipoles in the refrigerant. Its primary application is for ultra-cold research applications, and the use of gadolinium salts allows the cooling to within a minute fraction of absolute zero [19]. Acoustic refrigeration uses acoustic energy to drive gas flow and heat exchange during what amounts to a pistonless Stirling cycle operation with the advantage of fewer parts and little or no mechanical wear. Acoustic refrigeration is currently used in cryogenic work and may offer efficiency improvements for domestic and commercial applications.

Mass Transfer

Mass transfer differs substantially from the mass flow concepts previously discussed in this chapter with regard to fluids, and they should not be confused, particularly when attempting to measure package barrier characteristics. Mass transfer processes are typically defined as involving the diffusion or molecular-level transport of one material through the structure of another, whereas mass flow is regarded as the macroscale bulk flow of a material – most often a fluid – through a physical aperture or channel in another material. The equations used to model these processes are quite different from those used for fluid flow and are very closely related to those describing the diffusion and transport of heat energy. Of course there are always grey areas in this taxonomy; for example, the flow of fluids through dense, porous media (slow, pressure-gradient-driven flow through very tiny voids) has aspects of both bulk flow and diffusion, but these will not be considered in this text.

Diffusion Processes

The simplest example of mass transfer is the Fickian diffusion model developed by Adolf Fick, a German physician, in 1855. The model describes the transport rate of one material through another bulk media, typically a solid or static liquid in terms of a *diffusion coefficient* that is a basic property of a material. It should be noted that although Fickian diffusion is a useful tool in many types of mass-transfer models for materials in a rubbery or liquid state, it does not work well with materials that are undergoing glass transition because the Fickian model does not incorporate the necessary terms for viscoelastic changes in the bulk media as the glass transition occurs [20]. These types of transport require the use of more complex, continuum-mechanics-based diffusion models. Additionally, transport in rubbery or liquid materials, easily described by Fickian equations, is not well modeled in glassy regions where concentration profiles often change sharply.

One-Dimensional Diffusion

The generalized Fickian model for steady-state transport (Equation 2.61):

$$J = -D\nabla\oslash \tag{2.61}$$

can be reduced to the linear case, most often used when considering the one-dimensional linear cross-section of materials, to a simpler form (Equation 2.62):

$$J = -D\frac{\mathrm{d}\oslash}{dx} \tag{2.62}$$

Where

J: diffusion flux in $\frac{\text{Quantity Permeated}}{\text{Length}^2{*}\text{Time}}, \frac{\text{Mol}}{(\text{m}^2{*}\text{s})}$

D: diffusion coefficient in $\frac{\text{length}^2}{\text{time}}, \frac{\text{m}^2}{\text{s}}$

$\oslash$: the concentration in $\frac{\text{Quantity}}{\text{Length}^3}, \frac{\text{Mol}}{\text{m}^3}$

x: the characteristic length dimension in length, m

The one-dimensional Fickian diffusion case is mathematically similar to the Fourier heat conduction equation, and many mass- and heat-transfer modeling systems are derived from the same mathematical basis. The unsteady-state case for Fickian diffusion requires Fick's Second Law to account for time changes in the transport rate (Equation 2.63):

$$\frac{\partial\oslash}{\partial t} = D\frac{\partial^2\oslash}{\partial x^2} \tag{2.63}$$

For either situation, D can be experimentally determined as described in Chapter 7, and is dependent on a host of other factors, often including temperature, existing concentrations of solvents, co-solvents, or other constituents of the bulk matrix.

Mass Transfer through Polymer Films

As discussed in Chapter 7, the permeability of polymer films common to food packaging is based on a sorption, Fickian diffusion, desorption model. Permeants such as oxygen or carbon dioxide are very often presumed to be non-reactive with the packaging materials and therefore not to affect the sorption/desorption or diffusion rates; however, surface modifications of the polymer, additives, and plasticizers in the polymer matrix, whether intentional or taken up from the product or environment, and a very high degree of variability in the polymer manufacturing process itself will result in permeation figures published in the literature that can often be order-of-magnitude estimates at best.

Mass Transfer into Moving Fluids

Heat transfer into moving fluids is described by the previously mentioned Nusselt number, a dimensionless characteristic number used to determine the overall heat transfer coefficient, (h). In much the same manner, the Sherwood number helps describe the mass transfer into a moving fluid (Equation 2.64):

$$\mathrm{Sh} = \frac{K_c L}{D} \tag{2.64}$$

Sh: Sherwood number, dimensionless

K_c: the mass-transfer coefficient, $\frac{\mathrm{mol}/\left(\mathrm{s} \cdot \mathrm{m}^2\right)}{\left(\mathrm{mol}/\mathrm{m}^3\right)}$

L: the characteristic length dimension, often diameter, m (L is often kept to avoid confusing the diameter with the diffusion coefficient, D)

D: the diffusivity coefficient, $\frac{\mathrm{m}^2/\mathrm{s}}{\mathrm{length}^2/\mathrm{time}}$

In much the same manner as estimating the Nusselt number using the Prandtl and Reynolds numbers in heat transfer, the Sherwood number may be estimated using the Reynolds number as previously described and the Schmidt number (Equation 2.65):

$$\mathrm{Sc} = \frac{\nu}{D} \tag{2.65}$$

Sc: Schmidt Number, dimensionless

$\nu = \frac{\mu}{\rho}$: the kinematic viscosity, $\frac{\mathrm{m}^2}{\mathrm{s}}$

As with the estimation of the Nusselt number, there are estimation equations available for the Sherwood number based on empirical data for particular mass-transfer scenarios. Typical values for the Schmidt number are $0.5 < \mathrm{Sc} < 3$ for gasses and $100 < \mathrm{Sc}$ for liquids.

For evaporation via flow on the outside of a solid surface such as a flat plate and $\mathrm{Re} < 15{,}000$, the Sherwood number may be approximated by (Equation 2.66):

$$\mathrm{Sh} = 0.664 Re^{0.5} \mathrm{Sc}^{0.33} \tag{2.66}$$

and for the mass transfer on the outside of a sphere (usually taken to be a spherical droplet), the starting point is often the Ranz-Marshall equation (Equation 2.67) [21]:

$$\mathrm{Sh} = 2 + 0.60\,\mathrm{Re}^{0.5} \mathrm{Sc}^{0.33} \tag{2.67}$$

where

$$2 \le \mathrm{ReSc}^{0.67} \le 50{,}000$$

However, for practical applications, the Ranz-Marshall equation (which was developed to model a single droplet without interactions) is subject to considerable correction terms depending on the flow regime, ratio of boundary layer to droplet size, and the type of liquids and gasses in the particular system. In Ranz's words, "Today in designing a process it is much more difficult to find a general model for a general class of phenomena. However a miniaturized experiment, observed in real time, is always necessary to simplify the theoretical models to a tractable form for computations" [22]. Although numerical analysis has helped this, allowing some types of experiments to be run as computer simulations, the complexity of interaction still provides a challenging subject for research.

As with convective heat transfer being impeded by laminar sublayers, fluid flows may form a laminar sublayer over the evaporating surface that contains a curvilinear concentration profile. The practical implications of this are that some form of turbulence may be induced to achieve better mixing over the surface and a higher rate of mass transfer, much as convective heat transfer may be manipulated to maximum effect.

Drying, Dehydration, and Psychrometry

Another major method of food preservation is the reduction of water content in the food product itself. Although the actual basis for drying to prevent quality loss in the product is discussed in Chapter 7, the drying mechanism is relatively simple in principle and can be somewhat confusing in application because of the information necessary to account for energy and mass transfers.

Like any mixture of components, the evaporation of water into air (or the condensation of water out of air) is determined by temperature and pressure. This segment will concentrate on changes that occur near atmospheric pressure, but it should be remembered that liquids can be evaporated and condensed by manipulating pressure as well. This has few applications in the food processing industry due to high costs, but there are occasional applications in products that have unusual characteristics (such as being extremely temperature sensitive) where low pressure moisture or solvent evaporation is used.

Types of Air-Drying Operations

There is any number of types of drying and evaporative operations in food processing, ranging from simple rack-drying in the open to sophisticated freeze-drying techniques. The simplest types of drying use heated air flowed over a sliced or fragmented product conveyed in trays or on belts to remove moisture, with the initial impinging air often containing some of the removed moisture to avoid damaging the product by contact with completely dry air. Other methods include fluidized bed drying, which involves the bubbling of air through a bed of particulate material until the particles are suspended in the airflow, and spray and pneumatic drying that disperses fluid or solid particles, respectively, into the drying airflow.

The Psychrometric Chart

There are several psychrometric charts that are commonly used, but most contain similar information, although it may be laid out in many different formats, or may be contained in interactive form in a computer program. There are full-scale psychrometric charts in the appendix at the end of this chapter. The information contained in a psychrometric chart will most often contain a large number of curves, representing many different quantities – most of which are self-explanatory, but the following necessary information should be described.

Dry Bulb Temperature

This is the temperature that an ordinary (*bulb type*) thermometer will indicate in air. This is the root of subsequent determination of air properties, because every property except absolute humidity (which is a temperature-independent mass ratio) will vary with temperature.

Wet Bulb Temperature

This term dates back to the early days of humidity measurement and refers to a second thermometer that had a moistened cloth sleeve around its bulb. Evaporative cooling would lower the temperature of the *wet bulb* thermometer, and the relative humidity of the air could be determined by the temperature difference between the wet bulb and dry bulb thermometers. Lower relative humidity would increase the cooling effect, and thus the temperature difference between wet bulb and dry bulb would be larger, giving a dependable basis of measurement.

Many psychrometric charts still allow the determination of the state of air simply based on the wet and dry bulb temperatures, and some newer solid-state instruments still indicate this measurement as well. *Sling* psychrometers are still available, although they are generally used for teaching.

Relative Humidity

Relative humidity is the amount of moisture that air will hold, relative to a completely saturated mass of air at that particular temperature. This is a temperature-dependent quantity; air with a constant mass of water dissolved into it will increase in relative humidity as the temperature drops. Given enough cooling, this will eventually result in the precipitation of water out of solution as condensate in processing and as fog or precipitation in naturally occurring systems.

Absolute Humidity

Absolute Humidity is the mass ratio of water to air (usually g H_2O/kg Dry Air, or lb H_2O/lb Dry Air). This does not change with temperature because it is independent of the air's capacity to saturate. Older references may use grains H_2O/lb Dry Air, where 1 grain is 0.0649g, or 1.43×10^{-4} lb.

Enthalpy of Dry Air

The intrinsic energy content of the air, typically given both in kJ/kg dry air (or KJ/kg D.A.) or in Btu/lb dry air.

Specific Volume of Dry Air

Specific Volume is the volume per unit mass of dry air at a particular state for the air-water mix, and can be thought of as the *inverse of density*. Typically this is given in m^3/kg or lb/ft^3. From inspecting the psychrometric chart, one can determine that changing the temperature has the obvious effect of changing the specific volume, but changes in humidity at a given temperature can have a minor effect on the specific volume as well. Considering that convective systems are driven by density or specific volume differentials, some degree of convection may occur as a result of humidity changes.

Correction Terms

Depending on the particular charts used, there may be minor correction terms that are applied to enthalpy and/or specific volume values. These are usually overlain on the charts (adding to an already complex mass of visual data). For the purposes of classroom exercises (and many actual calculations), these are sometimes for the sake of simplification, though they should be considered for large-scale operations where their contribution may become significant.

Assumptions of Evaporating and Drying

In describing simplified drying and evaporator systems, there are two basic processes that occur: simple heating and cooling, which changes the dry bulb temperature at a constant absolute humidity; and adiabatic humidification or dehumidification of air via dehydration or hydration of the product that occurs along a line of constant enthalpy.

Simple heating and cooling affects only the dry bulb temperature of the air-water mix, and does not change the absolute humidity (moisture content), though it will change the relative humidity, specific volume, and other factors. Because the temperature of the air is changing, the process is assumed to change the enthalpy of the air-water mixture as well. Drying or humidifying the product releases moisture into the air, and in a conservative engineering system, the moisture released is considered to be completely taken up into the air without changing its energy value – an adiabatic process. Although this is a somewhat simplistic assumption for some applications, it illustrates quite well many of the principles involved, and is a good approximation of simple airflow drying operations as shown in Figure 2.22.

Thus, most drying operations can be seen as containing two or more discrete stages. The first stage is usually heating of ambient air to an elevated temperature, thus increasing its energy

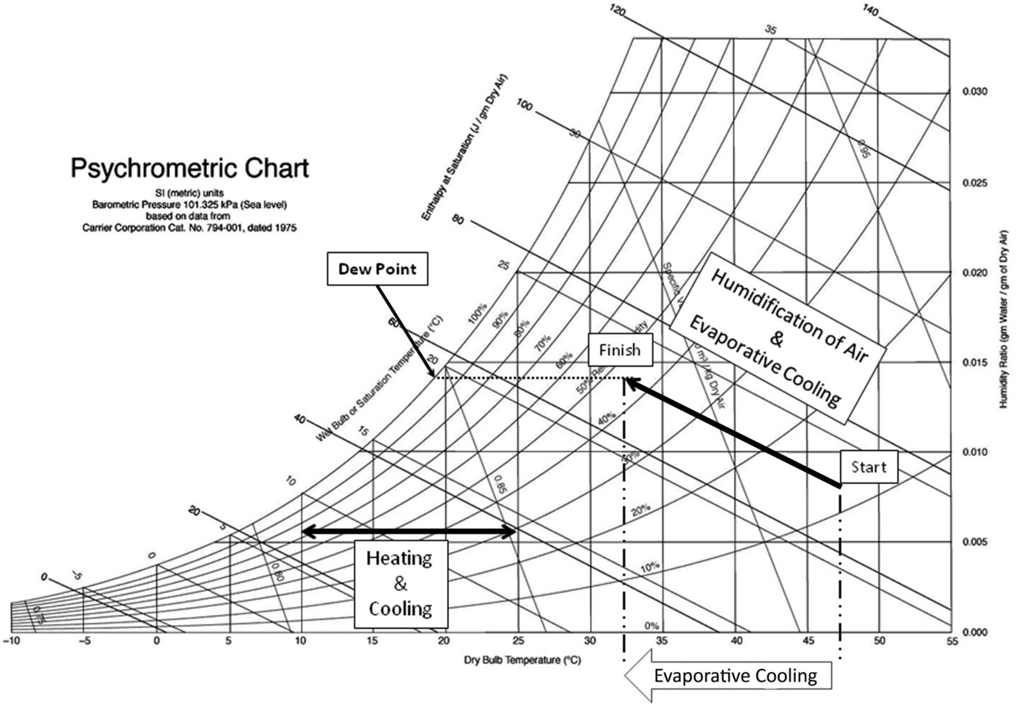


Figure 2.22. Psychrometric Chart with Process Lines for Typical Operations
Source: Underlying chart: Arthur Ogawa, with Permission

content and decreasing its relative humidity. The second step is exposing the product to the hot, dry air and allowing the product to be dried and the air to be similarly humidified – the moisture being taken up by the airflow being equal to the moisture being lost by the product, although it should be stressed that in an actual application, the heating stage will terminate at the beginning of the humidification stage providing a continuous process line. There may be systems that rely on multistage heating systems, or may have subsequent steps that occur, such as condensing moisture and recycling of moist drying air to "condition" the incoming product, but these simple rules and conservative engineering assumptions continue to allow reasonably straightforward analyses of the processes.

The Dew Point

The dew point, often mentioned in weather forecasts, is the temperature at which condensation or precipitation begins to occur. Cooling air will typically form fogs when the dry bulb temperature and the dew point are within about 3°C of one another and it is possible to supercool air-water mixtures to a certain extent, but this is not used for processing. In weather forecasting, the dew point is usually assumed to be the point where the air has cooled and dew, fog, rain, or snow begins. In broader terms, it represents a condensation temperature and can be observed on the sides of a cold beverage container on a humid day or in any situation with sufficient cooling.

To determine the dew point, the rules in the previous section can be applied. Simple cooling of the air will result in the movement of the air state along a line of constant absolute humidity until the saturation curve (relative humidity = 100%) is reached. That temperature at the saturation curve is then taken to be the dew point. A common mistake is to follow a line of constant enthalpy, which is incorrect because the air is neither gaining nor losing moisture as it is cooled.

Precipitating Moisture by Cooling

In engineering processes, removing heat from a humid air mass will cause the enthalpy value of the air mass to drop, with an attendant drop in temperature. If sufficient heat is removed, the air mass will be at the saturation curve. The air mass can be cooled further but because the air is already at the saturation point, it will begin to precipitate moisture and will continue to do so until the final dry bulb temperature state is reached. This is a ubiquitous occurrence when warm, humid air masses are cooled either by convection to higher altitudes or mixing with cold air masses, creating clouds or rain or other precipitation. Dehumidifiers are typically simply air conditioning systems that are used for moisture removal, and free-standing units have both the evaporator and condenser in the same air flow, temporarily dropping the temperature to remove water, then blowing the dry air over the condenser heat exchanger to reheat it. Larger cooling systems such as air conditioning units will precipitate excess humidity as a matter of course, an this can be seen dripping from window units or automobiles on hot, humid days.

Evaporative Cooling Effect

The evaporative cooling effect is the simplest of results from changes in the mass of water contained in air and is one of the oldest methods of cooling known because it is incorporated into human thermoregulation as the sweat response. Cooling can be measured as the reduction of dry bulb temperature that occurs as the airflow is adiabatically humidified. This adiabatic humidification will provide a change in temperature while holding the enthalpy of the air-water mix constant, which is often counterintuitive. The cooling effect is exploited in evaporation towers used in process operations and in building climate control, as well as other process cooling operations. Because the amount of energy absorbed in evaporation is proportional to amount of air that the moisture can absorb, evaporative cooling is most effective at low relative humidities. Small evaporative cooling units called *swamp coolers* are common in the southwestern United States and the interior of Australia where dry conditions favor their use as a low-cost cooling system, and spray-type coolers that directly mist the air to provide spot evaporative cooling are used in both livestock and human environments.

Cooling Towers

Cooling towers are typically designed as either natural draft towers that use the lift from expanding hot air to drive airflow, such as the iconic hyperbolic cooling towers seen at nuclear reactors, or mechanical draft towers that use blowers to create airflow. A typical evaporative cooling tower is called a *chilling* tower and may reject heat from refrigeration condensers, power plant turbines, or other sources. The capacity of cooling towers is equal to the ability of the air to absorb moisture and thus create a cooling effect. This can be calculated by (Equation 2.68):

$$\begin{aligned} \dot{q}_{\text{cooling tower}} &= \dot{M}_{\text{airflow}}\,(h_{\text{final}} - h_{\text{initial}}) \\ &= FR_{\text{volumetric}} \cdot \rho_{\text{air}}\,(h_{\text{final}} - h_{\text{initial}}) \\ &= \bar{V}_{\text{airflow}} \cdot A_{\text{cross section}} \cdot \rho_{\text{air}}\,(h_{\text{final}} - h_{\text{initial}}) \end{aligned} \tag{2.68}$$

$\dot{q}_{\text{cooling tower}}$: heat flow from cooling tower, J/s

$\dot{M}_{\text{airflow}}$: mass airflow through cooling tower, $\dfrac{\text{kg Dry Air}}{\text{s}} = \dfrac{\text{kg DA}}{\text{s}}$

h_{final}: enthalpy of air at exit point of cooling tower, kJ/kg

h_{initial}: enthalpy of air at entrance point of cooling tower, kJ/kg

$FR_{\text{volumetric}}$: volumetric air flow rate through cooling tower, $\dfrac{\text{m}^3\text{ Dry Air}}{\text{s}}$

$= \bar{V}_{\text{airflow}} \cdot A_{\text{cross section}} = \dfrac{\text{m}}{\text{s}} \cdot \text{m}^2$

$\bar{V}_{\text{airflow}}$: average airflow velocity through cooling tower, m/s

$A_{\text{cross section}}$: cross sectional area of airflow through cooling tower, m^2

ρ_{air} : air density, kg/m^3

Cooling towers generally are either cross-flow or counterflow types, and attention should be paid to the loss of cooling water into the air. This quantity can be substantial for large cooling operations, and provision should be made for make-up water to be added to the system to compensate for the evaporated water. Additionally, proper design practices and cleanliness should be observed as cooling water circulation systems have been implicated in health problems such as the Legionnaires disease outbreak at the Bellevue Stratford Hotel in 1976 in Philadelphia.

Legionella pneumophila organisms growing in the hotel's cooling tower water reservoir were carried back inside the building by ventilation air carrying droplets from the cooling tower's water spray, and were responsible for 235 cases of legionellosis and 34 deaths.

Evaporative Cooling as an Indicator of Process Control

In many processes, the evaporative cooling of the air as it flows through the system may be a primary indicator of whether the necessary evaporation (and thus dehydration) is occurring. Process controls in drying operations usually include a monitor of temperature both in the drying stages and in the exhaust to ensure that enough moisture is being removed from the system, with the cooling effect of the drying process being the primary indicator of moisture content being removed. Home clothes dryers often exploit this as well – the "automatic" setting is most often a simple temperature sensor that initiates the timed end of a drying cycle as the temperature of the exhaust air climbs past a certain generalized set point, typically 70°C (160°F), and indicates that the contents have reached a stage where they no longer contain high amounts of water. This can provide a simple process control for many types of drying operations, although for food operations, the drying characteristics will have to be described for each individual material being processed.

Other Types of Drying

Non-airflow types of drying will typically rely on contact heating to remove moisture or, in the case of freeze drying, the reduction of pressure to allow moisture to sublimate away. Drum or roller dryers rely on the fluid or particulate materials' contact with the drum for sufficient time to achieve the necessary drying and often utilize a scraper blade to separate the dried material from the drying surface. Plate dryers act similarly, although they are usually limited to items that can be easily removed from the drying surface. Freeze-drying relies on the ability of water to sublimate from frozen foods under reduced pressure when heated. These are discussed in more detail in Chapter 6.

Appendixes

Appendix 2.1. Heat Capacities of Selected Materials

Nonfood Material	Phase	*Cp* (kJ/Kg°C)
Air (Sea level, dry, 0°C)	gas	1.0035
Air (typical room conditions)	gas	1.012
Aluminium	solid	0.897
Animal (and human) tissue [15]	mixed	3.5
Ethanol	liquid	2.44
Glass [16]	solid	0.84
Helium	gas	5.1932
Hydrogen	gas	14.3
Iron	solid	0.45
Polyethylene (rotomolding grade) [17]	solid	2.3027
Polyethylene (rotomolding grade) [17]	liquid	2.9308
Water at 100°C (steam)	gas	2.08
Water at 25°C	liquid	4.1813
Water at −10°C (ice) [16]	solid	2.05

Source: http://en.wikipedia.org/wiki/Heat_capacity

Food Material	Above Freezing	Below Freezing
	(KJ/kg°C)	(KJ/kg°C)
Apples	3.64	1.76
Bananas	3.35	1.67
Bass	3.43	1.72
Beef, carcass	2.85	2.01
Blueberries	3.64	1.76
Brains	3.52	1.72
Broccoli	3.85	1.84
Butter	1.26	1
Carrots	3.81	1.84
Chicken, broilers	3.22	1.59
Eggs	3.18	1.67
Flour	1.59	1.17
Grapes	3.6	1.76
Ice cream	3.1	1.67
Kidney beans, dried	1.17	0.96
Lard	2.26	1.3
Lamb, leg	2.97	1.55
Lemon juice	3.85	1.84
Lobsters	3.43	1.72
(Cow's) Milk	3.77	1.97
Nuts	1.17	1
Peas, medium	3.39	1.67
Pineapple, fresh	3.68	1.8
Pork, bacon	1.51	1.05
Pumpkin	3.85	1.84
Saurkraut	3.89	1.84
Sausage, bologna	2.97	1.55
Tomatoes, red	3.98	1.88
Tomato, juice	3.98	1.88
Turkey	2.81	1.47
Veal, carcass	3.1	1.59
Watermelon	3.94	1.88
Whitefish	3.18	1.63

Source: http://www.engineeringtoolbox.com/specific-heat-capacity-food-d_295.html

Appendix 2.2. Properties of Saturated Steam – SI Units

Absolute Pressure	Temperature	Specific Volume	Density	Enthalpy of		
				Liquid	Evaporation	Saturated Vapor
				h_l	h_{lv}	h_v
kPa	°C	m^3/kg	kg/m^3	kJ/kg	kJ/kg	kJ/kg
0.8	3.8	160	0.00626	15.8	2493	2509
2	17.5	67	0.0149	73.5	2460	2534
5	32.9	28.2	0.0354	137.8	2424	2562
10	45.8	14.7	0.0682	191.8	2393	2585
20	60.1	7.65	0.131	251.5	2358	2610
28	67.5	5.58	0.179	282.7	2340	2623
35	72.7	4.53	0.221	304.3	2327	2632
45	78.7	3.58	0.279	329.6	2312	2642
55	83.7	2.96	0.338	350.6	2299	2650
65	88	2.53	0.395	368.6	2288	2657
75	91.8	2.22	0.45	384.5	2279	2663
85	95.2	1.97	0.507	398.6	2270	2668
95	98.2	1.78	0.563	411.5	2262	2673
100	99.6	1.69	0.59	417.5	2258	2675
101.33	100	1.67	0.598	419.1	2257	2676
110	102.3	1.55	0.646	428.8	2251	2680
130	107.1	1.33	0.755	449.2	2238	2687
150	111.4	1.16	0.863	467.1	2226	2698
170	115.2	1.03	0.97	483.2	2216	2699
190	118.6	0.929	1.08	497.8	2206	2704
220	123.3	0.81	1.23	517.6	2193	2711
260	128.7	0.693	1.44	540.9	2177	2718
280	131.2	0.646	1.55	551.4	2170	2722
320	135.8	0.57	1.75	570.9	2157	2728
360	139.9	0.51	1.96	588.5	2144	2733
400	143.1	0.462	2.16	604.7	2133	2738
440	147.1	0.423	2.36	619.6	2122	2742
480	150.3	0.389	2.57	633.5	2112	2746
500	151.8	0.375	2.67	640.1	2107	2748
550	155.5	0.342	2.92	655.8	2096	2752
600	158.8	0.315	3.175	670.4	2085	2756
650	162	0.292	3.425	684.1	2075	2759
700	165	0.273	3.66	697.1	2065	2762
750	167.8	0.255	3.915	709.3	2056	2765
800	170.4	0.24	4.16	720.9	2047	2768
850	172.9	0.229	4.41	732	2038	2770
900	175.4	0.215	4.65	742.6	2030	2772
950	177.7	0.204	4.9	752.8	2021	2774

(*Continued*)

Appendix 2.2. (*Continued*)

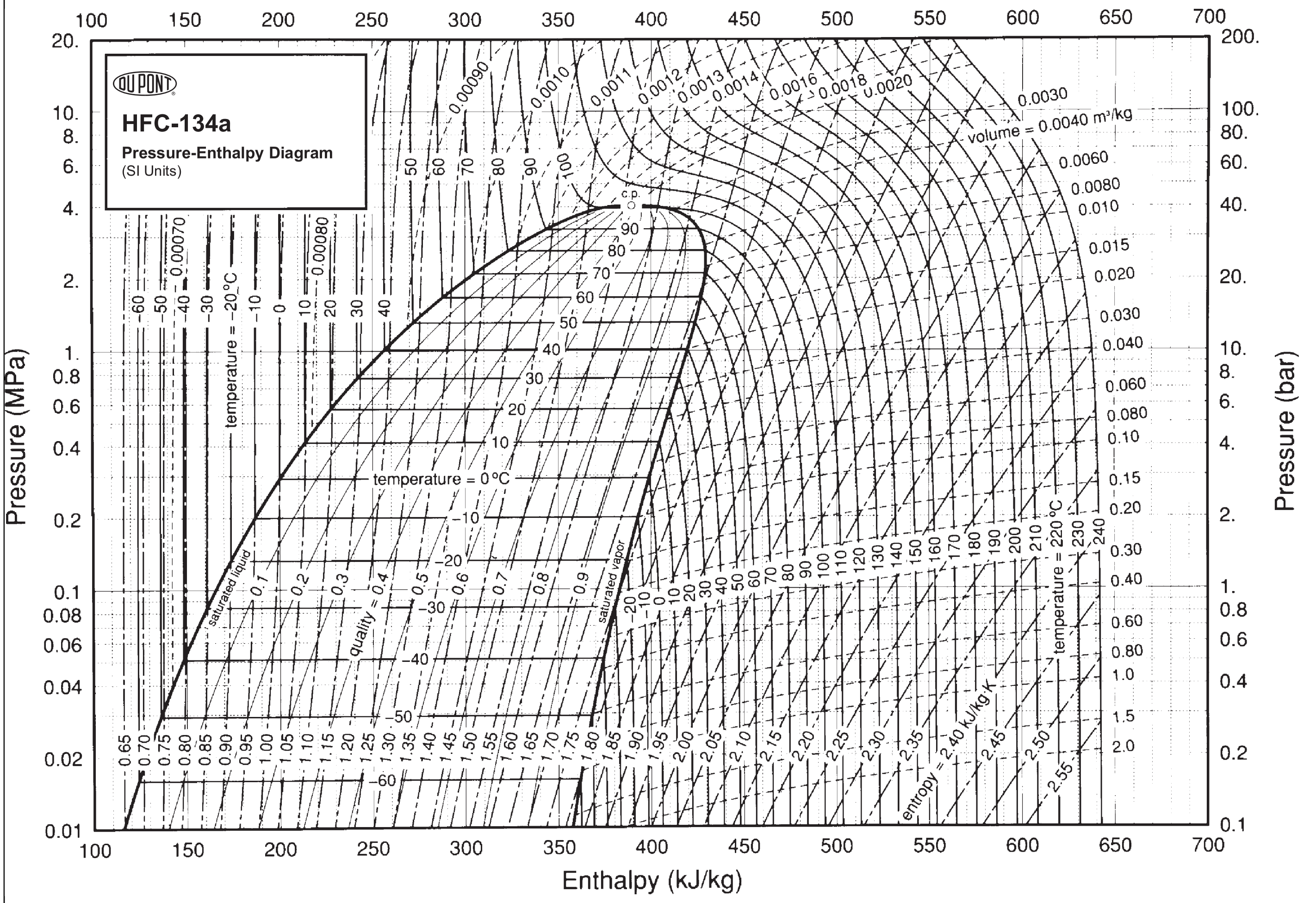
Absolute Pressure	Temperature	Specific Volume	Density	Enthalpy of		
				Liquid	Evaporation	Saturated Vapor
				h_l	h_{lv}	h_v
kPa	°C	m^3/kg	kg/m^3	kJ/kg	kJ/kg	kJ/kg
1000	179.9	0.194	5.15	762.6	2014	2776
1050	182	0.186	5.39	772	2006	2778
1150	186	0.17	5.89	790	1991	2781
1250	189.8	0.157	6.38	807	1977	2784
1300	191.6	0.151	6.62	815	1971	2785
1500	198.3	0.132	7.59	845	1945	2790
1600	201.4	0.124	8.03	859	1933	2792
1800	207.1	0.11	9.07	885	1910	2795
2000	212.4	0.0995	10.01	909	1889	2797
2100	214.9	0.0945	10.54	920	1878	2798
2300	219.6	0.0868	11.52	942	1858	2800
2400	221.8	0.0832	12.02	952	1849	2800
2600	226	0.0769	13.01	972	1830	2801
2700	228.1	0.074	13.52	981	1821	2802
2900	232	0.0689	14.52	1000	1803	2802
3000	233.8	0.0666	15	1008	1794	2802
3200	237.4	0.0624	16.02	1025	1779	2802
3400	240.9	0.0587	17.04	1042	1760	2802
3600	244.2	0.0554	18.06	1058	1744	2802
3800	247.3	0.0524	19.08	1073	1728	2801
4000	250.3	0.0497	20.09	1087	1713	2800

Source: http://www.engineeringtoolbox.com/saturated-stream-properties-d_101.html

Appendix 2.3. Values of the Ideal Gas Constant

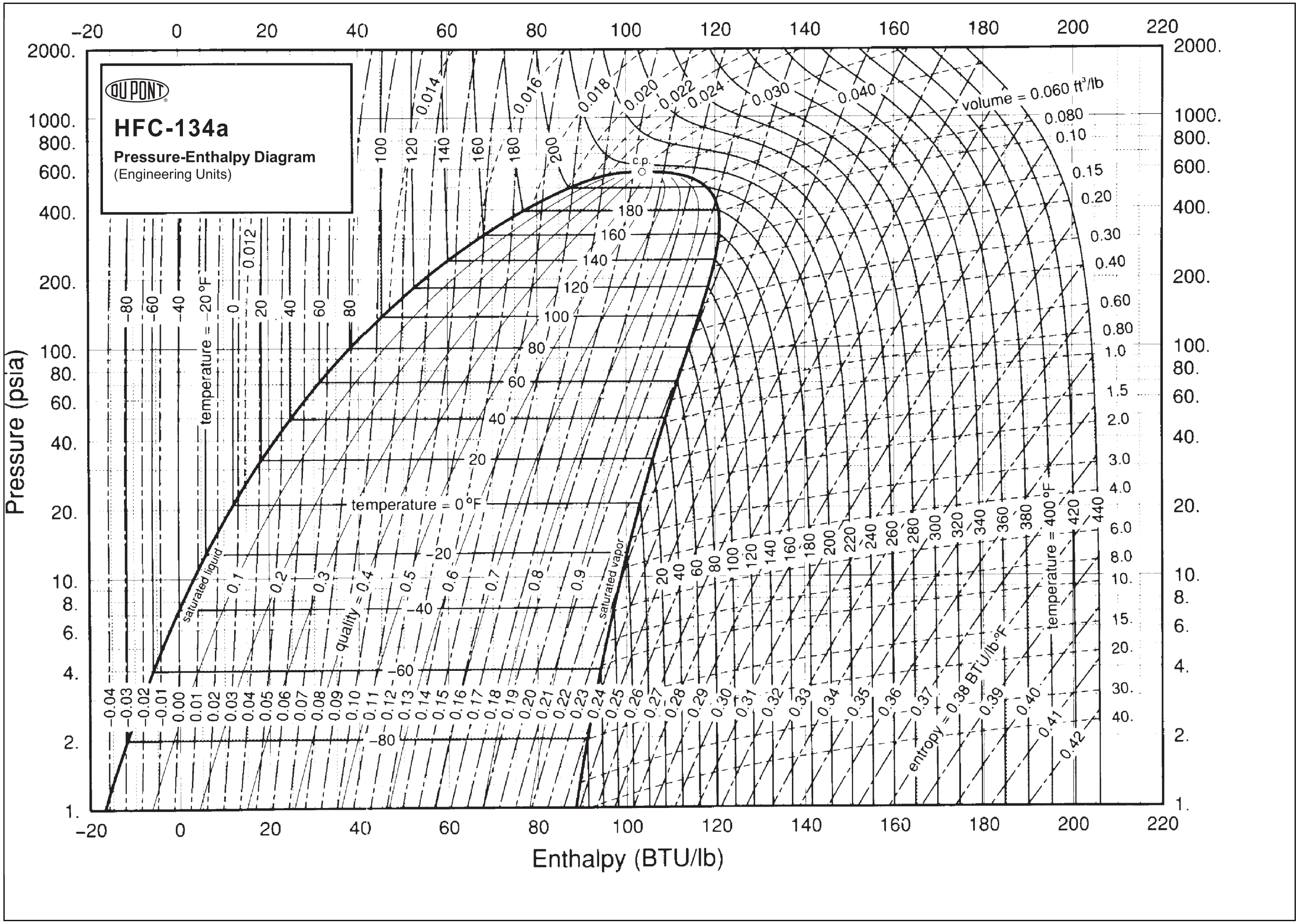
Values of R	Units
8.314472	$J\,K^{-1}\,mol^{-1}$
1.9858775	$cal\,K^{-1}\,mol^{-1}$
8.314472×10^{7}	$erg\,K^{-1}\,mol^{-1}$
8.314472	$L\,kPa\,K^{-1}\,mol^{-1}$
8.314472	$m^3\,Pa\,K^{-1}\,mol^{-1}$
8.314472	$cm^3\,MPa\,K^{-1}\,mol^{-1}$
8.205746×10^{-5}	$m^3\,atm\,K^{-1}\,mol^{-1}$
0.0821	$L\,atm\,K^{-1}\,mol^{-1}$
6.13244	$ft\,lb_f\,K^{-1}\,g\text{-}mol^{-1}$
1,545.35	$ft\,lb_f\,{}^\circ R^{-1}\,lb\text{-}mol^{-1}$
10.73159	$ft^3\,psi\,{}^\circ R^{-1}\,lb\text{-}mol^{-1}$
0.7302413	$ft^3\,atm\,{}^\circ R^{-1}\,lb\text{-}mol^{-1}$
998.9701	$ft^3\,mmHg\,K^{-1}\,lb\text{-}mol^{-1}$
1.986	$Btu\,lb\text{-}mol^{-1}\,{}^\circ R^{-1}$

Appendix 2.4. R-134 Refrigerant Table – SI Units



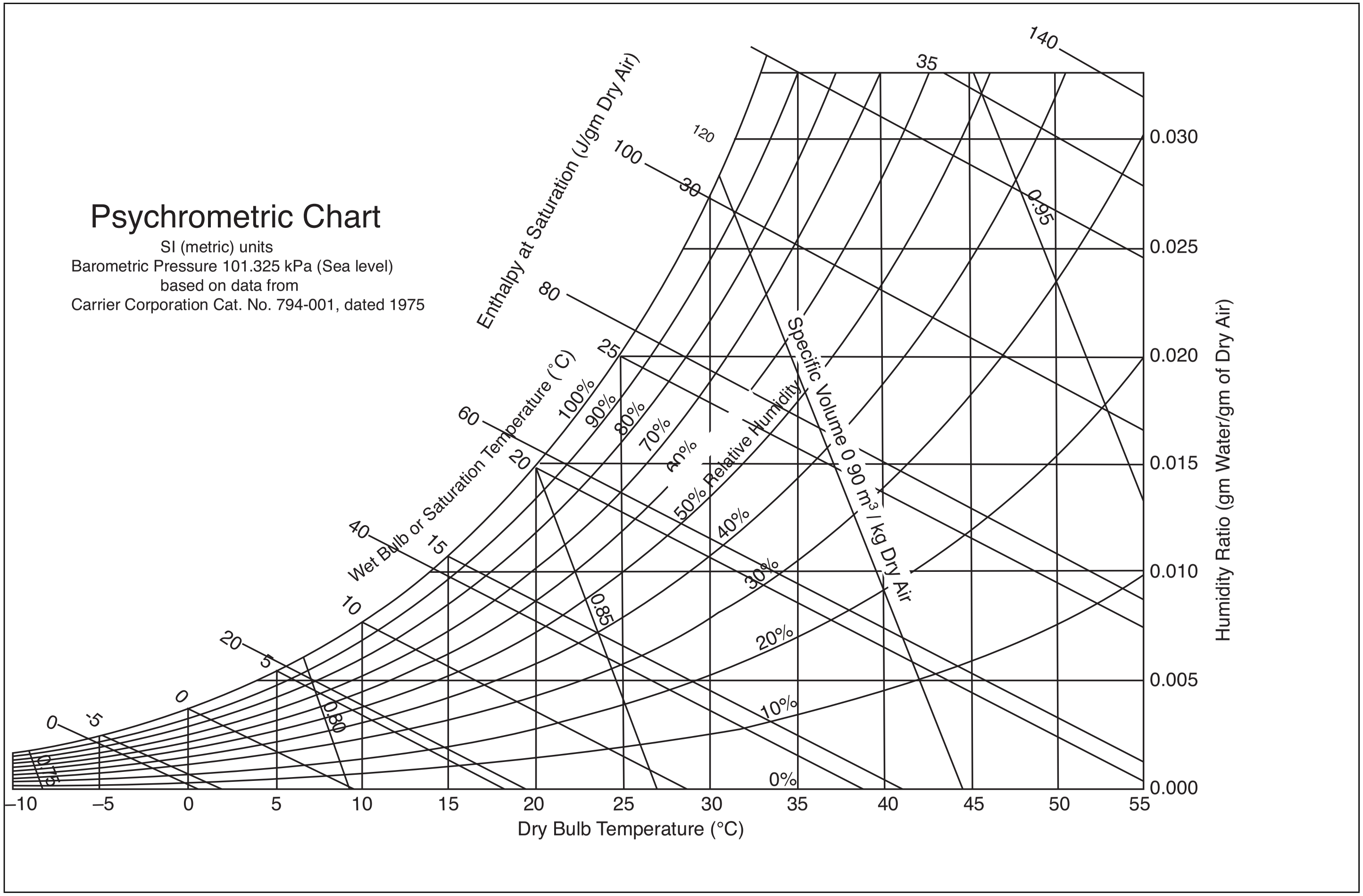
Source: DuPont, used with permission.

Appendix 2.5. R-134 Refrigerant Table – US Units



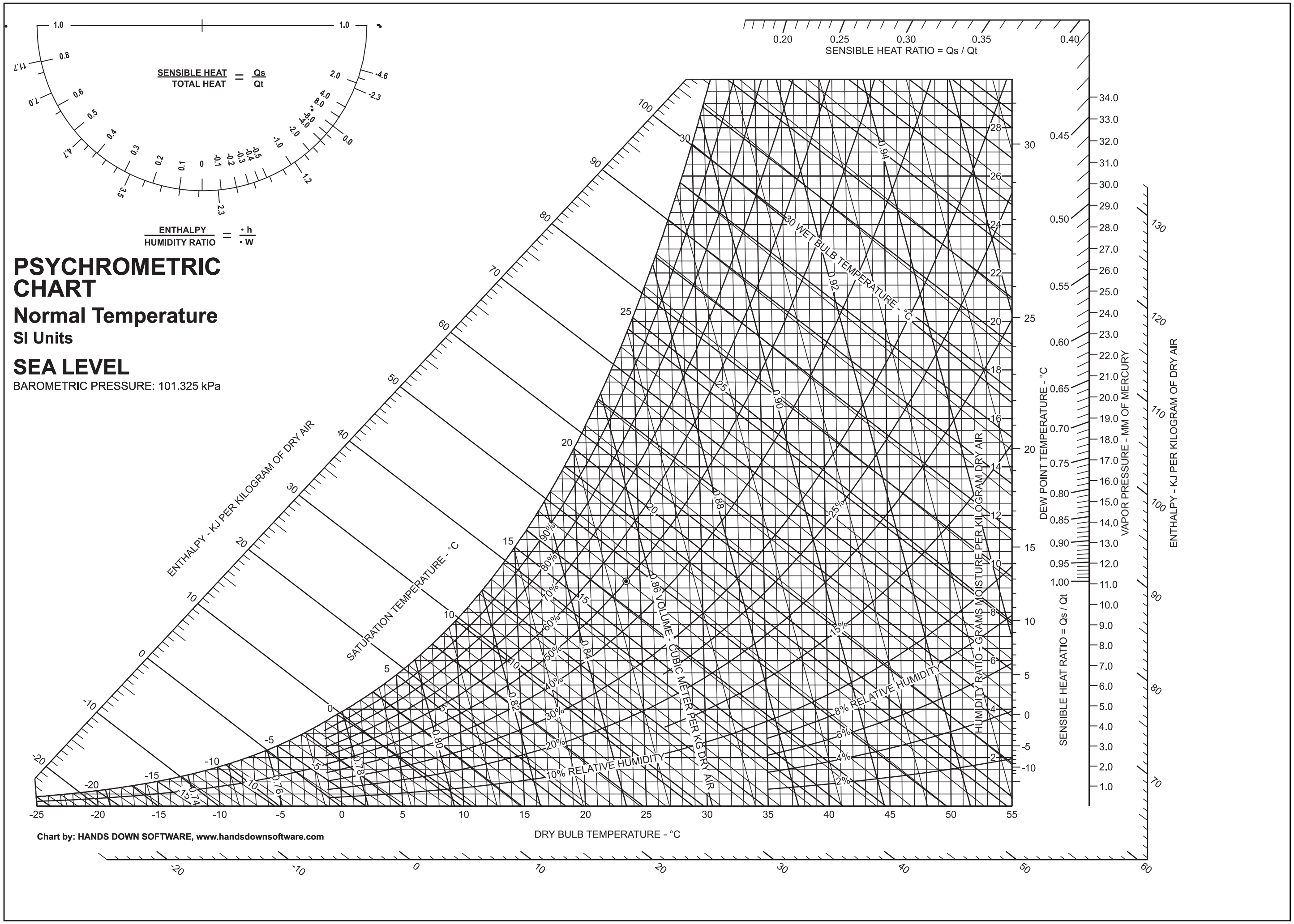
Source: DuPont, used with permission.

Appendix 2.6. Simple Psychrometric Chart, SI Units



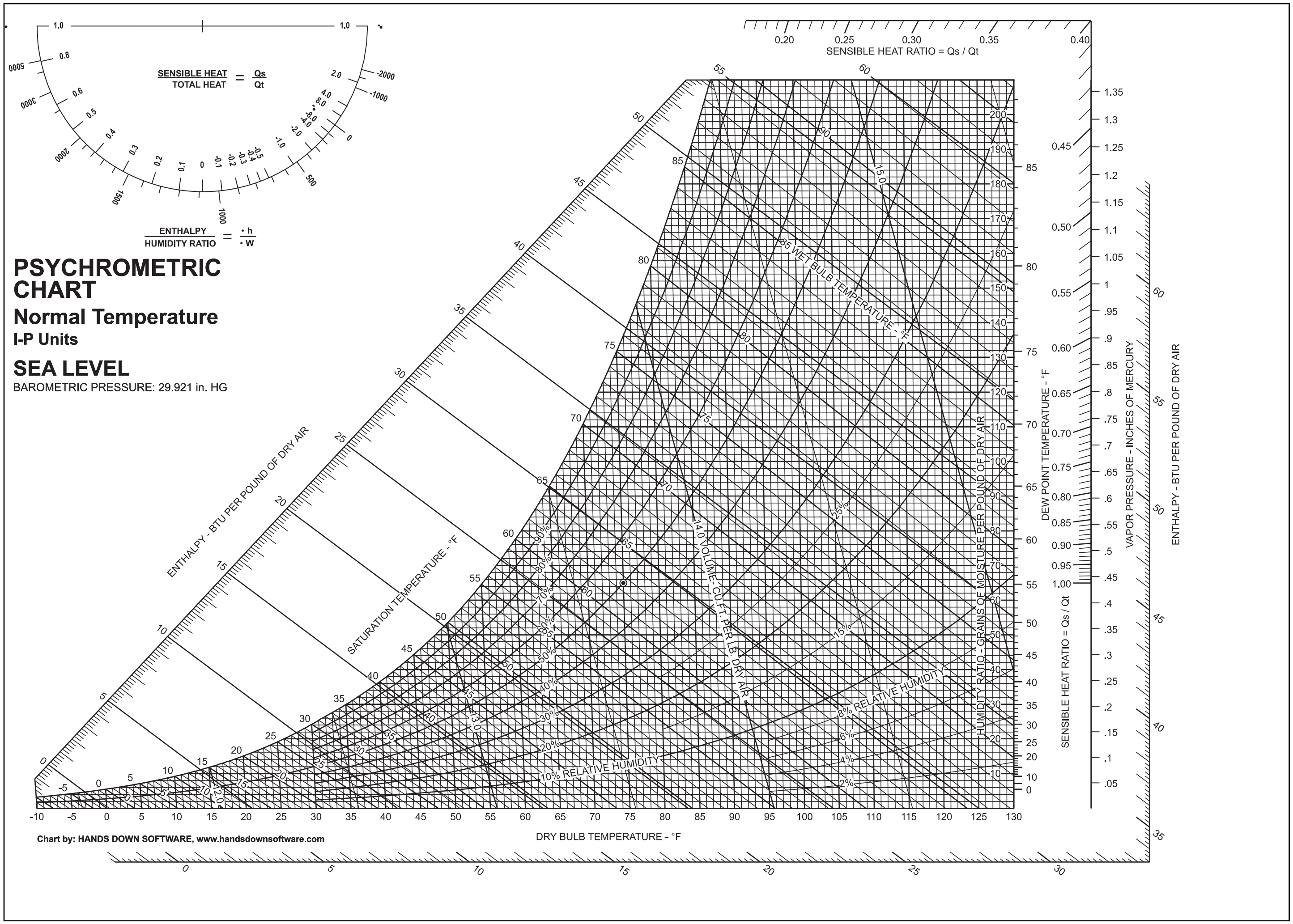
Source: Arthur Ogawa – Public Domain

Appendix 2.7. Commercial Psycrometric Chart, SI Units



Source: Bob Hanna – Public Domain

Appendix 2.8. Commercial Psycrometric Chart, US Units



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Chapter 3

Raw Materials

The packaging cycle begins with and additionally, via recycling, may return to the raw materials that make up materials in finished packages. This section is included as a starting point for considering the packaging cycle. As our societies become more aware of the need for recycling raw materials, and the supplies of raw materials become more uncertain, the packaging engineer can no longer assume that supplies of the basic materials that make up the components in a food package will be stable in either availability or price. The most obvious examples of this are oil and natural gas that are used both as a general source of energy and a source of raw hydrocarbon feedstock for polymer production. It has been estimated that the current world supply of oil may be approximately 50% depleted and whether this figure is accurate or not is of less consequence than the reality that oil supplies are becoming concentrated in fewer and fewer locations, and have long been connected with political problems and price instability for industrialized countries.

This, in turn, feeds back into the packaging and food-processing industry as uncertainty of prices and supplies that will impact the feasibility of a particular product design or choice of materials. Given that the food and packaging industries are highly competitive and price- and marketing-driven, these kinds of supply swings can be quite disruptive to the production flow of food-processing and packaging operations. Also of importance are ongoing environmental and sustainability concerns that may limit the cutting of timber for wood pulp, or the excavation of mineral stocks such as iron ore or bauxite, or beach sand used in the glass production industry. These can affect availability of basic materials and therefore of finished package components as well. The globalization of supply and demand have reduced or eliminated spot shortages of materials for the interim, but increased demand in developing economies and price fluctuations may affect the basic economics of packaging design and drive a move toward flexible sourcing of materials to avoid production losses.

Wood and Fiber

Although some wood is used for the manufacture of crating and palletization products, as well as fabrication of reusable bulk shipping containers, wood and fiber products are used in the packaging industry primarily for the manufacture of paper and related products. Because of increased financial costs and environmental impact of harvesting and processing timber, and increased competition for supplies of wood and pulp, the market for recycled paper fiber has become lucrative enough that paper mills, once only found near access points for timber, have been constructed to operate solely on recycled content. In some instances, paper manufacturing

Food and Package Engineering, First Edition. Scott A. Morris.

of this type has been situated to very profitably utilize the huge supply of recycled paper fiber coming from large urban areas and the low cost of *backhaul* – shipping containers returning empty – to ship waste paper to be remanufactured into paper for expanding Asian markets. Unfortunately, one of the other adaptations has been to situate paper manufacturing facilities in locations where the cost of harvested timber is low and the environmental impact is deliberately overlooked. The long-term cost of this in terms of economic and ecological degradation can be severe.

Paper can be made of many types of plant fibers, but with few exceptions, pulped wood fibers of a few species are preferred. As production of paper and paperboard products decreases in the United States, the types of species used for paper manufacture are becoming less distinct as wood pulp is shipped from one country to another, but the overwhelming source of paper fiber is from softwoods such as various species of pine and eucalyptus. In regions where paper production has escalated to match industry's increased demand for packaging and other paper products, the limitations on paper production facilities and pulp supplies can drive up the price of paper, but also can motivate the use of recycled paper fiber [1].

Paper Production

Wood fiber-based paper begins as trees of various species, typically softwoods, that are harvested in any number of ways depending on local economics and regulations. Logging may be very different in Bhutan than it is in Finland, and many operations, particularly those in more remote regions, still rely on manual cutting. The United States, with its enormous variety of forests, relies on everything from small hand-cutting operations and commercial dragline operations, where cut timber is carried by a powered cable out of the forest, to highly automated harvesters that clamp and cut a tree in a single operation. Countries with high labor costs or extensively engineered forest stock production economies may rely on these more automated cutting devices. Regardless of the felling method, logging is generally dependent on the ability to transport cut timber from the forest to the point of use – typically a chipping, paper, or lumber mill. This transportation is typically a combination of water transport, rail, and over-the-road truck, and from there the finished products will be distributed by truck and rail, with the exception of wood pulp for export that is almost universally carried by bulk cargo ship. When received at a paper mill, wood and wood chips are turned into cellulose fibers and converted into paper and paperboard products as described in detail in Chapter 4.

Resource Outlook

Because of environmental, political, and economic issues revolving around large-scale logging operations and the large amounts of land involved, cutting operations may be very controversial. In the United States, concerns about clearcutting practices, erosion, wildlife habitat loss, and forest replenishment are often strongly debated against issues of resource supply to the public, local economics, fire hazard, and profitability. Much of the timber and pulp in the United States and other countries (particularly New Zealand) comes from private land. Additional resources are cut on public lands, and the conflict between the profitability of logging on public lands and conservationists' objections has created a great deal of discord, particularly due to the fact that the government agencies charged with protecting these lands also handle the timber leases and resource estimates, with inevitable problems. In some cases, allegations have been made that the agencies have severely overestimated the available resources in order to allow more timber cutting, and in others that the Forest Service themselves cut profitable trees from protected resources [2, 3]. Environmental restrictions have been seen as both meddlesome and economically disastrous by people dependent on logging income – the spotted owl habitat preservation that closed millions of acres of the Pacific Northwest to logging has become an icon for the contention and economic disruption caused by conservation efforts.

In other countries, particularly those with developing economies, the logging issue has the potential to incite civil unrest as populations are impacted by the logging operations. In regions such as the Amazon Basin, New Guinea, and Indonesia, among others, the impact on indigenous peoples has often been one of displacement without compensation as well as deforestation. The contention regarding these issues is similar to that in the United States, although there are often fewer effective regulations of any type in place allowing logging to operate in any convenient fashion. In response to the complex nature of forest product utilization, several certification schemes have been put forward to assure customers that products are produced in a responsible manner, although the final impact of this has yet to be determined [4].

Pulp and paper supplies are impacted by these large-scale issues in addition to more mundane issues of energy and production capacity as well as the supply of recycled paper fiber, resulting in global shifts of price and production. Broadly speaking, pulp and paper production is slowly shifting to lower-cost areas of the world, as is much of manufacturing, with new species of wood such as eucalyptus becoming more common among the paper stocks. Capacity in the United States and Canada is slowly diminishing as capacity in Latin America increases, with Asian production increasing to meet the exploding production needs there [5]. The demand for paper and pulp imports by Asian and European markets will continue to pressure supplies, and the increased awareness of environmental impacts on both long-term sustainability and facets of the economies of many countries may create pressure on pulp and paper supplies.

Ceramic Materials

The primary raw material for ceramic materials used in packaging and processing applications is sand, typically taken from beaches or sand pits, as well as other minor mineral feedstocks, and usually chosen for a particular mix of minerals that will provide an approximate composition for a particular set of attributes, most often a particular color. Although sand is a plentiful resource, sand of the proper quality may be located in areas that have competition for use, such as beach areas for tourism or in areas where removal may have significant ecological impact. Because of the nature of glass manufacturing, recycling of broken glass moldings is standard procedure within plants, and the incorporation of post-consumer recycled glass materials is therefore relatively easy, but the demand for specific qualities in the final remanufactured glass product can impose some limitations on the ability for reuse of specific types of recycled glass. Typically the criterion is color – for example, *Flint* (clear) containers cannot be made from amber or green recycled glass – and purity as the inclusion of metallic labels may contaminate the glass batch. Unfortunately, glass also has a huge energy component when compared with other types of materials, and the escalating costs of energy have made the use of glass increasingly economically unfavorable for common products as more durable and lightweight substitutes become available from the plastic and laminate industries.

Glass Production

Glass and ceramics start as sand or clay deposits that are mined either from pits or surface deposits with large-scale earth-moving equipment. The sand must be of the correct type and grade for the intended purpose (for example, optical-grade glass requires a much purer raw material than fiberglass home insulation). Because of the energy content of glass and ceramics, production facilities are usually located near a convenient source of thermal energy (most often a gas pipeline or storage facility), a convenient means of delivering a raw material supply, and a suitable means of distributing the finished containers. With an increasing amount of recycled glass available, it is possible to construct glass plants that operate primarily on recycled materials, although cullet is always a large component of the furnace charge. Ceramics require kiln firing of castings made of ceramic *slip*, although uses in the packaging industry are very minor and the majority of production is for household fixtures and industrial components.

Resource Outlook

The costs of producing glass containers will continue to escalate with the rising prices of energy because container glass requires approximately 6.7 MJ/kg to manufacture [6]. Although the vast majority of glass manufacturers operate furnaces with natural gas that has been somewhat less subject to price fluctuations than oil, the costs of glass containers will make them increasingly subject to scrutiny for replacement by alternate materials. These replacements are primarily plastic containers for food, drug, and cosmetic applications, which have an additional benefit of not being a dangerous product contaminant if they fail. The glass industry is both mature and somewhat unstandardized in its methods and machinery, and the transportation costs of the heavy containers limit the economically feasible distribution radius of containers – this being subject to impact by energy prices as well [7]. Glass containers will not easily be completely replaced either for reasons of chemical resistance and inertness, such as with pharmaceuticals, or for reasons of the perception of quality that the perfume and high-value beverage industry depends on. However, the cost premium will continue to push the development of lighter and more efficient glass structures.

Metals

Aluminum

Aluminum is manufactured by the electrolysis and reduction of aluminum oxide found in bauxite ores, almost universally by the electrode smelting method first developed by Hall and Heroult in 1886. This is an energy-intensive method because of the highly stable nature of aluminum oxide, and the aluminum industry has been actively recycling metallic aluminum since the 1970s because of the energy savings and cost reduction involved. Aluminum-refining plants are often located near large electricity sources, often hydroelectric facilities or similar power plants, and will import bauxite as needed. Packaging consumed approximately 20% of North American production [8] in 2005. Aluminum has the paradoxical advantage that the same surface oxide stability that makes aluminum hard to refine makes it ideal for many applications because the oxide coating on metallic aluminum provides protection against further external corrosion. Under common usage conditions, this oxide layer may allow items made of aluminum, including beverage cans, to remain externally uncoated without fear of corrosion damage, which makes it ideal for high-volume beverage applications. Additionally, although the total tonnage used is relatively small, aluminum plays an increasingly important role as a barrier both as thin foils and as vacuum-deposited coatings on polymer substrates.

Aluminum Production

Bauxite ore is surface-mined from deposits that are on the order of 4–6 meters thick [9] at any number of locations, often quite remote. The ore usually requires transportation to a refining site because many of these are situated near energy sources rather than ore supplies. Most often, bauxite ore is directly exported via rail or bulk cargo ship to refining and smelting sites elsewhere, and the refined metal can be converted at the smelting site or distributed as aluminum ingots for further processing and conversion into sheet, foil, or extrusions.

Resource Outlook

The aluminum industry has been undergoing restructuring since the early 1980s and has undergone substantial changes, with primary production of aluminum migrating to countries with lower energy costs either as a result of natural power supplies, such as hydroelectric or geothermal power, or as the result of excess petroleum production. Aluminum production has been used as a means of converting power production into goods for world trade in some countries, and has proven lucrative enough for the import of bauxite ore for refining and smelting operations. World bauxite production, led by Australia, Brazil, and China, was 201 million tons in 2009, and listed world reserves are approximately 27 billion tons (approximately a 180-year supply), although the estimated total resources are thought to be 55–75 billion tons [10]. The developing economies of China and India will put pressure on increased production, and the substantial level of aluminum recycling that has been established and is being increased will provide an alternative source, so once again energy costs – approximately 25% to 35% of the final cost of production – will substantially affect the price of refined aluminum.

Steel

Steel is a very strong material but is seldom used in packaging beyond the fabrication of tinplate cans where corrosion can be managed. The steel and aluminum industries compete for market share among the non-beverage can markets in particular locations, and thinwall steel cans similar to the common aluminum beverage cans are available in some markets. Although steel can be recycled in a manner similar to aluminum, the relative energy savings are much less because of the smaller energy component involved in reducing elemental iron oxides to metallic iron. Steel, because of its high modulus and strength, is also incorporated into structural applications in nearly every kind of building and vehicle, so that the packaging industry is a relatively small market segment but is also affected by other demands for steel-based materials.

Steel Production

Steel is manufactured from reduced iron ore, typically surface-mined as oxides and converted to a more concentrated form such as taconite pellets before being transported to a production steel mill. At this point, the ore is combined with carbon and other minerals in a basic oxygen furnace that uses a series of chemical reactions and oxygen injection to convert the impure carbon-iron mix into purified steel melt. Recycled steel may be converted in the same manner, or an electric arc furnace may be used in smaller operations (so-called mini-mills that may have production levels as low as 50,000 tons per year). From this it may be cast into slabs and rolled into sheet to be used as can fabrication stock. Ferrous foils are not used in the food industry because of their lack of corrosion resistance. Sheet steel may be plated with tin or coated with a polymeric surface layer to prevent corrosion, and is then used as can stock for container fabrication.

Resource Outlook

With the globalization of the steel market and the explosive growth of Asian and Indian economies, iron ore as well as finished steel is in great demand. The increased demand for steel has driven the cost of both finished and scrap steel upward, increasing the cost of finished products such as food cans. Iron ore production is expected to increase to match demand, but there is substantial lag, particularly in the construction of new facilities to process ore or recycle scrap steel. The limiting factor is not the availability of ferrous ores, which are very common minerals, but the ability to efficiently mine, transport, and refine them. The packaging industry has responded by either replacing steel cans with ones made of polymers or composites, themselves subject to the increased cost of petrochemical feedstock materials, or by creating lighter-weight steel containers via structural modifications.

Tin

Tin as an alloying element for copper to make bronze dates back at least 5,000 years in southern England, and was traditionally mined in small pits and traded around Europe, the Mediterranean, and Africa at least as early as the 6th century BCE. Approximately 27% of the world tin market is used for the nontoxic anticorrosive coatings on steel food containers, described elsewhere in the book, and approximately twice that as a constituent in solder used primarily in electronic assemblies. Most electroplated steel that is utilized for structural applications uses a thick zinc coating unsuitable for food contact use.

Tin Production

Tin ore is smelted in a reverberatory furnace that isolates the heating fuel from the ore deposits while subjecting them to the hot combustion gasses [11]. Tin may also be recovered from scrap, typically in tin and electronics-recycling operations. Tin may be further refined by boiling or electrolytic processes as required, and then is cast into ingots. Food can coatings are typically made with Grade A tin (99.80% Sn), to avoid problems with residual compounds from the smelting process, such as bismuth or lead.

Resource Outlook

Tin in historic deposits in England, Europe, and even Africa required relatively difficult manual mining for relatively high-grade ore for use in making bronze. Currently, the largest principle tin production resources are located in China, Indonesia, and Peru, with several other South American countries producing substantial quantities mined from alluvial deposits either by surface removal, dredge, or hydraulic mining. Consolidation of tin producers and the increase in demand for low lead/high tin content solder for electronic devices has driven the price upward and caused several mines to be reopened. Tin is often recovered during the recycling of tinplated steel and electronic circuitry, so there is a mitigating source of supply. As alternative polymeric coatings for cans are implemented and there is progressively reduced solder content in ever smaller electronic devices, the effect on container costs may be reduced.

Petrochemicals – Oil and Natural Gas

Oil and natural gas are used as energy sources for all types of manufacturing, as well as the raw material for many types of polymers. Although the energy requirements for the manufacture of polymers is lower than that for glass, the politically volatile nature of the petroleum and natural gas supply is reflected in the fluctuating price of polymer resins. Apart from resin manufacturing, energy costs that are often tied to the price of oil and gas are frequently reflected in manufacturing and processing costs because many of the processes are dependent on a high-energy input in materials such as glass, aluminum, and steel. Indirect costs related to energy, such as transportation and manufacturing facility operation, will also be affected by fluctuations in petrochemical prices, supply, and availability.

Petrochemical Production

Oil and natural gas are primarily obtained by drilling wells into deposits locked in porous rock strata located in regions where prehistoric plant matter has been compressed and heated over time. Alternative sources of crude oil involve mining tar sands or oil shale and extracting the oil content from them, as well as the relatively inefficient conversion of mined coal into other petrochemical forms. Once the oil or gas is extracted, it is transported by pipeline or tanker either to refineries or to loading terminals for large vessels to transport them to refineries. Oil refineries use a combination of heat, pressure, and catalysts to break the oil down into its constituent components ranging from light gasses to asphalt. These products are distributed by ship, rail car, truck, barge, and pipeline. Natural gas is typically distributed by pipeline but may be shipped intercontinentally in specialized LNG (Liquefied Natural Gas) tanker ships. When separated into its constituent parts (primarily methane, ethane, propane, and butane), these gasses may be used in the polymerization processes that produce many packaging polymers.

Resource Outlook

As the primary source of energy for transportation as well as numerous other applications such as domestic heating and electricity generation, the petrochemical supply is central to the world economy, and as such is the subject of an extraordinary amount of concern, debate, and speculation (both philosophical and financial). Marion King Hubbert proposed in 1956 that world petroleum production would peak near the end of the 20th century at a level of 12 billion barrels a year (Figure 3.1), and although the model was elegantly simple, data has shown that the world's oil supply reached a peak in approximately 2000 (at 12.775 billon barrels per year) and is decreasing [12].

Many arguments revolve around these figures, but the inescapable reality is that the current mode of energy production and usage cannot continue indefinitely, and that alternatives must be developed. Hubbert, a geophysicist, argued that nuclear power was the only sustainable energy alternative. Other energy alternatives such as solar, wind, and geothermal sources may also supplement or replace the current means of electrical generation, but alternatives for simple,

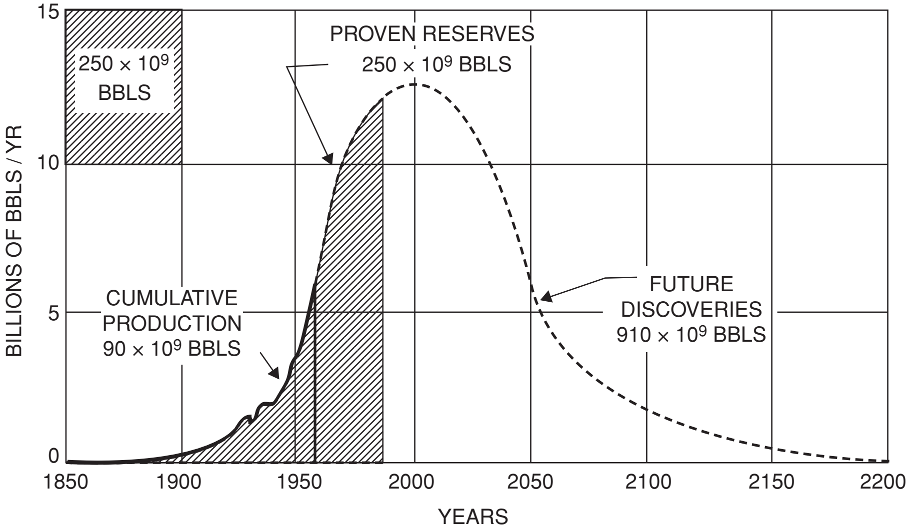

Figure 3.1. The Hubbert Curve
Source: M. King Hubbert (1956), "Nuclear Energy and the Fossil Fuels". Drilling and Production Practice, American Petroleum Institute & Shell Development Co. Publication No. 95, Figure 20, 22. http://www.hubbertpeak.com/hubbert/1956/1956.pdf

cheap, and durable polymer materials will be more difficult to produce, although there are promising biopolymers.

Other Gases – Propellants and Industrial Gases

The increasing use of gases in processing and packaging, both in the traditional areas of aerosol propellants and in the increased use of gas flush and modified atmosphere packaging, require that the supply and forecast for these are considered. Some aerosol propellants are simple petrochemical gasses (propane, for example) whereas others are more complex synthetics such as the HCFC propellants, but nearly all of them have a petrochemical base and are subject to price volatility induced by the world petroleum energy market.

Non-petrochemical gasses such as nitrogen are removed directly from the atmosphere via compression and liquefaction, and then typically separated either by membrane/molecular sieving systems or by pressure and temperature-based separation. Energy costs are a large component of the overall manufacturing costs with these compounds that have free feedstock but require energy-intensive compression for liquefaction. Interestingly, the drive for alternative fuels from agricultural feedstocks, such as ethanol and butanol, has provided a tremendous source of carbon dioxide as an industrial by-product.

Energy

Although energy is a more generalized and indirect concept, all processing and packaging materials and operations are dependent on some type of energy input. Thermal processing, discussed in detail elsewhere in this book, requires an enormous amount of heat input, and many food plants are not designed with large-scale energy use integration and savings in mind.

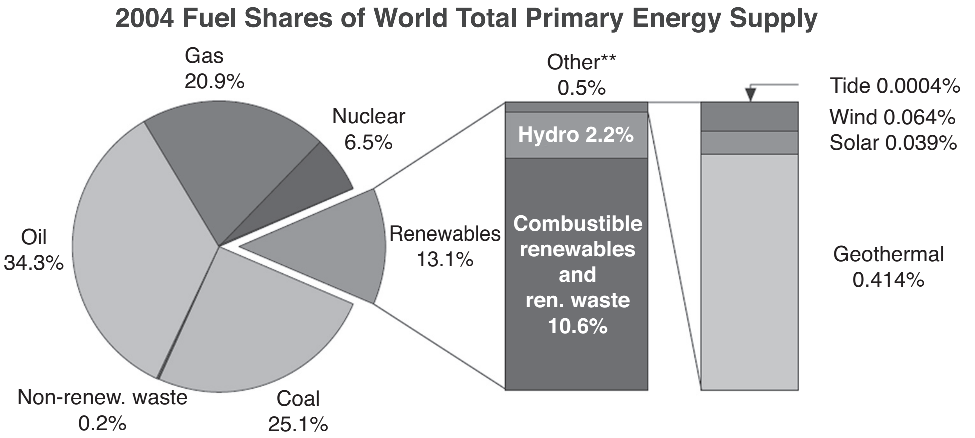

Figure 3.2. 2004 Fuel Shares of World Total Energy Supply
Source: Renewables in Global Energy Supply: An IEA Fact Sheet, ©2007, Figure 1, Page 3. Used with Permission

All too often, immediate cost factors, short-term profit goals, or a lack of basic understanding of the nature of energy consumption and use will hamper the efficiency of processing and packaging operations. Additionally, the energy content of a particular item may be as hard to quantify as its individual cost to manufacture in general. A meat product packed in a glass container and then thermally processed in a steam retort will have an enormous energy budget once one considers the energy contained in the food material – at the apex of the energy use triangle in agriculture – the energy content of the container, and the steam-based processing. Storage, distribution, and transportation costs will add another facet to the energy budget of the particular item, although all of them have alternatives and can be reduced [13].

Resource Outlook

The world consumption of energy was approximately 15 Terawatts in 2005, and is expected to continue to rise by nearly 60% by 2030, with the largest overall increase resulting from the economic expansion of China and India. Although many alternative energy sources are being touted, these contribute a very small component of the world's total energy budget.

As shown in Figure 3.2, 87% of the world's energy consumption in 2004 was from non-renewable resources (coal, oil, natural gas, and nuclear power), and this percentage is unlikely to change quickly, although it will increase over time because of price pressure from traditional fuels. Interestingly, these figures consider hydroelectricity to be a renewable resource when in fact dams and generating stations often have a finite life due to silting, and are subject to the effects of drought. Biofuels such as ethanol, although intermittently fashionable, have been the subject of debate questioning whether the net energy production of the synthetic fuels exceeds the net energy input to grow, harvest, and refine the materials. Other arguments center on the price increases in food resulting from the use of base food ingredient materials such as corn or vegetable oil as a fuel and escalating demand for those materials.

Marion Hubbert, mentioned previously in this chapter, argued that nuclear power would have to be extensively developed because of the finite nature of hydrocarbon power sources and the long-term sustainability of nuclear power production with known isotope reserves. This argument has some merit but, like many others, revolves around the presumed interchangeability of energy sources, which does not work in many practical applications. Although it is possible to convert a steam-generation facility from gas to electricity, the conversion of vehicles is much more difficult due to the inefficiency of current electrical storage devices and the high energy density of gasoline.

What is certain with regard to energy is that demand will remain strong, and that the technological changes that may be necessary to accommodate this are going to be difficult at best. In practical terms, there will be a premium both on energy efficiency and energy awareness in the food-processing and packaging industries, and the efficiencies of new types of processing such as aseptic thermal processing may play a much larger role in food preservation. Packaging, with materials fabricated from petrochemicals that are directly affected by energy prices and supply, or with energy-intensive materials that are subject to the whims of price fluctuation, will continue to be challenged to make better and more economical use of a smaller quantity of more expensive materials.

Additional Resources

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Chapter 4

Conversion of Raw Materials to Package Components

Once raw materials are produced, they must be converted into a useable form in order to create the structures and devices required for finished packages and other uses. This chapter will examine many of the processes used to convert raw resources described in Chapter 3 into packaging materials such as paper and corrugated board, plastics, glass, and metals, as well as some of the ways they are converted into finished packages.

Paper

Paper manufacturing dates back to the time of the Egyptians' use of papyrus reeds to produce relatively sophisticated sheets of papyrus for the production of documents and records. However, the papyrus sheets that were produced were not paper in any sense of the current material, in that the reeds were cut open and laid at right angles in progressive layers to form a thin, writeable sheet. Paper constructed from slurries of fibrous material dates back to 2nd century BCE in China where vegetable matter and cloth fibers were used to produce finer sheets of paper with randomly oriented fibers. Paper manufacture continued with sheets of paper being formed by dipping fibrous pulp onto rectangular straining screens of either cloth or wire, and being dried as single, relatively small sheets.

Modern paper manufacture has evolved from hand-dipped paper made of cloth fibers to the use of digested wood products that are cast as a continuous sheet (or *web*) using either Fourdrinier or cylinder machines, each of which has traditionally had distinct characteristics and advantages, although these have converged and blended as the industry has matured. Paper can be produced in sheets ranging from very thin tissues and onionskin to thick sheets of chipboard that may approach the thickness of home construction materials. The most common uses of paper-based materials in the packaging industry are for pouches, cards, cartons, and shipping containers; the latter two of these are often made of thicker carton board and corrugated board, respectively. Modern papers and paper-based materials can be produced to very consistent standards of manufacture, but paper itself is fundamentally a natural material and is influenced significantly by fiber length and environmental factors such as humidity and oxidation, as well as being time- and rate-dependent in its structural characteristics (Figure 4.1). Because of this, developing precise engineering equations for the design of paper-based structures remains elusive, and the use of paper materials remains something of an art.

Food and Package Engineering, First Edition. Scott A. Morris.

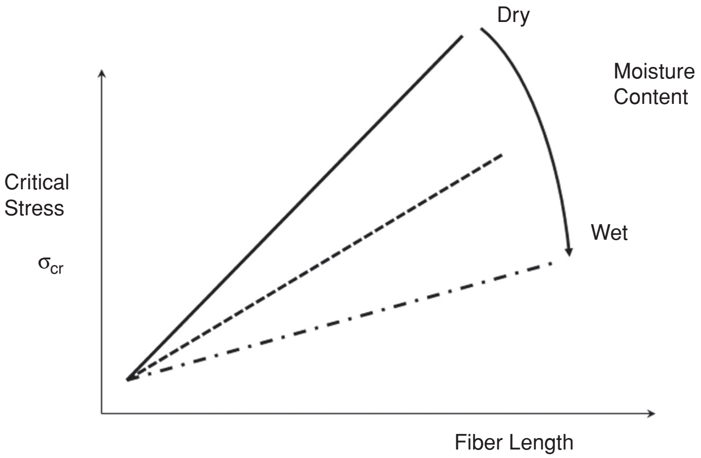


Figure 4.1. Relationship of Fiber Length, Moisture, and Strength in Paper

Cellulose Chemistry

The basic chemistry of the cellulosic plant materials, principally wood, that make up the raw material for paper manufacturing consists of three major components: cellulose, hemicelluloses, and lignin.

Cellulose is a polysaccharide polymer of cellobiose that is produced from glucose by green plants, and will form itself into closely packed fibrils with a molecular length of 300–2,000 units (Figure 4.2). In plants, these are synthesized by *rosette terminal complexes*, structures containing the synthase enzymes that produce the cellulose chains. Cellulose provides a primary structural component of cell walls and as a strong, naturally occurring fiber is used both in nature and manufacturing for a wide variety of applications, from textiles to explosives. Because of the hydrogen bonding between adjacent chains in fibrils, it is also hygroscopic and susceptible to many water-dependent physical effects (Figure 4.3).

Hemicelluloses are shorter-chain mixed polysaccharides that are usually somewhat alkali soluble and will assist bonding between cellulose fibers because of their ability to create water-based hydrogen bonding.

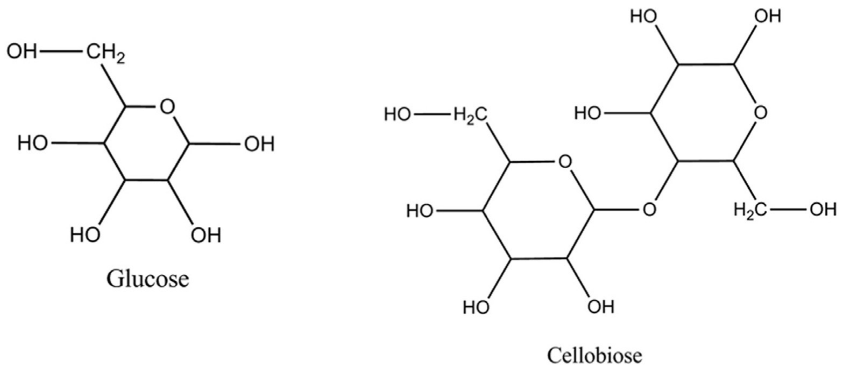


Figure 4.2. Glucose and Cellobiose, the Building Blocks of Cellulose

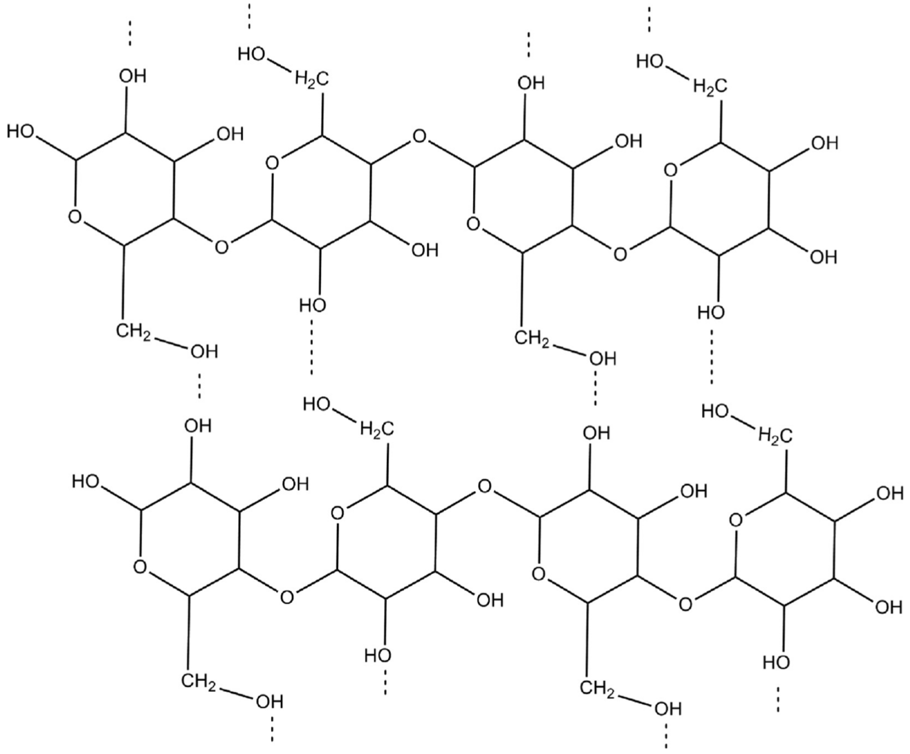


Figure 4.3. Interchain Hydrogen Bonding in Cellulose

Lignins are a class of heterogeneous biopolymers that constitute 25–35% of the mass of wood. These consist of a range of both compounds – typically, polymerized sugars and their derivatives – and polymer length. Because lignins, which are retained in mechanical pulp products like newsprint, can cause paper to yellow with age, their removal is important for the manufacture of high-quality paper. Lignins have a very high energy value and are often burned after extraction to power paper and pulp mills.

Chemical pulp manufacturing methods depend on the differential solubility of cellulose (which does not dissolve well in mild sodium hypochlorite or hydroxide solutions) and the lignin and some of the hemicelluloses that are dissolved in the chemical pulping process to disassociate the cellulose fibers for reforming into paper products.

Paper Manufacturing

The modern manufacture of paper in its most simplified form is simply the reduction of fibrous cellulosic materials, usually beginning as wood chips, to a water-based slurry of loose fiber by either mechanical or chemical methods, and then the reconstruction of the fibers into a dried, flattened mat of interwoven fibers, often several layers thick. The surface of the materials may be treated or coated to provide better printing surfaces, grease resistance, or *ovenability* (allowing it to be used for oven baking of foods at moderate temperatures).

The actual level of machinery implemented to economically mass-produce a consistent paper product may be enormous, requiring capital-intensive installations for production as well as the ability to handle large amounts of raw materials and to contend with wastewater treatment and other environmental issues.

Pulp Manufacturing

Pulp is produced in pulp mills that may be affiliated with a nearby paper manufacturing operation, although pulp can be shipped in bulk either by rail or ship to other manufacturing facilities depending on prevailing market conditions. This is done for many of the same reasons that iron ore is partially concentrated, then shipped to a fixed steel mill; it is less expensive to chip or pulp the product then ship that, than to construct a complete paper mill at each resource site. Because of this, an international trade in wood pulp has been created between timber-rich areas of the world and the processing plants of paper-consuming economies.

The first modern paper-manufacturing process was the mechanical grinding of wood fibers into a rough solution that could be cast into rough forms of paper. Modern manufacturing methods first automated this process, producing groundwood pulp (GW) with milling stones, and subsequently replacing it with thermomechanical pulp (TMP) processes that use heat and pressure to further soften the chips before the mechanically produced pulp is generated. This method has the advantage of using nearly all of the base fiber material in the paper pulp with a subsequent yield of 85–95% [1], and producing an absorbent paper well suited for printing because of the shredded cellulose fibers, but has the attendant disadvantage of having short fibers and not aging well due to the inclusion of lignins that are removed by chemical pulping methods. Chemical methods now produce the majority of paper fibers, but mechanical methods still produce roughly 10% of paper fiber. Other, less common types of pulp manufacturing that partially rely on mechanical pulping methods are refiner mechanical pulping (RMP) that is similar to simple GW except that rather than grinding logs or chips against a rotating stone, they are ground between a rotating stone and a fixed disk (stator), producing a stronger pulp from a wider variety of chipped fiber sources; and chemithermomechanical pulp (CTMP) systems that chemically pre-treat TMP source chips with various alkaline compounds as well as other agents at elevated temperatures to increase the fiber strength and bleach the fibers while retaining the lignins and keeping the process yield high.

Chemical methods rely primarily on the dissolution of the lignin and carbohydrate components that hold the desired cellulose fibers in place in order to free them into the slurry. The first of these dissolves hardwood fibers into an aqueous solution of sodium hydroxide and sodium carbonate to dissolve the lignins and related materials that hold cellulose fibers in place. This *soda* process is not commonly used, having been replaced by methods that can use softwoods and other less expensive sources of fiber, and produces a characteristically fine surface.

The *sulfate* process uses sodium hydroxide and sodium sulfide to produce a very strong mixture of hardwood and softwood fibers, commonly referred to as *kraft* paper, and in either natural or bleached-white form is the most commonly used sheet paper in the packaging industry. *Sulfite* processes use bisulfites and sulfuric acids in the same manner as the previous processes to produce an intermediate-strength paper that can be produced with a fine finish, although the residual acids cause it to degenerate over time. Archival papers are typically acid free for this reason, and are produced by other methods. Hybrid methods exist such as the semichemical pulps that rely on combinations of chemical, mechanical, and thermal treatments to produce low-cost pulps that retain a great deal of lignin, and are therefore not as attractive as other applications.

An additional source of paper fibers is recycled materials that require much less effort to recover the fiber content, although the inclusion of non-paper materials (such as waxes, adhesives, and other contaminants) can be a problem in producing the final web of material. Additionally, several studies have shown that post-consumer materials such as carbonless paper chemicals and copy machine and laser printer toners will be retained in the pulp and may be transferred into food products [2]. Additionally, the increasing diversity of wood supplies has also introduced a concern with non-native wood sources introducing unknown microbial species, tastes, and odors to paper. Generally, a chemical de-inking process must be applied to remove inks that are then removed via air flocculation of the recycled fibers, and *sticky* contaminants that may clog subsequent equipment are removed via screening and centrifugation.

Once the basic slurry is formed, the fibers are beaten in an agitator to allow the cellulose fibers to be fully released, and to allow smaller fibrils to be liberated so that the final paper product has a high degree of fibril entanglement and the potential for hydrogen bonding in conjunction with water. At this point, several different pulps may be blended and other additives may be included to affect the strength and absorbency characteristics, optical properties, stiffness, and strength so that the final mixture, called furnish, has the proper qualities to produce the desired paper product.

Bleaching of the paper, to provide a bright surface, is typically done at this stage. Traditionally this had been done with chlorinated compounds, but concerns about residual organo-chlorine by-products, particularly polychlorinated biphenyls (PCBs), being released into the environment have caused the industry to adopt other methods such as hydrogen peroxide and ozone-based bleaching processes.

This mixture then is fed to forming machinery, all of which work on the basic principle of extracting the water from the furnish (pulp slurry) to form a finished product, although the means by which this is accomplished may vary.

Papermaking

Papermaking is based on pulp that is formed into a continuous thin sheet of interlocked cellulose fibers that can be further processed into a final paper product. The oldest continuous-production type of machinery is the Fourdrinier machine, which was supposed to have been invented by Louis Robert in France in 1798, but was introduced by the Fourdrinier brothers (for whom the machine is named) in England in the early 1800s, and was subsequently developed into a

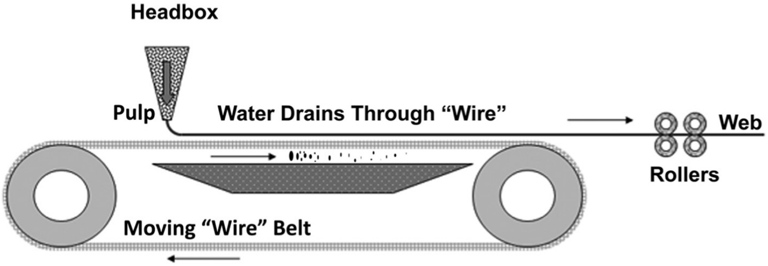


Figure 4.4. Schematic of Fourdrinier Papermaking Machine

large-scale production method. It is an automated extension of the old hand-dipped papermaking method in the sense that rather than dipping a mesh screen into a fiber slurry, the slurry is poured from a *headbox*, a reservoir with an adjustable slit allowing pulp to flow onto a continuously moving belt of metallic mesh (the *wire*), letting the water drain through the mesh (and through the fiber layer itself) to the point where it forms a continuous sheet that can be peeled from the belt and be further processed. Watermarks, if desired, are added by a dandy roll pressing the image into the paper web while it is still on or near the wire stage.

A modified version of this, the so-called *twin-wire* machine, has the slurry deposited at the convergence of two moving belts of wire mesh, which allows the web to be compressed between wires and dewatered more efficiently using gravity and suction. This method may be used for producing both paper and paperboard. To complicate things still further, multiply paper may be formed using a Fourdrinier-based machine that uses small Fourdrinier headbox and wire units to create individual plies that are then layered on a large wire to create thick-section papers and paperboard and avoid problems with the ability of the thick sections formed in a single machine to drain water properly.

The other major type of machine is the *cylinder machine* that was developed subsequent to Fourdrinier machine and relies on cylinders that pick up fibers from the slurry and deposit them in successive layers onto a *felt*, a moving belt of absorbent material, which is then covered with a second felt and pressed to remove the water. At that point, the web is sufficiently strong to be removed from the felt for further processing. Cylinder machines are constructed in one of several basic configurations, using either a cylinder mold former or rotary former to deposit paper fiber on the felt. The cylinder mold former lies in a flowing stream of slurry, and paper fibers are taken onto a rolling cylinder that has a slightly lower water level, creating a low-level suction to bond the fibers to the cylinder and then release them onto the felt. Rotary formers that were developed from the original cylinder designs have an inlet box on the surface of the roller before contact with the felt that allows drainage and suction to be used to dewater the pulp slurry more efficiently.

The significant difference between Fourdrinier machines and cylinder machines is the ease with which multiple layers may be added to provide thickness and specific properties to the finished material. Traditionally, Fourdrinier machines have only been able to provide a single layer of fibers, although the multiple-headbox machines have changed that somewhat. With

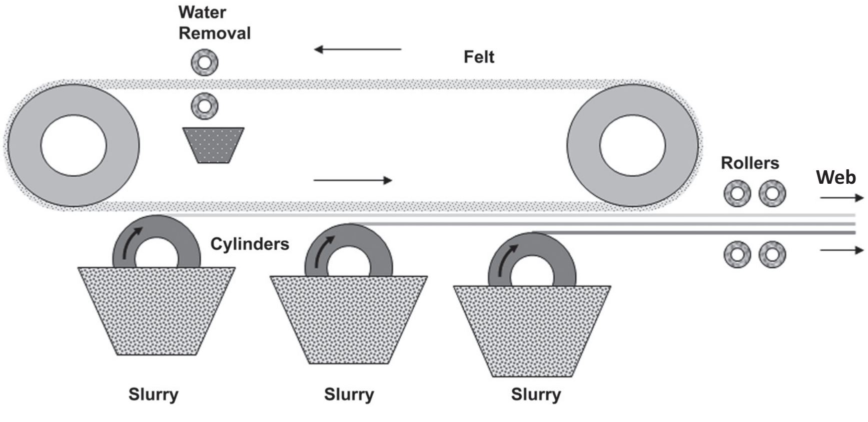


Figure 4.5. Schematic of Cylinder Papermaking Machine

each layer deposited by the Fourdrinier machine, drainage through the preceding layer becomes progressively more difficult, effectively limiting the number of layers that may be deposited. Similarly, cylinder machines were traditionally thought of as only being capable of producing thicker, coarse-grained papers, although subsequent developments have improved this as well. A cylinder machine can produce a paper or paperboard that has several layers of coarser or recycled materials sandwiched between outer layers of fine pulp to provide a strong, relatively inexpensive paper or board.

With either major type of process, once the web has been stripped from the wire or felt, it is fed through a succession of rollers in the press section to remove still more water and then to a dryer section that dries the stock using steam and hot air. At this point, the paper can be run through heated *calendaring* rolls that will form a glossy surface on the web by using slippage between a hot roller and the paper surface to iron a smooth surface into it before it is fed to a take-up reel. The surface finish can be tailored to the application by choosing whether to calendar a particular surface and the degree of slippage, heating, and pressure that are used if calendaring is chosen.

Paper Coatings and Additives

Paper may be coated, treated, or saturated with any number of materials depending on its final application. Sizing agents may be added to provide stiffness, strength, or resistance to absorption of inks, moisture, or oils and to add surface strength and resist fuzzing. Sizing is usually composed of rosin sizing or surface sizing. Rosin sizing, commonly used in most mass-produced paper, is an amphipathic (attracted to both fats and water) molecule that creates a hydrophobic surface by attaching its hydrophilic end to the paper structure. Surface or tub sizing is usually a glue or starch and is not common in mass-produced paper products.

Because many inks will wick along the fiber structures in paper and distort printed images, surface treatments of clay, chalk, or titanium dioxide can be added to fill pores and provide a non-directional, uniform printing surface for graphics reproduction. As a result, some glossy magazine papers have a substantial portion of their total weight from the clay coating needed for highly accurate graphics reproduction. Barrier coatings for resistance against moisture or gasses may be added if necessary, although truly gas-tight non-heat-sealed paper structures are rare because of gaps in their construction.

One of the most ubiquitous coatings of paper has historically been wax, to provide moisture and grease resistance, and although wax paper is still available for consumer use, it has been replaced in many applications by plastic film or plastic-coated paper. For extremely specialized use, coatings and additives to paper have been developed that involve microencapsulated inks for carbonless paper products, anti-counterfeiting features for currency, and even experimental uses of paper-based, printed flexible electronics. Printing processes and adhesives will both be discussed in more detail in Chapter 5.

Paper Properties

Commercial paper products are universally anisotropic (exhibiting different characteristics along different axes of reference) because of their methods of manufacture. The layering of fibers or straining of fibers through underlying materials dictates that, to some degree, there will be an increase of fiber length through the cross-section of the material, and the motion of the felt or wire will produce a predominant orientation of the cellulose fibers in that direction of travel.

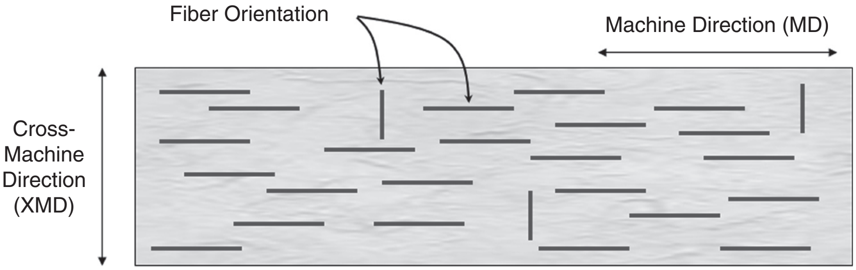


Figure 4.6. Machine and Cross-Machine Directions in Paper

This orientation – the *machine direction* – is important because it dictates how the paper will behave when stressed and the mechanical changes that occur as a result of moisture (Figure 4.6).

Additionally, because the cellulose used in paper is a naturally occurring hygroscopic, viscoelastic material, the effects of stress and strain may be dependent on time, temperature, humidity, rate of loading, and the amount of time that a load is applied. This makes the mathematical prediction of properties beyond general estimations very difficult, particularly where extremes of humidity begin to radically affect the fundamental nature of the paper chemistry.

Machine Direction Effects

The orientation of paper fibers in the direction of wire or felt travel carries over into the finished material in that the paper will tear preferentially along the direction that the majority of fibers are laid down because a tear will require less energy to separate fibers from one another – in the machine direction – than it will to break the fibers off in the *cross-machine direction*. This has the effect of making highly oriented papers, such as those used in the printing of newspapers, easy to tear in one direction (usually from top to bottom) and nearly impossible to tear in a straight line at right angles to that direction (Figure 4.7).

The effects of moisture on the hygroscopic cellulose fibers will also reflect the orientation of the fibers. Cellulose fibers tend to swell or contract along their diameter rather than lengthwise in response to changes in moisture, and the predominance of machine direction fiber orientation can result in paper curling around or buckling along the axis of orientation as the fibers swell when one side is wetted, or when one side is constrained by being laminated to a non-paper material

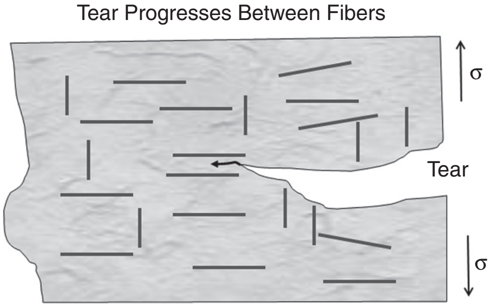


Figure 4.7. Tearing and Machine Direction in Paper

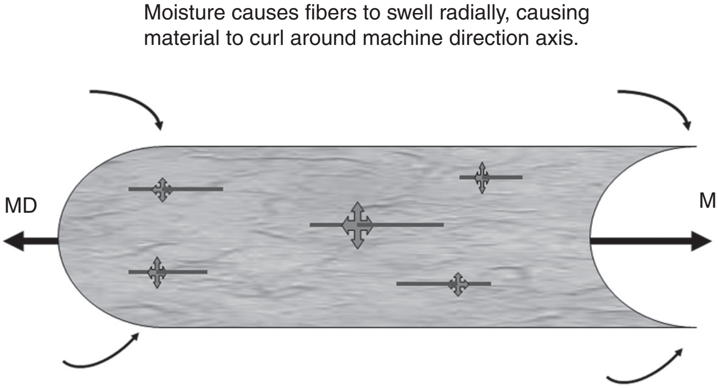


Figure 4.8. Moisture Effects and Machine Direction in Paper

(Figure 4.8). This may cause problems in high-speed packaging lines in wet environments such as food-processing plants and photography operations.

Specialty Papers

Glassine and Greaseproof Papers are produced by the extensive mechanical beating of the pulp, and are often not grease- or moisture-proof in and of themselves, but are used as a substrate that may be coated with water- or grease-proofing. Parchments are fully formed papers that have been re-digested by passing them through an acid bath that causes the surface cellulosic materials to fill the gaps in the paper, and provide a material that has a very smooth surface, is very strong when wet, and resists high temperatures well.

Synthetic "papers" such as Tyvek® and related materials are discussed more fully in the chapter on polymers, as they are compounded of polymeric fibers but are often used where extreme strength and durability are necessary. The most commonly visible use for synthetic papers is for express shipping envelopes, but they are often used to carry and ship sharp objects or to produce a reusable consumer package at low cost; they are also commonly used as a water-permeable draft barriers in home insulation systems.

Paperboard

Paperboard, defined as a paper material thicker than approximately 0.25-0.30 mm (0.010–0.012 in.), depending on local standards, is almost universally produced on cylinder-type machines or the multiple-pass Fourdrinier machines previously described. It may be produced in grades ranging from chipboard made of recycled and low-grade fibers and lined paperboard that may have one or two surfaces of high-grade paper fibers or clay coating to sulphate boards that are made completely of highly treated fibers. These provide good strength, excellent food contact surfaces, and, when bleached, a completely white structure that provides a high-quality appearance to the board. Because paperboard is constructed of several plies of material, the nature of the plies and their interlayer bonding will have an effect on the final mechanical properties of the finished board. Additionally, as the bending of board stresses the surface layers more than the interior, the surface plies of the paperboard should be made of a stronger pulp to stiffen it. The compromise is that in the fabrication of finished packages, paperboard cartons often are required to fold without surface cracking that will reduce or destroy the strength of the carton. Backing cards, die-cut liners, and other structures that may form by interlocking or remaining rigid may be made of much more brittle material because these structures do not flex extensively in use.

Molded Pulp Packaging

Molded pulp is formed directly from pulp that is poured through a three-dimensional mold screen, leaving a paper-fiber-based molding that is increasingly used as a substitute for expanded foams and thermoformed sheets in many segments of packaging. Molded pulp is an extension of the paper-making process that can produce intricate moldings that range from rough carton fitments to thermoformed pulp structures that are somewhat similar to those produced by thermoforming sheet and foamed plastics and are becoming more competitive based on their recyclability and cost.

The most familiar molded pulp item for most consumers is the food tray that many fast-food and coffee shops use to carry several cups at once, although they are often used in the food industry as separators for fresh fruit and specialty display items (Figure 4.9). The consumer electronics and computer industries have led the development of even more complex molded pulp packing caps to replace those made of expanded polystyrene and other types of plastics, to permit easier recycling of materials and the use of recycled paper in the formation of the molding.

Molded pulp is formed by applying pulp in suspension, either by pouring or dipping, to a screen that carries a three-dimensional shape corresponding to the shape required in the final molding. Typically the *screen side*, with its smooth finish, is designed to be the side in contact with the product so that loose fibers from the non-screen side do not come loose onto the

Figure 4.9. Molded Pulp Bottle Holder
Source: Enviropak, with Permission

product. The pulp may be dyed to correspond with a particular design scheme or to mask the color variation that occurs with the use of recycled pulp in the molding.

Newer types of thermoformed pulp molding are available that rival thermoformed plastic sheet in appearance but offer easy recyclability for consumer items at the cost of low moisture resistance.

Corrugated Board

Corrugated board is commonly called *cardboard*, even though true cardboard, used for making display and playing cards, is actually a paperboard product. It is typically formed from three or more layers of either cylinder or Fourdrinier paper that form two *liners* and a crenulated *medium* layer that spaces the liners and makes the liner boards absorb bending stress in a manner similar to the web of an I-beam forcing the top and bottom plate to absorb a structural bending load (Figure 4.10).

Corrugated board can be produced in any number of thickness and layers of material ranging from the simple corrugated *medium* used as packing (and that was the hat band material that was the origin of corrugated board) and single-faced board often used as an underlayment for pastry and pizza to single and multiwall boards for more structurally demanding operations. Moreover, the thickness and spacing of the flutes can be configured for different applications ranging from the ubiquitous "C" flute to specialty grades. A common example of specialty corrugated board are the thin, very high flute count varieties that are used to form corrugated sandwich boxes for the fast-food industry, replacing difficult-to-recycle foam clamshell containers. Fine grades of corrugated board are often produced with printed copy as one of the outer liners, or laminated to the liner, producing a nearly flat surface for good graphics reproduction in the electronics and consumer appliance industry and for some types of higher-volume food containers.

Fabrication of Paper-Based Packages

Because of the incredible variety of paper containers, there is not enough space in this volume to describe the design and manufacture of all available types, but in general, paperboard containers are die-cut after printing (corrugated board may be cut and then printed, depending on the application) using either a rotary or platen-based cutting die; a factory seam is joined either with glue or, in the case of large corrugated cases, stitching – semi-automatic stapling – may be used to allow the carton to be erected into a rectangular shape on a packaging line, and it will typically have some type of end flaps that either interlock or are sealed to close the package. The specific parts of a paperboard folding carton are shown in Figure 4.11. These are typically shipped in stacks, ready to be used in the manufacturer's packaging line. Small folding cartons may be supplied in overwrapped stacks to ease placement in cartoning machine's feed magazines.

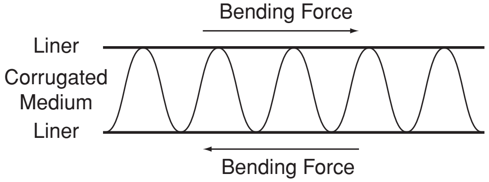


Figure 4.10. Corrugated Construction and Reaction to Bending

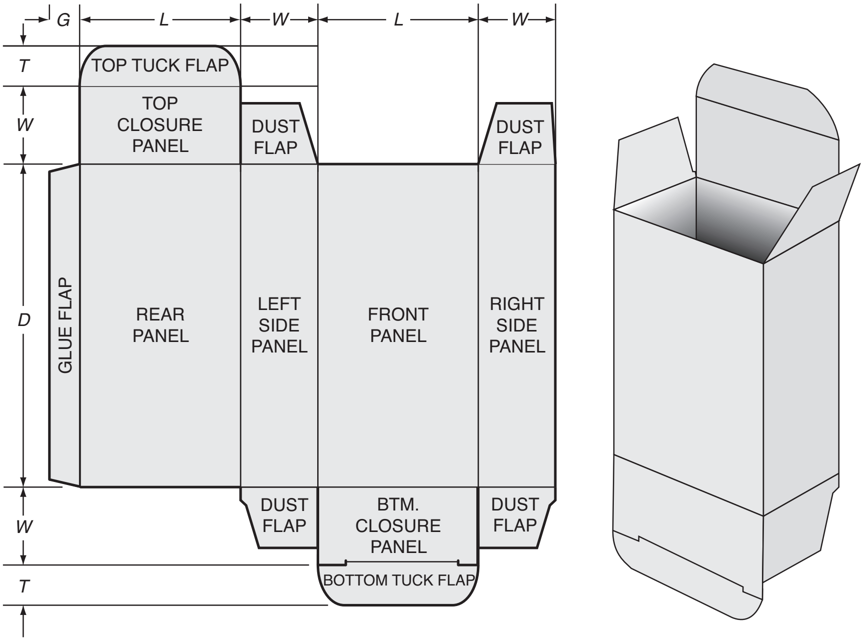


Figure 4.11. Parts of a Folding Carton
Source: Paperboard Packaging Council, with Permission

Cylindrical and rounded paper containers such as tubs and cups are typically wound on a shaped mandrel from tapered blanks, with a bottom seamed in during manufacturing, whereas paper-based cans are manufactured by producing a continuous winding on a mandrel, sectioning it, and seaming on the ends. In many cases where these are obtained from outside suppliers, these are tapered slightly so that they will nest, conserving shipping space while empty.

Paper sacks, as distinct from pouches, which are typically formed in form-fill-seal machinery described elsewhere, are still used as multiwall structures for large-scale shipping of materials such as grains, pet foods, food ingredients, and building materials, as well as for some types of food products in smaller quantities. These are described in more detail in Chapter 9.

Paper cartons for liquid products are similar in design to folding cartons used in other applications, but are sealed to prevent leakage. Although these were originally manufactured from waxed paperboard, this has almost universally been replaced by polymer coatings. Additionally, multilayer cartons and carton-like structures are laminated for use with extended shelf-life products ranging from refrigerated fruit juices to aseptically packaged foods.

In general, the design requirements for the physical structure of a paper-based package are straightforward. The package must be appealing to the consumer and be strong enough for use; it must protect the product (usually contained in a primary package inside the container) and must be easily handled and erected during production.

Strength of Cartons and Containers

The strength considerations for cartons and containers are almost always related to stacking strength. Folding cartons typically do not support enormous layers of product stacked on top of them, but corrugated shipping containers must often support many times their own filled weight during shipping and handling. The stacking strength of corrugated containers may be predicted by one of several means. Historically, the McKee formula – a semi-empirical formula developed at the Institute for Paper Science and Technology in 1963 and subsequently modified to improve accuracy – uses the edge-crush strength of the corrugated board as well as the buckling mechanics of plates to estimate the final strength of the board (Equation 4.1) [3]:

$$P = 1.014(P_m)^{0.746}(D_x \cdot D_y)^{0.127}\left(\Sigma\,(W)^{0.492}\right)\left(1.593\,(d)^{-0.236}\right) \tag{4.1}$$

P: Box Compression, $\mathrm{lb_f}$
P_m: Edge Crush Test Strength, $\mathrm{lb_f/in}$
D_x: Machine Direction Flexural Stiffness, $\mathrm{in - lb_f}$
D_y: Cross-Machine Direction Flexural Stiffness, $\mathrm{in - lb_f}$
W: Width of each panel, in
d: box depth, in

Other methods, based on finite element simulations, have been implemented, but they all depend on a large number of parameter inputs from the base material. These are all estimates at best, given that paper is a somewhat variable material that will change properties with age, temperature, and humidity, among other factors. Additionally, the effects of box additions such as handholds and internal dividers are not considered in this model, nor were a large variety of box types used for the experimental work. Whereas a robust shipping carton may perform well when first filled, the time-dependent properties of paper may cause a carton stack to deform or collapse. This can be aggravated by high humidity conditions and cyclic loading during use, which argues for a substantial *safety factor* in design, often several hundred percent [4]. ASTM D5639/D5639M–09 lists safety factors between 150% and 800% for stacks of single-product items depending on their weight, whereas the amount of load supported by the product and environmental factors while single-package shipments in the mixed-shipment express delivery environment have been shown to require safety factors of up to 370% [5, 6]. Because stronger boxes use more material and are more expensive, the final design is always a balance between strength and cost, with better solutions sometimes evolving out of structural design or the ability to pass some of the stacking load onto secondary containers in the package when possible. For example, glass jars or steel cans do not require a shipping carton at all and are often shrink-wrapped in unitizing trays, because the high stacking loads will be borne by the primary containers themselves. Fresh fruit, by contrast, cannot bear any of the load, and most fruit-shipping containers are extremely robust for this reason. Given the severe environmental variation and mechanical input experienced during shipping, it is prudent to follow up shipping container designs with damage assessments to determine the optimal level of strength and cost for a particular application.

Glass

Glasses are a class of material formed by the fusion of materials, usually silicate minerals, and having little or no discernable grain structure. Naturally occurring glass, Lechatelierite (obsidian) and Fulgurite, are formed by volcanoes or lightning strikes in sand, respectively, but the most common connotation of glass is the hard, artificially formed material that is molded into objects or cast into sheets for windows. Glass is one of the oldest synthetic materials known, after fired pottery (which is seldom used for commercially processed food). Phoenician merchants transporting stone in the region that is now Syria in approximately 5000 BCE were reported to have discovered glass. Pliny, the Elder wrote of merchants who rested cooking pots on blocks of nitrate placed by fires. The intense heat of the fire eventually melted the blocks and mixed with the sand of the beach to form an opaque liquid glass. As glassmaking progressed over the next 7,000 years, the items that were manufactured went from simple opaque beads to exquisite pieces of art glass from the renaissance and on to the durable and attractive implements and packages that we use every day.

Glass beads and glassy glazes on potshards date back to approximately 3500 BCE, and the first pieces of glass containers date back to approximately 1600 BCE. The Egyptians were credited with the first large-scale craft glass production, with little changing until the development of glass blowing in Syria around 20 BCE. Industrial glass manufacturing remains dating from the 4th century BCE have been found in Beth She'Arim near Galilee and indicate that glass was made in large slabs, broken up, and shipped for reworking by artisans, simplifying the manufacturing process for local markets. From this, glassworking showed a slow progression of technical knowledge in formulation, kiln design, and production methods until the mid-1800s when glass was hand-blown into closed metal molds.

An American engineer, Michael Owens, developed the first practical automatic bottle-blowing machine in 1903. By the year 1920, there were around 200 automatic Owens Libby Suction Blow machines in operation in the United States. Adoption in Europe was somewhat slower, but soon displaced manual labor in all but crafts production.

Today, modern bottle-making machinery is accurately producing glassware that is thinner and lighter than in previous years, and is aimed at preserving a market that is increasingly being taken over by lighter, more durable, and less dangerous plastic containers. The conversion from press-and-blow to blow-and-blow technology, as well as multiple station blowers, is making glass a continuing competitor for upscale products and specialty items such as alcoholic beverages, cosmetics, sauces, and oils, particularly where glass's perceived quality adds marketing leverage.

Better understanding of the structural and thermal nature of glass itself, combined with the ability to do advanced computational structural modeling relatively inexpensively, and highly automated production facilities have combined to pare production costs of glass to an absolute minimum. Although glass excels in clarity, strength (though not toughness), recyclability, and dimensional stability, it suffers from problems with high energy cost, high weight, extreme impact fragility, and the attendant injury liability. Most glass-manufacturing facilities use natural gas to provide heat both to the glass kiln and to ancillary heating operations such as the annealing lehr and various heat-treatment stations. This puts the glassmaking industry directly at risk from fluctuating prices and supplies of natural gas, with the attendant marketing uncertainties that can result from this.

One of the greatest non-energy factors that affects the glass industry is the initiation of container return policies – a reusable glass bottle can replace approximately 12 disposable ones during its service life – so the increased number of bottle bills in the United States has caused a reduction in the number of glass-producing facilities. This has political consequences since the loss of jobs has to be considered against the environmental benefits. As a result, the glass container industry is a large contributor to efforts to lobby against bottle return legislation as discussed in Chapter 11.

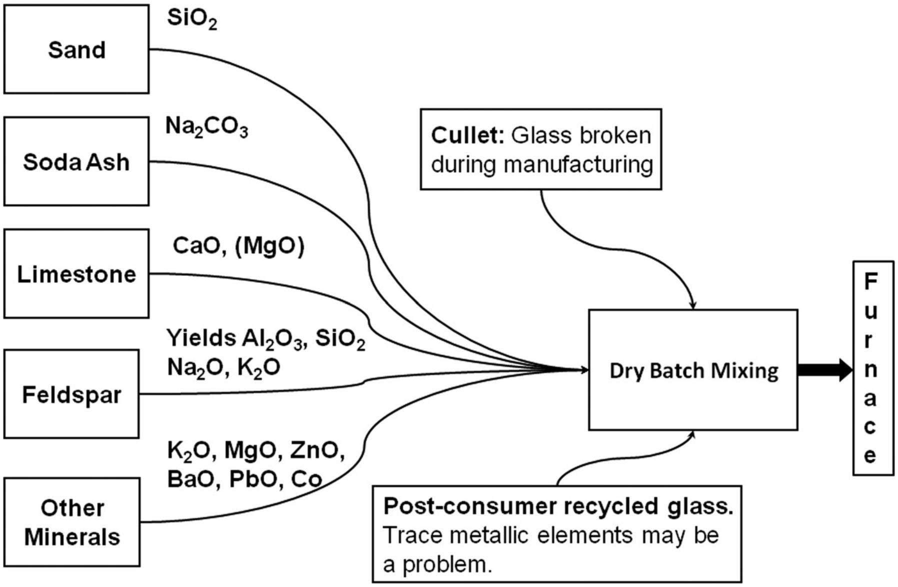


Figure 4.12. Glass Compounding

Glass Formulation

Glass at its most simple is a mixture of silicate sand, usually from beaches, lime rendered from limestone and soda ash, that is heated above the melting point of silica (ca. 1,610°C) to produce *Soda-Lime* glass. This is typically mixed with *cullet* – broken glass either from recycling operations or from within the production line – and then melted with other trace elements to affect the clarity, color, refractive index, or strength of glass (Figure 4.12).

Types of glass sand are usually classified according to purity and trace mineral content. Glass sands that have a mineral composition close to that needed to produce a particular color of glass are highly prized by the glass industry provided it can be transported economically. There has been some debate over the mining of glass sand from beaches and desert environments, although there is no known incident of glass plant closure from these concerns. Mineral additives are included, usually in small quantities, to change the color or strength characteristics of the glass melt as shown in Table 4.1.

Manufacturing Methods

Modern manufacturing methods create a nonstop stream of materials from a raw mineral and energy feedstock to finished containers, making glass unique in that the materials are not held at an intermediate state as with plastic resins, metal sheets and foils, and paper rolls and sheets. The capital costs of production and the specialized nature of the materials makes a modern glass plant an almost completely automated, non-stop production process that handles thousands of pounds of glass per day, as shown in Figure 4.13.

The first step in producing glass is to melt the components of the glass that have been added to charge the glass furnace, and to heat them to approximately 1,500°C. This produces a homogenous melt that is allowed to degas and for impurities to stratify in the mix. The melt then

Table 4.1. Chemical Ingredients Used in Glassmaking

Type of Component	Chemical Composition	Purpose
Antimony oxide	Sb_2O_3	Yellow colorant
Aragonite	$CaCO_3$	Calcium source
Boron	Bo	Produces high-strength borosilicate glass (Pyrex®)
Cadmium sulfide	CdS	Red colorant
Calcium fluoride	CaF_2	Produces opalescent glass
Carbon/Sulfur	C, S	Grey and amber colorants
Chromic oxide	CrO_2	Yellowish-green colorant
Chromic oxide	CrO_2	Green colorant
Cobalt oxide	CoO	Deep-blue colorant
Copper oxides	CuO_2, Cu_2O_3,	Red colorant
Cullet	Broken/recycled glass	Recycled component
Feldspar	$KAlSi_3O_8$ - $CaAlSi_3O_8$	Sodium, potassium source
Ferrous sulphate	FeS_2	Green colorant
Iron oxide	FeO_2	Yellow colorant. Will produce opaque black glass when used in large amounts.
Lead	Pb	Changes refractive index for crystal manufacture
Manganese	Mn	Violet colorant
Silica	$Si0_2$	Major constituent
Soda ash	Na_2CO_3	Sodium source

travels through an arched *throat* that allows only the molten glass to pass underneath, and then through a refiner and a forehearth stage to cool the melt from a fully liquid melt to a plastic state (ca. 1,000°C–1,200°C) where it can be molded. A *gob* – a small cylinder of hot, pliable glass – is extruded from the bottom of the glass kiln, picked up by automated handling equipment and delivered to a molding system.

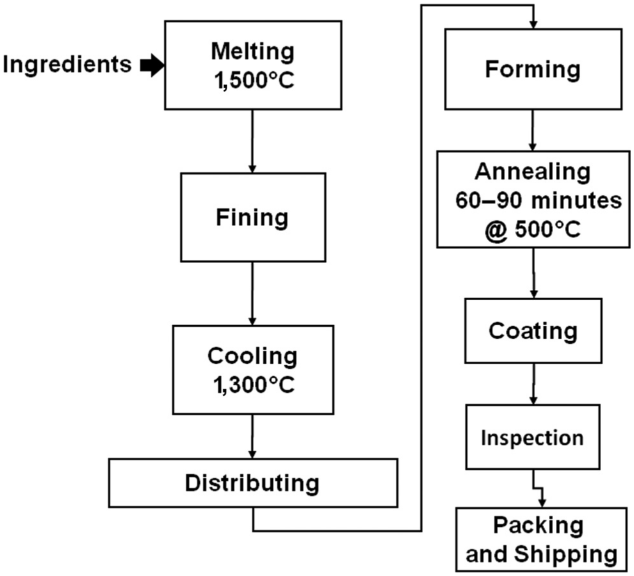


Figure 4.13. Glass Manufacturing

Types of Molding Systems

Glass molding of containers operate by a very similar method. The molten glass gob is initially molded into a *parison*, an intermediate molding that includes a precision mold of the finish to ensure proper closing, and a *transfer bead*, a small ring just under the finish on the bottle to facilitate handling of the container. The parison is then usually inflated with compressed air inside a second mold to form the body of the container. The exception is the *press molding*, which uses simple mechanical pressure to form glass items such as lens blanks, and is seldom used in package manufacturing. Molds are usually coated with high-temperature release agents to help prevent the molded piece from adhering to the hot mold surface. This basic blow-molding method has subsequently been carried over into the manufacture of plastic containers with few changes other than the method of parison formation and the much lower temperatures needed to operate the machinery.

The two principal types of glass molding systems are *press-and-blow* systems, which use mechanical compression in an inverted mold to force the molten gob into a parison mold before blowing into a finished container, and a *blow-and-blow* method, which uses compressed air to form the preliminary parison molding in an inverted mold before it is transferred to the final blowing stage. In the final blowing stage, compressed air forces the walls of the formed parison outward so that it conforms to the inner walls of the mold surface. Because of the highly viscous nature of glass, even the most carefully controlled processes may show some thickness variation, though this has been controlled much more effectively using newer manufacturing techniques.

Bottles are removed from the mold using the transfer bead with a fork-shaped handling device to move the still-hot container, and then the finished moldings are transferred to an annealing belt.

Once the container is blow-molded, it must be *annealed* – allowed to cool slowly so that residual stress will not cause the bottle to shatter. Before this process was understood, production facilities would simply allow containers and moldings to cool and ship the ones that did not break – hardly an efficient method. This involved a huge loss of product, as well as danger to workers and customers, that have been reduced since the annealing processes have been implemented. Currently, glass bottles are allowed to cool on a slow, continuously moving belt in a zone-controlled oven that moves the containers through a hot zone, heating them to approximately 1,300°C, to lower the viscosity to approximately 10^{13} Poise, and holding them at that temperature for several minutes, cooling the containers slowly to approximately 1,000°C over several minutes, and then rapidly cooling them to room temperature. The whole annealing and cooling process will usually take a total of 30 to 60-plus minutes for mass-produced moldings.

Surface Treatment of Glass Containers

Glass containers are usually treated with an exterior surface coating of material to reduce friction and scratching during handling, so that stress concentration areas are not formed on the bottle. Typically, there are two sets of coatings that are applied. The first, a *hot end* coating, is a coating of tin or titanium that condenses into a monomolecular layer on the surface of the glass and improves the adhesion of the second coating. The second, *cold end* (a relative term considering that the containers are still between 70°C and 170°C) coating, is usually a fine coat of oil and/or polymer applied at the "cool" end of the annealing lehr and provides a lubricating action between the bottles as they are handled in production lines. Historically, these coatings included soaps, waxes, stearates, silicones, glycerides, oleic acid, and polyethylene compounds. Few of these are still in use because of restrictions on amounts that may be contained in foods as noted below, and silicones were eliminated because of their effect on label adhesives. Polyethylene and oleic acid, both relatively inert and often present in food from other sources, have remained as coatings applied as an emulsion and vapor, respectively. Oleic acid has the advantage of being easily removed in washing and being able to label with dextrin glues, whereas polyethylene is more durable [7]. Because these coatings are sprayed on open containers, it is inevitable that some of the coating gets into the container, and thus into the product contained inside. Thus, there are strict limits to the amount of certain types of bottle lubricants that may be contained in the product as indirect food additives:

> (1) From a coating intended for or employed as a component of a container not to exceed 1 gallon and intended for one-time use, not to exceed 0.5 milligram per square inch nor to exceed that amount as milligrams per square inch that would equal 0.005 percent of the water capacity of the container, in milligrams, divided by the area of the food-contact surface of the container in square inches. From a fabricated container conforming with the description in this paragraph (c)(1), the extractives shall not exceed 0.5 milligram per square inch of food-contact surface nor exceed 50 parts per million of the water capacity of the container as determined by the methods provided in paragraph (e) of this section.
>
> (2) From a coating intended for or employed as a component of a container having a capacity in excess of 1 gallon and intended for one-time use, not to exceed 1.8 milligrams per square inch nor to exceed that amount as milligrams per square inch that would equal 0.005 percent of the water capacity of the container in milligrams, divided by the area of the food-contact surface of the container in square inches.
>
> (CFR21 § 175.300 (xxxvii)(c)(1,2)) [8]

Increasingly, labels, sleeves, shrink-fit covers, and other bottle decorations are supplementing or replacing these exterior coatings, providing a contact slip material to reduce or eliminate scuffing from contact between containers.

Inspection and Cartoning

Inspection of finished glass containers was done entirely by human inspectors, but the problems of visual fatigue, increasing line speeds, and increasingly tight production tolerances drove the glass industry to be one of the pioneers in automatic visual and acoustic inspection of containers. Containers now travel through light boxes that provide the containers with a diffuse light source that highlights defects for inspection cameras that use computers to highlight defective containers and remove them from the production line. Acoustic testing uses an acoustic transducer to inject specific frequencies of acoustic vibration into the finished container and then sense if frequencies characteristic of mechanical flaws are present in the finished container. This is combined with data taken from the raised-bump heel codes on the bottom of the containers to correlate defect data during production. Even with all of the careful control of the manufacturing processes, 10–15% of glass containers may be recycled as cullet in any given production run.

Decoration, Labeling, and Shipping

Once past inspection, the finished containers may be pre-labeled for a particular customer, other decorations may be added, and the combination is usually packaged for shipment to filling lines in re-shipper cases that are pre-printed with the customer's product information, because it makes little sense to unpack them from one carton, fill them, and then pack them back into another. For this reason, filling lines that use glass containers handle both empty containers and empty cases automatically, reinserting the filled containers into the re-shippers, so that there is little carton waste.

Failure in Glass Containers

Glass has many advantages, as previously described, but although an extremely strong material, it is also brittle in that it does not undergo plastic deformation before failure, and it is not a tough material that can absorb a great deal of energy before failure. The basic mechanics of glass failure are usually associated with various types of brittle fracture covered more extensively in Chapter 2. The material failure will begin at a stress concentration point, typically a material defect or a damaged area such as a surface scratch, or at an abrupt change in geometry of the molding. Once the failure point is established, the crack will focus the tensile force in the material and will continue to travel through the material – often at the speed of sound – until the stress is relieved or until the crack travels completely through the materials. Recent research has shown that although glass appears to fail in a manner different from other brittle materials, such as steel, the failure mechanism is very similar, with nanoscale voids opening in the material just ahead of the progressing crack tip, with effects accentuated in pressurized bottles [9].

The stress in a cylinder created by pressure can be estimated as shown in Equation 4.2:

$$\begin{aligned}\sigma_{\text{Circumferential}} &= \frac{Pr}{t}\\ \sigma_{\text{Longitudinal}} &= \frac{Pr}{2t}\end{aligned} \tag{4.2}$$

P: Pressure differential across cylinder wall, Pa
r: radius of cylinder, m
t: wall thickness, m

Unfortunately, few glass containers are truly cylindrical in nature, particularly at the ends, which means that this estimation will not give accurate answers, particularly for complex configurations. Computer simulations have given better answers for complex molding using soda-lime glass and have shown that the maximum stress when highly pressurized is at the edge of the base of the bottle. Further tests showed that increasing internal pressure increased the crack density in failed containers, resulting in smaller fragmented pieces with the potential for wider distribution from hydraulic and pneumatic explosion during failure [10].

Thus, the stress concentration in a piece of glass can be increased many times by the addition of a single shallow, sharp scratch. This fact is exploited in the manufacture of sheet glass and in the making of art glass projects where the article is scored, then stressed to break off the required pieces. In glass containers, however, the effect may be quite destructive, causing breakage or explosion of pressurized containers. To prevent damage from occurring in glass containers, contact areas are often reinforced with extra material in *shock bands* and may be textured to avoid formation of stress concentration points.

General failure conditions in glass containers are usually a result of thermal, impact, or hydrodynamic (*water hammer*) stresses that provide enough energy to promote failure at defect

Figure 4.14. Thermal Failure in Glass Bottle

sites and section thickness changes, and eventually to cause breakage in a well-formed and well-designed container.

Thermal Failure

Glass containers that are subjected to thermal stress in processing, distribution, or use may develop extreme stress areas due to the differential expansion and contraction. Because glass is both a poor heat conductor and a brittle material, moderate temperature changes, mild surface damage, included defects, or section thickness changes can cause an abrupt failure of the container. This may manifest itself, for example, as a container with a thick bottom section and a thin sidewall losing the bottom as an intact piece as the failure progresses circumferentially around the base's transition from thick to thin sections, as shown in Figures 4.14 and 4.15.

Significant advances have been made in the numerical modeling of glass containers to reduce or eliminate problems of post-manufacture thermal stress. Additionally, the trend toward thinner and lighter glass containers has been beneficial in that it promotes more uniform heat conduction throughout the container, reducing the failure rate.

Impact Fracture

As anyone who's accidentally thrown a ball through a window knows, glass does not have the ability to deform extensively before exceeding the critical stress in the materials. In the case of glass packaging, the nature of the impact fracture is often critical both in understanding the failure mode of the materials and, all too often, in dealing with the legal disputes that may follow the actual damage caused by the fracture. Usually the pieces of a glass container can be carefully reassembled to discover the point of impact that caused the original fracture (Figure 4.16), and any subsequent factors such as internal pressurization that may have accelerated the failure.

It is often important to decide whether the container failed from impact or from internal pressure. A clue that may be useful in this is the nature of the fracture surface itself. When one

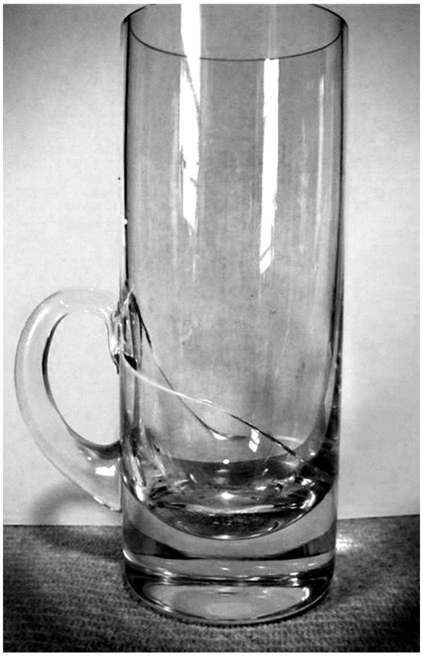


Figure 4.15. Thermal Failure at Section Thickness Changes

examines the edge of the fractured piece at the impact point (Figure 4.16), there will be surface features such as hackling that are indicative of the point of maximum stress at failure (on the inside for a pressure failure, and on the outside for an impact failure), and often can indicate its magnitude as well via measurement of the *mirror* and *mist* regions, as shown in Figure 4.17, and the application of fractographic analysis.

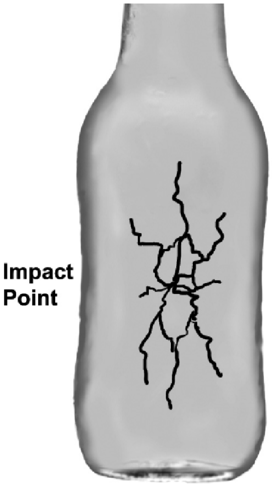


Figure 4.16. Bottle Impact Failure

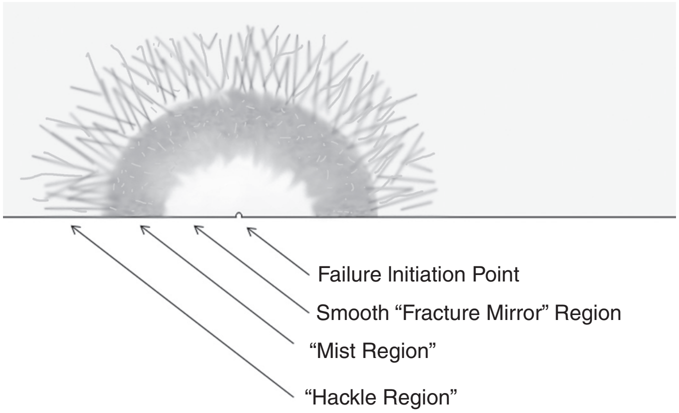


Figure 4.17. Fracture Features at Point of Failure in Brittle Materials

Water Hammer Effect

Sudden movement, particularly a small drop, of a container full of liquid or semiliquid materials can cause a catastrophic pressure failure in glass containers. This has been described as water hammer failure, which is usually the resultant inertial effect of suddenly stopping a flow of fluid, with its resulting shock. True water hammer failures involve fluids with a great deal of kinetic energy, whereas packaged fluids do not exhibit instantaneous flow when subjected to shock. Water hammer failures in packages are more likely hydrodynamic surge effects, occurring most usually around the bottom circumference of the container. These often have a distinctive appearance, as the pressure transient will "blow out" the sidewall of the container radially around the base, as shown in Figure 4.18, most likely from the pulse of hydrostatic pressure that travels through the fluid as the container is subjected to shock. Fluid viscosity will

Figure 4.18. Water Hammer Failure in Glass Bottle

affect the likelihood of failure, with less viscous fluids being more likely to contribute to failure, although the non-linear fluids that comprise many of the food products in glass containers may complicate this by sudden shifts in viscosity as shear-thinning or initial stress levels are overcome. This type of failure is distinctly different from failures due to thermal stress because thermal stress failures around the bottom of a container often will have only a single fracture line that propagates under internal stress rather than the distinctive shattering around the base.

Design Considerations for Glass Containers

Glass container structural design is an important consideration if glass is to be used in the production of a packaged product. Because of the enormous costs involved in producing glass molds and creating a glass production run, it is common to have a single type of glass container used with a broad variety of different labels to produce an entire product line packaged in the same container, thus reducing inventory costs. The basic considerations that one must incorporate into the structural design of a glass container – neglecting the esthetic considerations – are light weight, strength, and stability. A container whose shape causes it to tip over easily or wedge tightly in a production system will be difficult and expensive to produce, and may show the same faults when in use by the consumer.

Containers must be adapted to the type of product they contain. Liquid products may need smaller necks for dispensing than heavy, viscous, or semisolid materials, and the amount of headspace must be determined as well. Shape and color may be of critical importance to selling the product, but a particular shape may prove very difficult to produce because of the difficulty of molding glass in some configurations, and once produced may be difficult to integrate into a filling line. The design of the finish area of the container that accepts the closure that seals the container may be of critical importance in maintaining product integrity. Since glass is relatively impermeable to all gasses except hydrogen, it is an excellent barrier when hermetically sealed. Unfortunately, the production of high-accuracy moldings on the finish segment of the bottle is complicated by the viscous nature of glass (which impedes flow into fine mold cavities) and the very high mold temperature, which makes easily machined mold materials such as aluminum unusable and maintaining mold tolerances more difficult. This, in turn, leads to problems in producing a high-accuracy fit between the finish and the closure, requiring the use of flexible lid liner materials to seal the container. Compression force from the vacuum in thermally processed foods also increases the friction of these materials against the finish, contributing to difficulty in opening glass containers with large closures, such as jams and jellies.

Closures are discussed more fully in Chapter 5, but it is critical that the closure match both the dimensions and the thread type of the container's finished, as the shallow, easily molded threads on glass containers may be different than those on plastic containers of the same size, and mismatching can then cause jamming or leakage.

Metal Packaging Materials

Metal containers have nearly always been an integral part of mass-produced food packaging, and represent an improvement over the fragility of the glass wine bottles originally used for "canning" processes developed by the French. The lack of a substantial glass-blowing industry (vital to the French wine industry) in England left the British military looking for a suitably competitive container for the preservation of military rations after French demonstrations of long-term food storage on Caribbean voyages in the early 1800s. The burgeoning industrial revolution in Britain, with its substantial iron and steel works, provided an answer in the form of thin steel plate, coated with Cornish tin, that could be used to form a sealed food container that would be quite durable. Initial products were hand-formed and soldered, filled, and then cooked, with production speeds being very slow (a good craftsman could produce 60 cans per day). The presence of lead-based solder, the absence of practical knowledge of the microbiology of spoilage, and the absence of regulations regarding food content led to some spectacular cases of food poisoning.

One of the substantial causes of non-battlefield death in the American Civil War, the Crimean War, and other conflicts of the era was poisoning from preservatives, such as formaldehyde, included in meat products by unscrupulous manufacturers. This level of poisoning continued until the effects of inadequate thermal processing and heavy metal toxicity were understood and inappropriate additives were banned many decades later.

Changes in fabrication techniques have replaced soldered seams with welded ones, processing conditions are now very well understood, and toxic additives have been largely eliminated (though bisphenol-A, a can-lining resin thought to be a teratogen, is currently the source of a good deal of debate), so that food in metal cans is currently both safe, durable, and very inexpensive.

Aluminum containers, primarily used for carbonated beverages because of the need for the supporting internal pressure in their soft structure, are a development of the latter half of the twentieth century and dominate the beverage can market in the United States, although British steel manufacturers produce a two-piece drawn can out of special low-carbon steel that is quite similar to the aluminum two-piece can. Steel and aluminum are both used for the construction of food and beverage containers, but steel foils are almost unknown in consumer food applications because of the ease of production and corrosion resistance of aluminum.

General Structural Consideration in Cans, Drums, and Pails

Cans most often fail because of applied stacking stress causing the sidewall of the can to buckle. Because of this, unpressurized cans are typically fabricated with flexible ends and *rings*, circumferential ridges around various parts of the central can body that prevent the initiation of buckling under vacuum, and therefore allow the use of lighter grades of steel in can fabrication. Although the buckling stress of a smooth cylinder can be estimated by Equation 4.3:

$$\sigma_{\text{critical}} \cong 0.605 \frac{E \cdot t}{r} \tag{4.3}$$

σ_{critical}: critical stress, Pa
E: elastic modulus, Pa
t: thickness, m
r: radius, m

in practical application, cans are rarely smooth cylinders because of end structures and design geometry. Can collapse without buckling usually involves the extensive deformation of the bottom of the can under excessive load or impact and will exhibit a characteristic bulging. Pressurized cans rely on the internal pressure of the contents, usually a carbonated beverage, which can be in the range of 60 kPa to 300 kPa. At this point, the thin-walled can acts as a metallic balloon, and the amount of axial force it can withstand without buckling will be a direct function of internal pressure and the area of the can ends, because the ductile material of the can adds little strength.

$$F_{\text{pressure}} = p \cdot \frac{\pi d^2}{4} \tag{4.4}$$

F_{pressure}: force, N
p: internal pressure, pa
d: diameter of can end, m

Production of Steel

Steel is an alloy of iron and several common elements, principally carbon in varying quantities. For the manufacture of food containers, the need for ductility in the material demands that the steel used is *low carbon* steel, which typically has low tensile strength relative to many structural alloys, but is relatively easy to form and weld. Low carbon steel typically has less than 0.3% carbon content (0.3–0.6% is termed *medium carbon* steel, and over 0.6% is considered *high carbon* steel) and can contain other alloying elements such as sulfur, manganese, silicon, and phosphorus, as well as approximately 25% recycled steel (Table 4.2). Iron ore, often from domestic sources, is usually concentrated into pellet form and then shipped to refining mills. The concentrated ore is combined with a carbon source (most often the coke used by refining raw coal) using a basic oxygen furnace and heated along with alloying elements to form a final melt, which is then cast into slabs and ingots. If the steel is produced exclusively from scrap, it is most common to use an electric arc furnace to produce ingots, because these types of furnaces are well suited to recycling refined ferrous metals, and are common in small specialty steel mills. These ingots are then hot-rolled into *coil* – long rolls of strip steel – that is further reduced to its final thickness after cooling. It then may be electroplated with a very thin layer of tin (approximately 0.14 mm). Other coatings may include electroplated chromium or a polymer coating on unplated steel. It can then be cut and shaped into finished can bodies and ends.

Steel Cans

Steel cans are primarily manufactured as either deep-drawn two-piece cans or welded-seam three-piece cans. The traditional, soldered side seam three-piece can has given way to welded side seams because of the concerns with lead extraction into food products, although they are still produced in some countries and may be used for non-food products without problem. Additionally, competition from aluminum cans and plastic bottles has nearly completely usurped

Table 4.2. Composition of Common Can Steel Types

	Maximum Composition (%)								
Classification	C	Mn	P	S	Si	Cu	Ni	Cr	Mo
D Type	0.12	0.6	0.02	0.05	0.2	0.2	0.15	0.1	0.05
L Type	0.13	0.6	0.02	0.02	0.02	0.06	0.04	0.06	0.05
MR Type	0.13	0.6	0.02	0.05	0.02	0.2	0.15	0.1	0.05

the steel beverage container market – a multibillion dollar loss – so the steel container industry is continually searching for new market niches and competitive market positions.

Three-Piece Cans

As the name suggests, the three-piece can consists of two ends, one of which may have an easy-opening or other feature, and a body that is formed from sheet stock. The steel body is usually formed with a series of *rings* – circumferential corrugations that prevent denting and collapse under the vacuum that is often induced in packaged foods to reduce corrosion and product degradation. The body is then welded along its side seam by passing the blanks through a side seam welder that uses an electric current passed through contact wheels to resistance-weld the seam area. The weld fusion surface on both the interior and exterior is then usually coated to prevent corrosion in the area where the weld has oxidized away any protective coating or electroplating. At this point, the edges are flanged outward to accept the can ends, and then the can is usually shipped with the bottom edge flanged on.

Welding and Soldering Considerations

Welding is the fusing of two materials, often with the addition of additional material to replace that lost to oxidation in the heating process, and produces a joint that is as strong as the base materials. Although there are many types of welding, including solvent and friction welding for plastics, thermal welding of metals will be discussed in this section. Metal welding requires that the two materials are compatible and have similar melting points. For this reason, welding broadly dissimilar metals such as steel and copper is impractical, and so welding is typically done between very similar types of single materials, particularly steel. Additionally, welding metals will cause the surface to oxidize, which may require some adaptation of the methods and materials to compensate for this. An extreme example of this is the welding of aluminum, which must be done under an inert gas stream to prevent immediate and destructive oxidation during arc welding. Industrial welding of thick steels often uses a flux compound to clean oxidation from the surfaces to be joined and to protect the hot surfaces somewhat from subsequent oxidation as the molten metal cools. For sheet fabrication, and particularly for food-contact applications, flux would represent an unacceptable contaminant, so the welding process is carefully controlled and the weld surface is coated with an approved protective coating as soon as possible after the welding step.

By contrast, soldering is the use of a low melting point (usually below 400°C) filler metal to join two compatible metal surfaces by flowing filler into a heated joint by capillary action and cooling it to a solid. The resulting bond is not nearly as strong as the base materials, but the ease of bonding and simplicity of equipment makes soldering a very good method for permanent joints between metal components, particularly in electronic assembly. Most solders usually contains a percentage of lead to assist in lowering the melting point, which may then dissolve into food products and represent a health hazard, particularly for children, since lead may cause many types of neurologic and renal problems and is not readily excreted by the body. Brazing, not used in the packaging industry to any significant degree, is the higher-temperature version of soldering, with brazing fillers melting above 425–450°C and producing very strong bonds in metals. It is particularly useful where the excessive heat or difficulty of welding would be a problem, such as jewelry manufacturing and fabricating tempered-steel bicycle frames.

Although the interior surface of traditionally soldered can seams was coated, the lead content of the solder reduced, and the solder joint reduced in size to reduce the potential exposure, the food industry in the United States had stopped using soldered-seam cans by late 1991. The US Food and Drug Administration finally banned the manufacture of soldered side seam cans in 1995 and required that they be removed from commerce (along with lead foil capsules for wine) by June 1996. Although not legal in the United States, soldered-seam cans are still produced in some countries, and there is a great variety of restrictions on lead exposure worldwide.

Two-Piece Cans

Two-piece drawn cans are very commonly used for shallow-draft cans such as small fruit tins, and are rapidly replacing three-piece cans in many traditional applications such as vegetables and soups. These deep-drawn cans are fabricated in a manner similar to aluminum two-piece cans described in this chapter. A flat blank is deformed into a cup and then successively formed in separate *ironing* processes into a deep can that replaces the body and bottom assembly of a three-piece can. This body is then trimmed and both flanged and ringed as required. The advantages in two-piece cans are the potential for lower cost because of fewer components, better material use, and reduced potential for failure and corrosion because of the elimination of the bottom and side seams.

Corrosion in Steel Cans

Corrosion in steel cans throughout their service life follows a progression of processes that are somewhat predictable, as are some of the factors that can affect them. Although there is both a tin and often a polymeric coating to protect the steel, these coating will have microscopic defects that may allow corrosion to be initiated, and without the electrochemical protection of the tin layer, the container structure would soon have corrosive perforation. The general progression of corrosion in steel cans follows a three-step process (Figure 4.19).

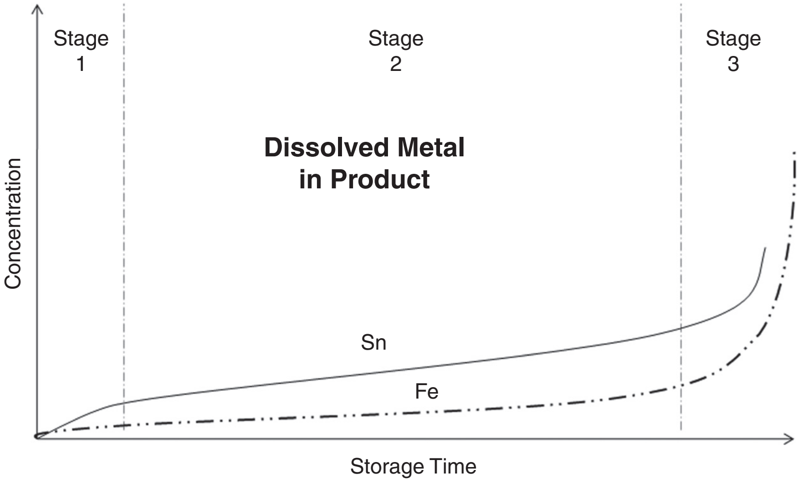


Figure 4.19. Dissolved Metal in Product Due to Can Corrosion

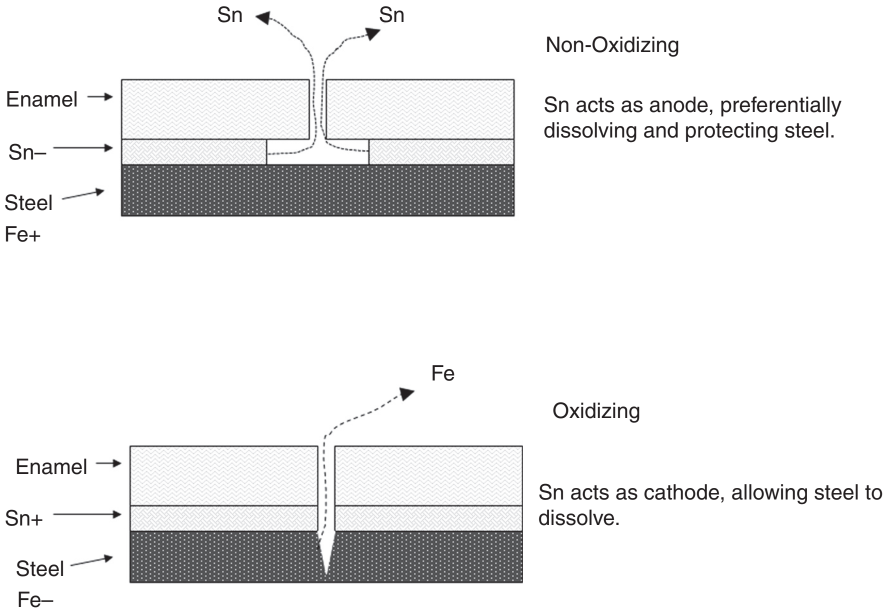


Figure 4.20. Oxidizing and Subsequent Non-Oxidizing Stages of Can Corrosion

Stage 1 (Oxidizing)

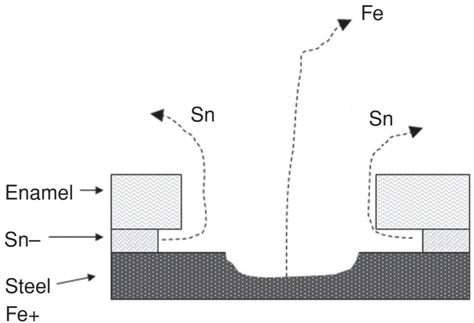
Immediately after closure, the interior of the can and the product will both contain some residual oxygen. In this oxidizing environment, the tin coating is cathodic and does not provide protection for the steel layer, as shown in Figure 4.20. After a brief interval, residual oxygen is bound up in oxidation products in the product and can material.

Stage 2 (Non-Oxidizing)

Once the oxygen in the system is bound up, the internal environment becomes non-oxidizing, and the tin, now acting as a sacrificial anode, protects the steel while slowly dissolving into the product. Depending on the various corrosion accelerants present, this may go for months or years until the tin coating becomes substantially depleted. Any additional source of oxygen will again allow the tin to become cathodic, accelerating corrosion of the underlying steel.

Stage 3 (Terminal)

As the tin is depleted in the non-oxidizing environment, the protection for the steel is removed, allowing corrosion and pitting of can, staining of product and can surface, and sulfide gas (H_2S) formation, as shown in Figure 4.21. This usually causes the can to build pressure and swell or burst, and the product will take on a rotten-egg smell even though it still may be microbially safe. If the can simply perforates, the product will become contaminated and will also swell – a primary indication of spoilage in either case.



After a loss of large portions of the tin coating, attack on steel may occur regardless of polarity.

Figure 4.21. Terminal Stage of Can Corrosion

Corrosion Accelerators

Certain components in the product itself may enable or accelerate corrosion in the steel cans, as is illustrated in Table 4.3.

This illustrates the necessity of close monitoring of can performance, particularly when product formulations change as the shift in ingredients may have a secondary, unintended effect of changing the durability of the packaging. Sulfur and sulfide compounds may cause staining of cans as well as acting as a depolarizer; nitrates may reduce to NH_3 and act as corrosion accelerators; oxygen will act as a depolarizer as well as causing direct product decomposition; and thermal treatment and storage will affect the rate and nature of can corrosion.

Aluminum Production

Aluminum is produced very differently than steel, and has always had an extremely high incentive to include recycled metal due to the difficulty of producing metallic aluminum from aluminum oxides that are extracted from bauxite. The stability of aluminum oxide is both a blessing and a curse for aluminum, because it provides a corrosion-resistant coating on the metal's surface, but it also made the production of aluminum a difficult task until 1866, when Charles Martin Hall in the United States and Paul Héroult in France simultaneously and independently patented the process in which alumina (aluminum oxide) is refined electrolytically. The Hall-Héroult reduction process remains the only method to produce aluminum in commercial quantities, although continuous work on refractory cell design, electrode systems, and other components of the practical implementation of the process continue to yield steady gains in efficiency and purity of metals produced. Packaging currently accounts for approximately 21%

Table 4.3. Corrosion Changes Resulting from Different Acids Used in Canning

Acid	Oxalic	Citric	Malic	Tartaric
Dissolved Sn (ppm)	20.3	10.5	8.5	5.5
Rate nÅ/cm^2	26.8	13.9	11.2	7.2

of the aluminum used worldwide and is used as can blanks, a thin sheet for forming trays, foil for coverings and barrier applications, and laminated foils and vapor-deposited coatings that use the barrier properties of aluminum with the mechanical support of other materials.

Aluminum is cast into plates or ingots in a manner similar to steel ingots, and then may be rolled, re-tempered, and re-rolled into varying thicknesses of sheet or foil, depending on the application. Other mills will produce aluminum sheets and foils in a continuous process that starts with a continuous casting and progresses, being extruded through ever-narrower roller gaps until the final product is wound on a reel for shipment. Thicker sheets are often used to produce the stampings that aluminum cans are shaped from, whereas thinner foils, less than 0.15 mm (or 0.006 in), may be used to form trays and cups. Aluminum foil less than .025 mm (0.001 in) thick may be folded and rolled into very fine foils down to approximately 0.005 mm (0.00017 in) that are included in laminates as a barrier material. Finally aluminum may be evaporated as a coating on polymer films as a means of providing a good barrier or a reflective surface – this topic is considered as a surface coating of polymers later in this chapter.

Aluminum is a very ductile material and has less tensile strength than steel, though its final strength-to-weight ratio is higher, making it useful in aerospace applications. The high ductility allows the material to be shaped and formed with relative ease, and it may be easily embossed or textured for specific applications, but also makes it very fragile in thinner grades. Aluminum is resistant to attack by many food and beverage components, but is readily oxidized by materials containing organic acids and/or salts, so coatings may be necessary for some types of food products. For the relatively benign contents of beverage containers, often no coating beyond the naturally occurring oxide layer is necessary.

Typical alloys used in food packaging contain minute amounts of copper, zinc, manganese, chromium and magnesium, with 1xxx and particularly 3xxx series alloys being favored for foils and can bodies, and stiffer 5xxx series used for can ends. Specific choices are shown in Table 4.4.

The commonly-used "O" temper foil has been reheated above 340°C, which both softens and effectively sterilizes it. Partially annealed aluminum foil has temper H-25 and H-27 available, and is available in foils thicker than 0.05 mm. H-19 temper is the hardest temper available in thinner aluminum foils.

Table 4.4. Aluminum Alloy Compositions

Designation	AL	Fe + Si	Other*
1100 H-19 foil and O	0.99 – 0.993	0.009 – 0.006	Cu .00005 – 0.002
1145 H-19 foil and O	0.9945 – 0.9960	0.005 – 0.0035	
1235 H-19 foil and O	0.09935	0.0065	0.001 Zn
1350 H-19 foil and O	0.995	.005	
3003 H-19 foil and O	0.967 – .099	0.013	.01 – .015 Mn
3004 H-19 foil and O	0.955 – 0.982	0.01	0.0025 Cu, 0.008 – .013 Mg, 0.01 – .015 Mn, 0.0025 Zn
5052 H-19 Foil	0.957 – 0.977	.0065	0.022 – 0.028 Mg
5056 H-191, H-38 and O	0.957 – 0.977	.0065	0.022 – 0.028 Mg

*Other major alloying elements > 0.5% (.005). There are small amounts of other elements that are not listed in this chart and may distinguish similarly numbered alloys.

Aluminum Cans

Because of near-impossibility of efficiently welding paper-thin aluminum in a production situation, aluminum cans are formed as two-piece cans, having a body and an end, usually with an easy-open feature. The can bodies are formed by stamping flat sheet into *cups*, the sidewalls of which are progressively stretched by extrusion with successive dies until the desired height is achieved, and finally trimming and flanging it, and then the end features such as necking rings or other desired structures are added.

Because the bottom material is neither severely deformed nor stretched significantly in comparison to the sidewall, the resulting container usually has a relatively thick bottom structure and very thin sidewalls. To extensively deform the aluminum in this manner, a Mn-Al alloy such as Type 3004 may be used, and these have been specifically modified by adding more manganese to produce a finer, more ductile crystalline structure that does not score or tear during forming.

Can ends for beverages are formed separately from thinner stock than the can body, because the deformation required is less, but the alloy must be ductile enough to allow a rivet stud to be formed in the center (rather than as a separate, more costly separate piece), which allows the pull tab to be attached simply by flattening the protruding stud over a matching hole in the tab. The forming of the rivet from the can end was a necessary step in making the aluminum can cost-competitive with competing products at the time, and has been retained as an assembly feature. Additionally, the top stamping must tolerate being very accurately scored in the opening area so that leverage produced by the opening tab will be sufficient to tear the scored area and open the can.

The ductile nature of aluminum, which makes the two-piece can structure attractive in terms of manufacturing costs, works against using the cans for unpressurized products because there is little intrinsic container body strength in the material without supporting internal pressure. Although there has been some movement toward pressurizing aluminum cans with an inert gas to provide structural support so that the cans may be used for non-carbonated food, there has been a great deal of reluctance to implement this, particularly on the part of regulators. This is primarily due to the consumers' knowledge that gas pressure in a can is a primary indicator of spoilage or degradation. Artificial pressure would lead either to discarding safe products or learning to ignore pressure caused by dangerous spoilage. There has been some success in increasing pressure in carbonated containers by using low-solubility, inert gasses such as nitrogen to avoid over-foaming the beverage while still keeping the container rigid – a method that can be used in restaurant dispensers for low-carbonation beverages.

Aluminum cans with simple enamel coatings are stable at pH values above 5.0 with a simple enamel coating, but more acidic foods will show shelf lives and corrosion similar to steel (12–18 months), although aluminum cans do not produce blackening effects in sulfurous foods.

Bottle Cans

Newer developments have allowed the production of severely necked "bottle can" containers for use with aerosol products and potentially replacing some aluminum and plastic containers. Bottle cans are aluminum bottles formed to the approximate shape of glass bottles, most often, beer bottles, with fully formed closures capable of accepting a roll-on screw cap. These have also made considerable inroads on traditional designs for aerosol containers in cosmetic, household chemical, and lubrication and engineering compounds. They have the advantage of being unbreakable, but to date have seen little success in unpressurized beverages because of the tendency of the soft aluminum sidewalls to dent badly and appear damaged on store shelves. The bottle can process depends on both the extreme ductility of aluminum and the lubrication and barrier properties of a PET lamination on the surfaces of the aluminum stock that is used to form the container.

The container begins as a flat sheet of laminated aluminum and is progressively formed in a draw-redraw process that requires no fewer than 15 steps to complete. A deep-draft thin-wall container is first formed, then domed inward in several stages, then a thread and curled bead finish is progressively formed, with final steps involving necking and flanging. The end result is a threaded-closure aluminum bottle with a fully curled opening that does not present sharp edges to the consumer. Work is being done on using pressure ram forming of aluminum sheet at elevated temperatures (approximately 250°C) to form aluminum bottles without the PET lamination. In this process, an annealed aluminum pre-form fabricated in a draw-redraw process is heated and pressurized in a closed mold in a manner very similar to the pre-form blowing operations described elsewhere in this chapter, with a result being an aluminum bottle that is produced with many fewer steps and good control over residual stresses in the material.

Aluminum Foils

Aluminum is a ductile enough material that foils can be readily produced by folding and rolling thicker sheets. Foil grades commonly used for packaging are shown in Table 4.5.

After forming, the foil may be embossed, coated, or printed to achieve a desired appearance. It is common to laminate thinner films to a substrate, most often plastic film or paper, before these treatments to provide strength. Thick aluminum foil is essentially impermeable to everything except hydrogen, but aluminum foil thinner than approximately 0.015mm will show small defects that will lead to permeation that increases as the foil becomes thinner. Other studies have shown that pinholes are formed by a variety of causes ranging from contamination in the rolling processes from a variety of sources to mechanical stress concentrating around metallic and non-metallic impurities, as well as the imprinting of defects in the rollers themselves.

Table 4.5. Aluminum Foil Types

Designation	Translation	Meaning
B1S, B2S	Bright, one or two sides	Specular, reflective finish on one or both sides. Matte finish on non-bright side, if any.
EB1S, EB2S	Extra bright, one or two sides	Brilliant reflective finish on one or both sides. Matte finish on non-bright side, if any.
M1S, M2S	Matte, one or two sides	Diffuse finish on one or both sides. Bright finish on non-matte side, if any.
MF	Mill finish	Non-uniform finish, seldom used except for internal laminations.
Foil, scratch brushed	Scratch brushed	Abraded surface to provide roughened or textured surface
Foil, annealed	Annealed	Foil fully softened using thermal treatment.
Hard foil	Hardened alloy	Foil work hardened by rolling
Intermediate foil		Foil hardness between annealed and hard
Embossed foil		Foil that has been textured or patterned using an engraved roller, plate, or other contact fixture

Aluminum foils are susceptible to crack formation from flexing and handling, and this and pinholing can lead to delamination as well as decreased barrier effectiveness. Very thin foils are almost always laminated to a substrate, and the barrier properties of these laminated materials are very similar to thicker grades of aluminum foil, presumably because the small defects in the foil are sealed by the laminate. A more extreme example of this is the tremendous increase in barrier properties of metallized plastic films, which have only the thinnest metallic layer (and similar problems with pinholing and scuffing of the coating) and are subsequently discussed in this chapter.

Other Metal Packaging

Although increasingly manufactured from non-metallic materials or metallic laminates, there are several types of traditionally metal packages that are still in substantial use. Steel drums, pails, and disposable tanks are more often used for construction and industrial chemicals than for domestic food items, but they still represent a significant component in the world's packaging industry.

Steel, Plastic, and Fiber Drums

Steel drums, first fabricated to replace wooden barrels in the early 1900s, are usually fabricated in a manner similar to the three-piece food can, with a welded side seam and several reinforcing rings pressed outward from the body to strengthen them and facilitate rolling, because their cylindrical shape was not as well suited to being rolled as the bulged wooden barrels they replaced. Plastic drums are usually fabricated using blow or rotational molding and are most often used for liquids and are fitted with a bung and/or threaded opening to allow the removal of product. Because of the relative ease of molding, plastic drums may be formed in unusual shapes for specific applications and may be specially formed to be included in industrial or dispensing equipment.

Drums range in size from approximately 19 liters (5 gallons) to 420 liters (110 gallons), although "a drum" is often used as a rough standard measure corresponding to 55 gallons (210 liters), as adapted from various common wooden barrel uses. One standard barrel of oil equals 159 liters (42 gallons), whereas a standard American barrel of beer is 117.3 liters (31 US gallons). In the UK, a standard barrel of beer will be 163.7 liters (36 Imperial gallons or 43.3 US gallons), and European beer barrels may range from approximately 34 liters to 110 liters, depending on the type of product, with no standard size at all.

Industrial barrels of different volumes are often fabricated to be a constant height, both for ease of manufacturing (since the width of the steel sheet used for the body will be the same) and because of the convenience of having mixed loads of barrels have a standard height for stacking palletloads. Drums can be lined with a variety of coatings or flexible bags, depending on the type of product to be contained, such as polyethylene and polyester bags or phenolic and epoxy coatings, and can be provided with sterile liners if necessary. Barrels for industrial use are typically fabricated as either an open-head or tight-head types. An open-head drum has a cover that fits into the end with a compressible seal and is retained either by a releasable ring that is bolted closed, held by a lever lock that can be opened without tools or by lugs that must be bent open, whereas a tight-head drum will have the cover permanently seamed on, but will be traditionally fitted with standardized 51 mm and 19 mm fittings for emptying and venting the container, respectively. Other fittings may be incorporated into the drum as required, depending on the application. Drums may be tested for integrity using a helium leak detector or a similar method, and as barrels are often re-used, any re-conditioned barrels should be checked for damage and flex-cracking as well.

Open-head drums can be used to pack nearly anything that will fit into the container because the cover can be lifted and a liner or other packing material incorporated, and these types of barrels are occasionally used for machine parts and other unusual items because of their availability and sturdiness. Tight-head drums are limited to materials that can flow through the openings, and are almost always used for liquids.

Because of the durability of steel drums, they may be re-conditioned and re-used. This typically involves the minimum of cleaning and testing for leaks, but may be more extensive depending on the type of product involved and the condition of the barrels. Systems that can restore physical dimensions, re-coat the drum, burn them clean of contaminants, and perform other re-conditioning are available.

Fiber Drums

Fiber drums, although considered a paper product, are included in this section because they complement the steel drum applications and market. They are essentially enormous, spiral-wound cans manufactured as described in this chapter and fitted with ends held in place by a seamed-on end in a manner similar to metal drums. They represent a low-cost, low-weight solution for containing many types of products and can be fitted with liners or sterile bags to transport moist or perishable items. These are typically available in sizes approximating standard drums (55 gal/210 liters) and smaller, and are very often fitted with a lock-ring cover that is easy to remove in order to access the contents.

Beer and Syrup Kegs

Beer kegs are specialty items that are used for the relatively small-quantity bulk distribution of beer to bars and restaurants, and are almost always re-used. They are constructed of either aluminum or stainless steel, with the manufacturing method being similar for both materials. The body is deep-drawn into shape and has a skirt that is inert-gas-welded to the top and bottom ends to accommodate both standing upright and being lifted by the handles incorporated into the skirts. Kegs are either the Hoff-Stevens type, which has a bung in the side, or the more common SVK/Sankey® type that is equipped with a concentrically vented center fitting that allows automated cleaning and filling equipment to handle them efficiently. Smaller "pony", "log," and similar kegs may have synthetic rubber skirts bonded to the top and bottom to reduce cost, weight, and handling noise, and decorative outer barrels can be molded on to resemble wooden barrels. Similar small containers have been used for soft drink syrups for years but are rapidly being replaced by bag-in-box systems that are less expensive and do not require return, cleaning, and re-filling.

Metal Pails

Metal pails are formed in a similar manner to steel drums, with a side-seamed cylindrical body flanged to a bottom. The tops may be attached by any number of methods, though simple pull-off tops and flanged tops are most common. Because of problems with interaction with products, very few food ingredients are shipped in metal pails rather than molded plastic containers.

More common uses are for materials such as cleaners, roofing compounds, and chemicals, with molded plastic pails making steady inroads into traditional markets. The additional feature of child-resistant tops has given molded plastic pails the edge in markets such as pool chemicals and bulk cleaners.

Metal Tubes

Metal tubes bear the distinction of being one of the few commonplace items that was started by artists and is arguably one of the first packages that became popular because it added convenience to an already common product. Metal tubes were first developed as a means of reducing the annoyance of having to grind and mix pigments by the American artist, John Rand, during his apprenticeship, and were patented by him in 1841. These first tubes were similar to fast-food condiment packets or sample tubes in that they had to be torn or punctured open and could not be re-sealed. In 1842, Rand developed the production system for extruding tubes from soft metal, originally tin or lead, since aluminum cost approximately the same amount as silver at this time. These included a threaded neck and nozzle, and the design remains largely unchanged. Tubes were immensely popular in Europe, and their implementation allowed the beginnings of pre-fabricated art supplies.* Tubes remained as a niche market for paints and were originally manufactured in Britain and imported into the less industrialized United States, but were immediately successful in Europe where they were adapted for a variety of uses, from food to ointments.

A druggist, Dr. Washington Wentworth Sheffield, had invented a type of toothpaste in 1850, and his son, Dr. Lucius Tracey Sheffield, who had studied in Paris and had seen metal tubes used by artists, began selling toothpaste in collapsible metal tubes that customers immediately found more convenient than jars. Tubes were increasingly adopted by other cosmetic and dentifrice

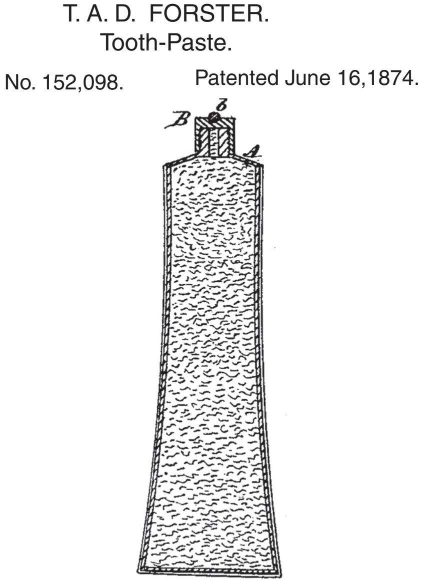


Figure 4.22. Early Toothpaste Tube
Source: USPTO Patent 125,098

companies throughout the late 1800s, and improvements such as embossing and printing were incorporated.

Metal tubes are now formed from aluminum and occasionally tin (lead may also be used, but not for food or pharmaceutical use) in an impact extrusion press that pushes the ductile material into a neck die and simultaneously extrudes it up the sides of the press to form the tube body. The extrusion is trimmed and at this point, aluminum tubes must be softened by annealing them so they will collapse properly without cracking, as the forming process work-hardens the aluminum and makes it brittle. Tin tubes, although more expensive, are still used as very small containers because of tin's ductility after being worked, and are typically used for medical compounds and other specialty applications. Tubes may be internally coated to help prevent product interaction with the material, but in most instances, reactive products have been given over to plastic or plastic laminate tubes discussed at the end of the chapter. Printing can be done before filling and requires the use of very flexible coatings, and labeling can be done either before or after filling, though proper label application is more challenging after filling. After filling the tube, the end is rolled over and crimped, often with a die that will include a date or product code. Screw caps, dispensers, or other fittings may be added before filling for tubes that are formed with an open neck, and afterward for products that must be opened by puncturing a seal in the neck.

Plastics and Synthetic Polymers

Polymers – organic and inorganic – are a natural constituent of most materials and all organisms. The materials that are commonly referred to as polymers, however, usually are man-made materials, and are usually organic polymers (although synthetic inorganic polymers – ceramics – are finding increased use in aerospace and specialty consumer applications). Development work using macrodefect-free cement and other inorganic compounds have been used to make packaging components such as formed cans, but there is no current industrial implementation.

The earliest synthetic polymers were a result of the booming industrial development of the chemical industry in the 1800s, when chemists found that they could dissolve cellulose using nitric acid and remold the resulting materials into nitrocellulosic materials – often referred to as collodion materials. The first uses for these materials were in early photographic processes, and in the manufacture of billiard balls as the cost of ivory from ever-scarcer elephants rose. These materials, whose use continued well into the 20th century, were notoriously flammable and volatile, and did not withstand the test of time well. The addition of camphor to nitrocellulose produced celluloid, which proved more stable and was used as one of the first truly useful thermoplastics – materials that can be melted and reformed many times under heat and pressure. The first completely synthetic man-made polymer, a thermoset named Bakelite, was developed in 1907 by Leo Baekeland. Bakelite was a phenolic-formaldehyde resin that was impervious to most conditions of heat and aggressive chemicals; once molded, the shape would never change, and it would chemically decompose before it was substantially altered by heat, pressure, or solvent attack.

The booming market for plastic materials in the 1920s and 1930s resulted in materials such as nylon, PVC, and the disruption of supply of natural raw materials for the war efforts of both the Allied and Axis armies in World War II caused a flurry of research on both sides intended to find suitable replacements for scarce natural rubbers and rope fibers that had been cut off by war in the Pacific region. The incorporation of new materials into aerospace structures, as well as use in consumer goods such as radio parts, lamp components, and related high-durability applications, pushed the chemistry and manufacturing technologies of synthetic polymers into its current state as the predominant source of structural materials for most consumer goods and many types of packaging applications.

The relative ease of forming simple organic gasses – most often derived from petrochemicals or coal – into long chains has seen a steady progression of control and sophistication from the initial days of producing relatively soft and fragile moldings that did not stand up to use to the current wide range of inexpensive materials that have very specific properties. These can be tailored to suit a particular application either by initial compound formation or by subsequent modification of structure by mechanical or other means.

Unfortunately, the inherent source of plastics production in the petrochemical industry has put resin availability and prices at the mercy of the unstable world oil and natural gas market. However, considering that this is a direct use of petrochemicals rather than using them as a heat source for the conversion of other materials, it represents a relatively efficient use of resources to produce synthetic materials. In times of oil and natural gas market upheaval, resin price and availability may fluctuate wildly, although this will in all likelihood be a smaller variation than with materials that have very high basic energy content, such as glass.

Basic Polymer Synthesis

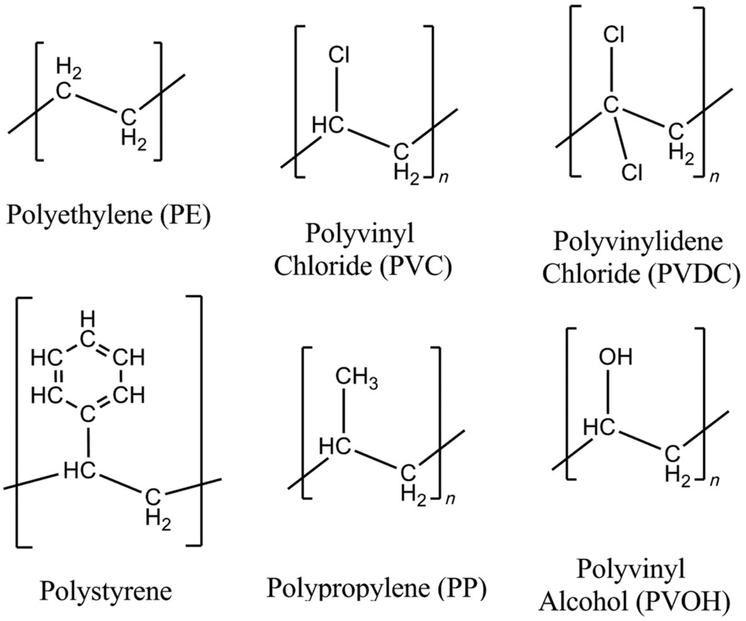
Although polymer synthesis is a broad field of basic research and industrial production, the relatively simple types of plastics used in many packaging materials can provide a clear illustration of the simple types of manufacturing processes that are used to produce them. Although the reactions that are shown here are quite simple to describe, the actual processing conditions and degree of control of the processing variables involved have required many years of work on process design to allow polymer synthesis operations to accurately and predictably control the formation of reliable polymer structures.

Most polymers are synthesized from *monomers* – small, simple units that are typically linked into long chains or networks, forming *polymers*. For the simplest types of polymers that are used for the majority of applications in packaging, the structure of the polymer is simply an endless repetition of a small sequence of chemical compounds, so for the sake of convenience, these are often given as *repeat units*, the smallest repeating structure in the finished polymer, usually with any end structures indicated, as shown in Figure 4.23 for many common polyolefins used in packaging.

Additive Synthesis

Additive synthesis is, as its name implies, a process of adding compounds together to produce a synthetic result. The most common are single-monomer syntheses, although, as will be discussed later, multicomponent syntheses, producing *copolymers*, are also commonly used to produce high-durability polymers for use in the manufacture of tires and high-impact plastics. There are additional polymers that will be discussed, but most of the polyolefins result from the polymerization of alkenes.

Although there are many types and variants of additive synthesis, in its simplest form, additive synthesis polymerization has three major steps: initiation, propagation, and termination.


Polyethylene (PE)

Polyvinyl Chloride (PVC)

Polyvinylidene Chloride (PVDC)

Polystyrene

Polypropylene (PP)

Polyvinyl Alcohol (PVOH)

Figure 4.23. Repeat Units of Common Polyolefins

Initiation

Initiation is usually caused by a combination of heat, pressure, and the addition of a catalyst, and causes the relatively stable monomer structures – in this case, ethane – to shed a hydrogen atom and provide an *active site* to which other such molecules can bind.

Propagation

During the propagation step, the molecules with available sites bond ends to form longer and longer chains that are led by the progressively catalyzed site. Random attachment of side-chains may cause branching in the structure as well.

Termination

At some point, the chains will have grown until they either encounter an impurity or the end of another growing chain that blocks the ongoing addition reaction; run out of molecules to add to the grown chain; or until the reaction is quenched by the manipulation of external variables such as heat and pressure, as shown in Figure 4.24.

The conditions under which the polymerization reactions are stopped will have a great effect on the final material qualities of the polymer. Very rapid termination will result in very short chains, providing thin synthetic oil, whereas long reactions will result in very high molecular weight polyethylene (UHMW) that is used as a solid and very strong engineering material. Thus, by controlling the polymerization conditions, the chain length, and thus the molecular weight of the polymer chains, can be controlled.

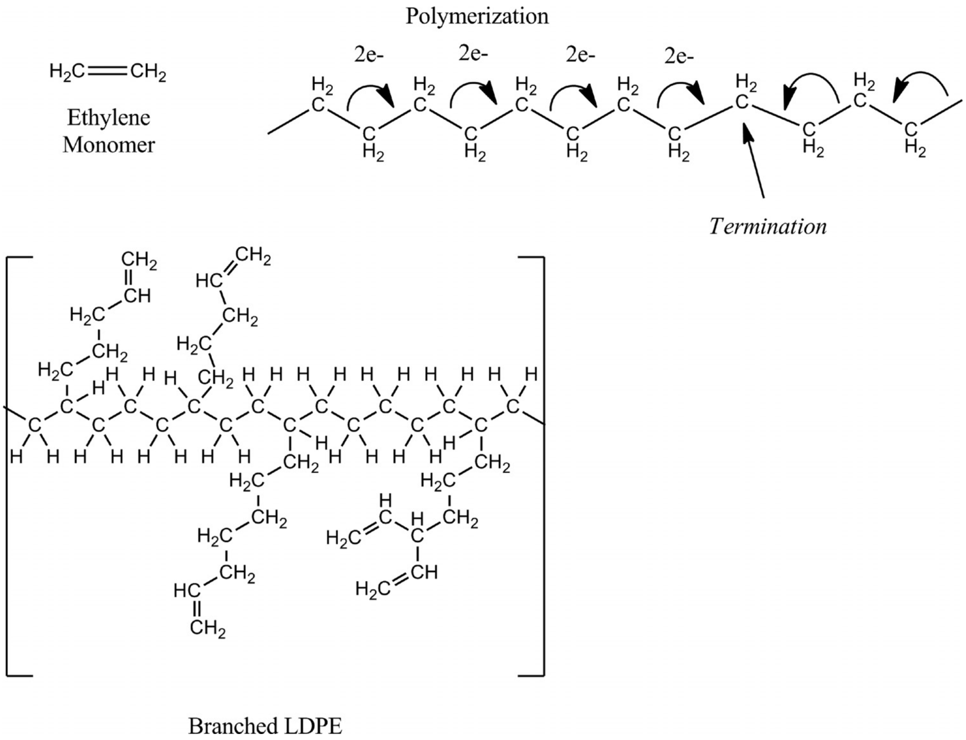
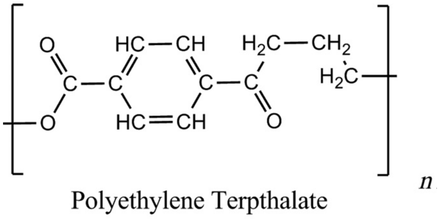


Figure 4.24. Monomer, Polymerization, and Branching in Polyethylene

Other Common Types of Chain-Addition Thermoplastics



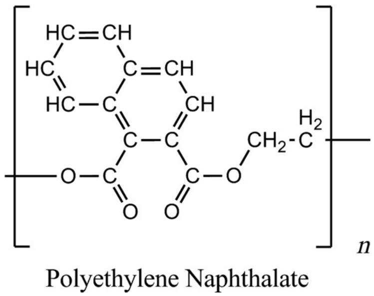


Figure 4.25. Common Packaging Polyesters

In a manner similar to the polyethylene described earlier, other common types of chain-addition thermoplastics can be constructed by the linking of suitable repeat units, as shown for packaging polyesters and nylon in Figures 4.25–4.27.

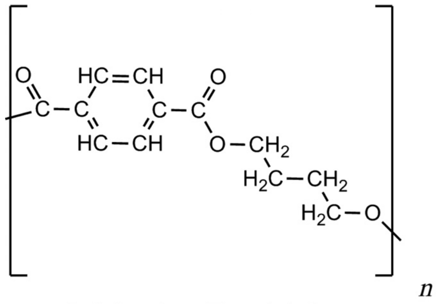

Polybutylene Terephthalate

Figure 4.26. Polybutylene Terephthalate

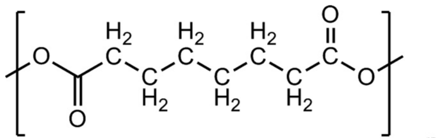

Nylon 6,6

Figure 4.27. Nylon 6,6

Biopolymer-Based Resins

To explore non-petrochemical feedstocks for commercial resins as well as develop biodegradable polymers for packaging, a good deal of research is being done on biopolymers, chiefly based and funded in several general commodity groups. Although there is a wide range of biopolymer sources under investigation, several have proven commercially viable in niche markets and others are actively being investigated.

Fermentation Biopolymers

Polyhydroxyalcanoate (PHA)

PHA is the intracellular energy source for microorganisms, and is extracted by enzyme cell wall degradation, lyophilization, and chloroform extraction. Currently, the process uses a detergent breakdown of cell structure, but research has indicated that it is possible to engineer *E. coli* to respond to a signal so that it lyses, spilling the PHA inclusions into the culture medium.

Polyhydroxybutyrates (PHB, PHBV)

PHB, a similar cellular product, is water-insoluble and a good barrier. Originally produced by Monsanto, it is currently commercially produced as Biopol by Metabolix. It can be used for packaging applications and as a light engineering plastic for medical devices and consumer goods. It is currently used as internal suturing thread because it biodegrades over time. A PHB copolymer, PHBV–Poly(3-hydroxybutyrate-co-hydroxyvalerate), is also under development.

Polylactic Acid (PLA)

PLA is produced from microbial fermentation of plant polysaccharides (chiefly dextrose) into lactic acid, and is polymerized using either of two methods: high vacuum and temperatures and solvent water removal, or lower-temperature water extraction and vacuum distillation of intermediate products, then polymerization using heat.

PLA can be used as a moderate engineering plastic as well as for packaging materials, and is currently sold as Cargill-Dow's NatureWorks® polymer. Its chief market is disposable food service tableware and snack food containers, but it has been used for some time in surgical implants and single-use medical equipment that degrades if autoclaving is attempted for reuse.

Plant-Based Biopolymers

Starch-Based Plastics

Starch is a naturally occurring polymer consisting of various levels of amylose and amylopectin depending on the species from which it is derived (unmodified cornstarch is approximately 25% amylose and 75% amylopectin). Low starch content plastics have up to 20% starch content in petrochemical polymers, and will enhance the disintegration of the structure but do not add to biodegradability. Medium starch content plastics (approximately 50% starch by weight) are considered a plastified starch material and can be processed with many types of existing commercial plastic-processing equipment. These will biodegrade but leave substantial petrochemical residue. High starch content plastics are 90% or more starch and can be difficult to form. Injection molding in particular can be very difficult because starch does not melt and flow readily with heat. This high modulus behavior is exploited in the production of stiff starch foams, used as packing pellets for padding shipping containers, and which is the bulk of the current bioplastics market.

Soy Protein-Based Plastics

Soy-formaldehyde composites have been made since the 1920s. Cross-linking made them non-biodegradable, as previously described, but current efforts are aimed at creating a commercially viable molding resin that approximates commercial thermoplastics with soy protein isolate as the usual starting point. The polymers are approximately 90% protein, extracted from protein concentrate with alkali leaching and re-acidification. These can be molded using injection or compression molding, extrusion blow molding, or casting.

Other Naturally Derived Polymers

Chitin 2-acetamido-2-deoxy-β-D-glucopyranose

This is typically extracted from shellfish and fungi walls and can be formed into fibers and films. Its deacetylated form, Chitosan 2-amino-2-deoxy-β-D-glucopyranose, has antibacterial properties and is formed into medical films and fibers.

Factors That Affect the Behavior of Polymers

Copolymerization and Blending

In some instances, it may be desirable to combine several monomers at the molecular level to provide a proper mix of material's properties. The two most common examples are Styrene-Butadiene-Rubber (SBR) used in car tires, and Acrylic-Butadiene-Styrene (ABS) used in many high-impact molding for sporting goods and vehicle construction. These individual-component polymers are combined during chain formation and should be distinguished from blends, which are simple mixes of the finished resins usually done at the molding or formation stage. Although each has its benefits, the former allows very specific and predictable product properties to be produced during resin formation, whereas blending is usually done at the final production step and may be subject to a degree of variability, particularly in the case of forming equipment that does not mix the resins thoroughly. The advantage that blending offers is simplicity – simply a matter of stirring together resins and colorants and fillers as required during the production step to produce very specific properties on demand.

Branching and Cross-linking

As might be expected in a polymerization reaction, more than one active site may be made available on a particular backbone molecule as it grows. When this occurs, polymerization proceeds in more than one direction creating a *branching* phenomenon, as a predominant backbone molecule has long secondary chains propagating outward from a point on the main backbone chain. Control of branching has been an ongoing subject of applied polymer research for many years and has resulted in several specific types of polymers that are commonly used in packaging.

Low Density Polyethylene (LDPE) has a high degree of branching, as previously shown in Figure 4.24, where there are a large number of side chains that provide a large amount of interstitial space in the polymer structure, giving it its characteristic of low density and, unfortunately, a low modulus and failure strength.

High Density Polyethylene (HDPE) has had the degrees of branching severely controlled, resulting in a chain morphology that packs tightly and provides a high level of strength. The drawback to this particular variant of polyethylene is that the costs of controlling the branching during polymerization are quite high, which makes this particular material somewhat unappealing from a cost perspective.

Linear Low Density Polyethylene (LLDPE) has evolved as a compromise between these two materials. It is produced with a number of side branches similar to that of LDPE, but the length of the side branches is controlled so that the ability of the side branches to affect the strength of the material is minimized. The costs of production are significantly lower than with HDPE, and the material has found widespread uses in packaging materials, grocery bags, and similar applications.

Role of Catalysts in Polymerization and Branching Behavior

The type of catalyst used in producing polyolefins has had a central role in producing more accurately controlled chain lengths and degrees of branching. The first industrial catalysts were so-called Zeigler-Natta catalysts (named for the discoverers of the general class of reactions that they promoted) that used to polymerize olefins and were revolutionary in that they allowed the production of a variety of polymers with a high degree of stereospecificity. Typical Zeigler-Natta catalysts were originally titanium and aluminum compounds, and had the disadvantage of providing too many active sites during active polymerization. This had the result of producing a broad and poorly controlled range of molecular weights and branching. To better control the catalysis, *metallocene* catalysts have replaced the original Zeigler-Natta catalysts, although the reaction follows the same pathway discovered by Zeigler and Natta. Metallocene catalysts based on positively charged titanium, zirconium or hafnium, which date to the original Zeigler-Natta catalyst era, were originally rejected because of their low activity, but were adopted to better control the catalysis reaction when it was found that a methyl aluminoxane co-catalyst would increase their activity and allow them to be economically viable. The metallocene catalysts have a single reaction site and result in a much more controllable polymerization reaction, but have the disadvantage of being unable to efficiently polymerize highly polar monomers such as vinyl and vinyldiene chloride as well as many acrylics. To overcome this, work is being done to produce catalysts from late transition metals, such as the Brookhart catalysts that are complexes from palladium or nickel. These offer the advantage of activity nearly as good as the metallocenes, but with the ability to polymerize polar molecules. Research and development of catalyst systems continues and is a continuingly competitive field in the polymer industry.

Cross-linking in Polymers

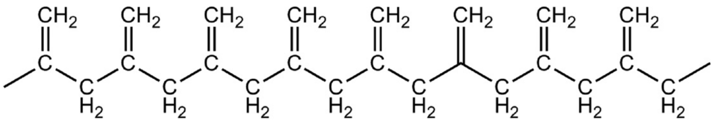
Cross-linking can be thought of as an extension of unintentional branching in some theoretical sense, but more often it is an intentional step in the manufacture of materials. One of the first artificially cross-linked material was vulcanized rubber, developed by Charles Goodyear and patented in 1844. The process used heat and sulfur as a cross-linking agent to produce a rubber material that was not sticky and would not soften in hot weather, allowing it to be used for a wide range of consumer and commercial goods. By extension, a high degree of cross-linking is associated with thermal stability to the point where a thermoset plastics are considered highly (and permanently) cross-linked and will break down and pyrolize before softening when heated.

Because cross-linked materials' structures are completely bonded into a huge network of linked polymer chains, thermoset and highly cross-linked thermoplastic materials are often considered to be a single molecule of material. Less complete cross-linking will have the effect of binding the polymer chains into a rigidly elastic network that is temperature-stable and has a high modulus of elasticity. Highly cross-linked materials such as natural rubber are often very elastic yet can be considered brittle in the true sense of the word because they break before undergoing large-scale plastic deformation. Lower levels of cross-linking will reduce this effect, providing a lower modulus, more ductile material that will usually be "tougher" – able to absorb more impact energy.

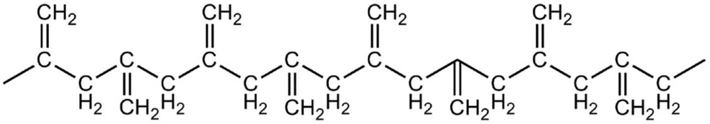
At some point, the interaction of highly branched materials and materials with a low degree of cross-linking becomes approximately similar, owing to the similar interactions of the three-dimensional structure of the polymer, although these will often be distinguished by different thermal and melt characteristics during analysis.

Tacticity and Conformation

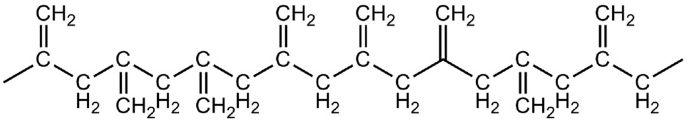
When polymers have functional groups bonded to their backbone chain, the geometry of the distribution of these groups becomes an important factor in the determination of physical



Atactic Polypropylene



Isotactic Polypropylene



Syndiotactic Polypropylene

Figure 4.28. Polypropylene Tacticity

and chemical properties, particularly barrier properties in packaging applications. A simple chain polymer such as polyethylene might be considered to have some degree of tacticity if the branching that occurs has any degree of regularity to it, but this is rare in any practical application. Co-polymers will have similar tacticity considerations if the co-polymer is compounded with a central chain of one polymer and the secondary polymers bonded as side groups. There are three predominant types of tacticity that are commonly referred to: isotactic, syndiotactic, and atactic, as shown in Figure 4.28.

Atactic

Atactic polymers have side groups that have a random arrangement on the chain; these may exhibit the least amount of interchain interaction because of the random nature of the distributions of high and low polarity on the chains.

Isotactic

Isotactic polymers have all of the relevant functional groups in the same position in the repeat units. Interchain interactions may be significant in this conformation because of stearic interaction between the side of the group that has a large number of functional groups on it on one chain and the side that has relatively few on the chain adjacent to it.

Syndiotactic

Syndiotactic polymers have the relevant functional groups on alternating sides of the chain. This also effectively doubles the length of the repeat unit. This conformation may represent the lowest energy state due to the minimization of stearic interactions between side groups, but may also exhibit a great deal of interchain interaction because of the Velcro®-like nature of the interlocking of the chains that may occur.

Molecular Weight and Molecular Weight Distribution

As has been mentioned previously, the molecular weight is proportional to the chain length for a given monomer type, but because precise control of the molecular weight can be somewhat difficult, it has been the subject of ongoing polymer production engineering research. Because the chain length of a polymer, which is usually measured by size exclusion/gel permeation chromatography, can be described as a statistical function, there are several descriptors for the molecular weight distribution of a polymer. The most important of these is the average molecular weight because it quickly – albeit incompletely – describes the physical characteristics of the polymer. Most common usage truncates this to *molecular weight*, and this is usually incorrect. Molecular weight is actually a statistical function of the distribution population of chain lengths, and this misunderstanding has caused intermittent problems in the manufacture of goods from synthetic polymers when the polymers do not perform as anticipated.

If the statistical distribution of a polymer is centered around its average, it can be said to have a *normal* distribution, that is, the number of chains at some length shorter than average is roughly equal to the number of chains that are longer than average by the same length (Figure 4.29). If this happens, the mean (numerical average) and median (length that is halfway between the largest and smallest value) will coincide. Even within a normal distribution, however, the

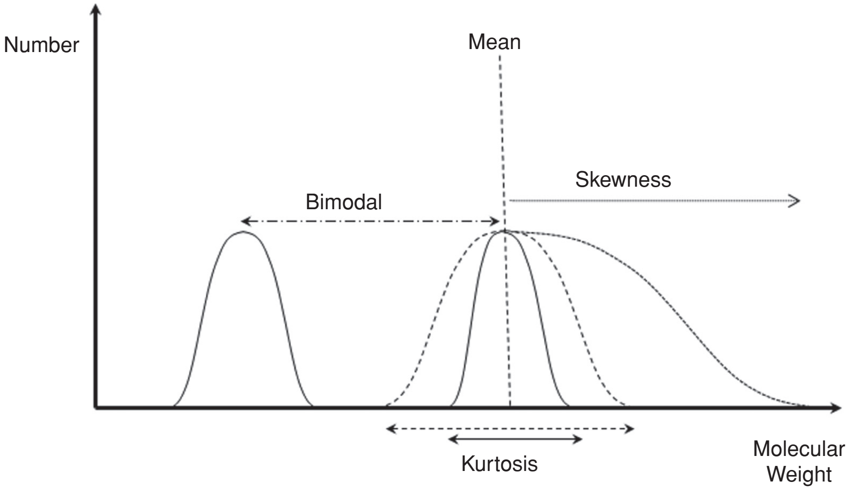


Figure 4.29. Molecular Weight Distribution Terminology

distribution's kurtosis may be considered *broad* or *narrow*. The narrow distribution of polymer chains and molecular weights will have a very tightly defined set of mechanical properties and will likely be suitable for precise applications, whereas the broader distribution will probably exhibit a broad range of strength and temperature stabilities.

If the polymerization process proceeds with the rapid formation of chains and the reaction is then allowed to continue for a long period of time, forming an ever smaller number of very long/high molecular weight chains, the chain length distribution will exhibit some degree of *skewness*, in which the mean and median chain lengths no longer coincide. This has significant implications for the properties of the polymers in that there may be a large number of chains some distance away from the average value that are dominating the polymer structure and defining its physical properties.

In an extreme example, the polymer may exhibit a bimodal distribution of chain lengths and could be considered to be an odd mix of light liquid and very dense solid, yet the simple value for the average molecular weight would not indicate that there is anything unusual at all about the material. The practical significance of this, particularly for packaging applications, is that the packaging engineer should be aware of the molecular weight distribution characterization as well as the simple molecular weight of the polymer resin to be used in production, because the difference between the two has occasionally resulted in production problems with moldings and extrusions that can be very hard to diagnose.

Crystallinity and Density

Crystallinity in the polymers used in packaging is not usually possible in the classic sense that is used for pure elements such as carbon, but refers to a high degree of three-dimensional order on a molecular level. By definition, then, some degree of disorder is considered acceptable, even with a high degree of crystallinity in a polymer. Remember that a high degree of crystallinity will result in a sharply defined melting point, glass transition temperature, or other thermal feature. More commonly, particularly in the polyolefins such as polyethylene and polypropylene used in packaging plastics, the polymer chains will have regions of high crystallinity (high degree of chain order) and regions of amorphous morphology (random orientation of chains). These can be directly observed using a high-power microscope and polarized light, or by indirect observation with coherent light sources, but each of the two types of regions will have different mechanical and thermal properties (Figure 4.30).

Highly crystalline materials are typically denser for a given material, owing to the close-order packing that occurs between chains, and they tend to have a higher modulus of elasticity, will soften abruptly at a reasonably well-defined temperature, and will be more brittle. The correlation between molecular weight, crystallinity, and many other properties is shown in Figure 4.31. Because there is little space between the adjacent chains, the polymers will often have a much lower ability to diffuse materials through their structure, resulting in a lower permeation rate – a feature that is exploited as a barrier in many modern plastic containers for carbonated beverages and oxygen-susceptible foods.

Amorphous materials will be less dense because the chains are randomly scattered and have a good deal of space between them. They have a broadly distributed melt temperature – that is, they will soften gradually as heat is applied – and tend to be mechanically tougher, more able to absorb energy by deformation before failure. Because there is a large interstitial space between the chains for compounds to diffuse through, the permeation rate of an amorphous polymer will be higher for a given amount of material.

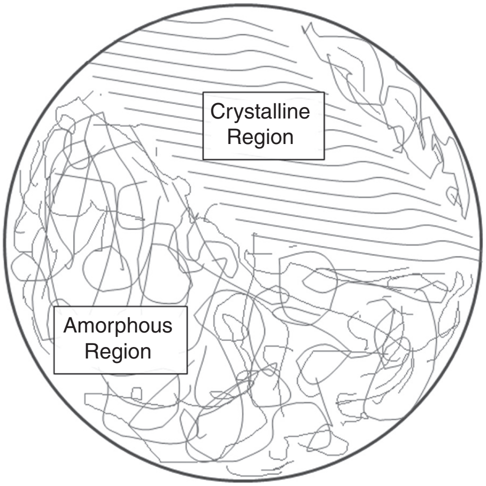


Figure 4.30. Crystalline and Amorphous Regions in a Polymer

As will be discussed later in the chapter, it is possible to convert a highly amorphous material to a highly ordered material by mechanically orienting it in one or more directions and pulling the polymer chains into the direction that the materials are stretched. This operation, if done correctly, has been shown to convert amorphous regions into crystalline ones, resulting in a nearly complete high-crystallinity material with the attendant low permeation – a feature that is exploited in the mass production of soft-drink bottles.

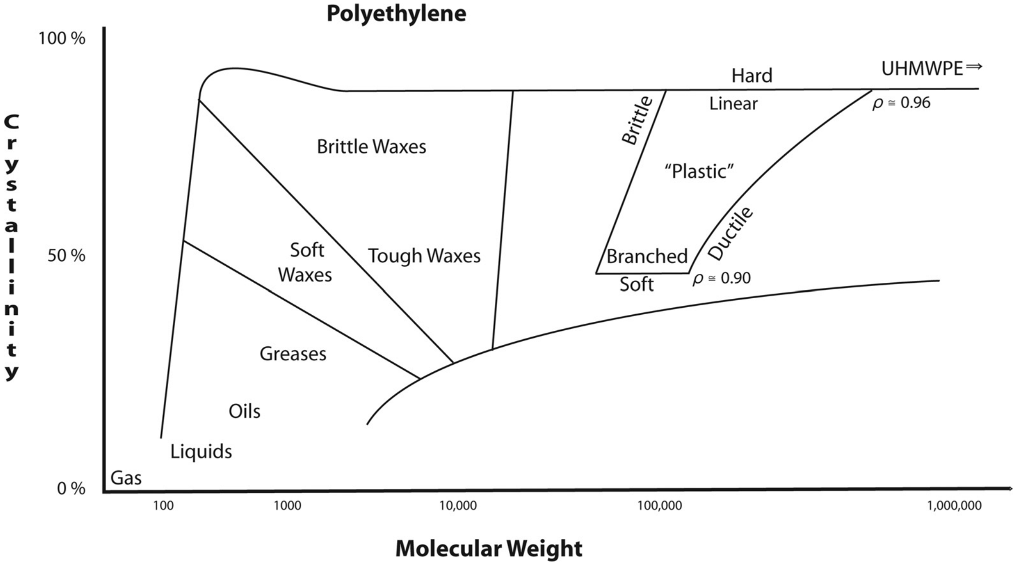


Figure 4.31. Density, Molecular Weight, and Physical Properties of Polyethylene

Thermal Characteristics of Polymers

Because thermoplastics are a statistical distribution of molecular chains of varying length, and because they are not completely cross-linked into a crystalline structure the way a crystal of salt might be, the melt characteristics of most thermoplastics are somewhat different than the classically sharp melting points of crystalline materials. In most cases, and particularly for the low-complexity polyolefins used in the packaging industry, the polymers will go through three distinct phases with increasing application of thermal energy.

Glassy: Polymer chains are not free to bend or rotate to any significant degree, and will not flow past one another. This state often represents the highest-modulus, lowest-permeation state of the polymer, but – as the name implies – may also be the most brittle because the polymer chains have very little latitude for movement when subjected to impact or excessive force.

Rubbery: The chains are free to bend and rotate, but will not flow past one another readily. This may represent a more durable state of the material, because the polymer can readily absorb impact energy in bond deformation and flexing, but is still dimensionally stable.

Melt: Chains are free to bend, rotate, and flow past one another. Obviously, this is usually not a useful state for a material expected to maintain its dimensional stability in a packaging application, but melt temperatures and melt-flow behavior while heated are of great interest to the fabricators of packages and packaging materials.

One of the distinctive measures of polymers is the *Glass Transition Temperature* (T_g) – the temperature at which the polymer makes the change from a glassy to a rubbery state. This is usually a well-defined temperature and is dependent on the polymer type, molecular weight distribution, and composition of any additives to the polymer matrix (particularly plasticizers). Glass transition temperatures are usually determined by calorimetric scanning methods, because the actual transition is endothermic and creates a distinctive signature in the calorimeter data.

For some types of polymers, the glass transition temperature can be a critical factor in design, because a glassy polymer may be very brittle at freezer temperatures, and the packaging material may fracture in use. In more practical terms, whether a polymer is above or below the glass transition temperature will have profound effects on the mechanical and chemical properties, particularly permeation that increases markedly above T_g, and may have critical impact on the final success or failure of the application.

Thermosetting Plastics

Thermosetting plastics are defined as being those that cannot be re-softened by the application of heat, and although they will have a thermal breakdown temperature that provides a practical limit of use, they do not have a useful melting point once they have been polymerized. In the packaging industry, one of the few remaining applications of thermosetting plastics is the manufacture of threaded caps for chemical containers or containers of extremely volatile materials, due to their chemical stability, but nearly all other applications have been replaced by thermoplastic resins because of the relative ease of molding, lower cost, and recyclability.

That the lack of a useful capacity for material reuse limits the recyclability of thermoplastics is of little concern to the packaging industry that no longer uses them, but if one considers the number of discarded tires that have to be disposed of, one can see that there would be a great deal of interest in finding ways to break these types of materials down to some useful set of components so that they may be re-used. Some types of packages that use large quantities of thermosetting components must be disposed of rather than recycled.

Orientation

Once the basic resins are produced, the materials are usually molded in a series of steps to produce a stock material such as a film, sheet, or a finished package. The direction of strain in the formation process causes a resulting realignment of the polymer chains in a manner very similar to the alignment of paper fibers during paper manufacture. This effect may be simply a by-product of the manufacturing process, or it may be specifically engineered into the production method to allow the oriented material to perform a specific task.

Linear Orientation

Linear orientation is the result of deformation of the polymer in a single direction during manufacture. This will result in the statistical majority of the polymer chains lying along the direction of stress, with a result of a higher degree of tensile strength in that direction, as well as a reduction of permeability and an increase in density as the chains are reoriented from random orientations to a general orientation along the major axis of strain. This may be achieved in a number of ways, but the most common is the orientation of films and sheets during production by stretching the film after it is extruded.

Biaxial Orientation

As the name implies, biaxial orientation of materials occurs on two major axes. This changes the material from a more or less random orientation to one that can be visualized as a tight mesh of polymer chains, with the attendant increase in strength and decrease in permeability. Actually producing films and sheets that have a biaxial orientation is a challenge owing to the difficulty of adding the second direction of orientation during manufacture. The most common ways of providing a biaxial orientation for a polymer film are to either use a film-blowing tower or an orienting device that progressively pulls the film sideways using tenter grips, as well as orienting it along its major *machine direction* using increased take-up speed. The latter is a slow and somewhat expensive method, but can be used for many different types of materials.

For polymer films that are produced using a film-blowing tower, the orientation of the materials can be controlled somewhat by controlling the inflation regime and the take-up speed from the top of the tower, providing a radial and longitudinal orientation, respectively. This provides a low-cost, high-speed method of producing oriented tubular films that can either be slit along one side to provide flat stock or end-sealed and cut to produce bags.

Biaxial Orientation in Molded Bottles

The technology of orienting molded polymer packages has been the cornerstone of the production of high-barrier plastic bottles and jars to replace glass and metal containers for foods. The basic production steps strongly resemble the blow-and-blow processes that are used in the glass industry in that a *preform* (a parison-like structure) is molded, then allowed to cool below the glass transition temperature, and then blown into its final shape at a carefully controlled temperature and rate. Because the final blowing step is done at a cool temperature, a process roughly analogous to cold drawing occurs in the polymer structure, with the end result being a container that is highly oriented, with very good clarity (if desired) and good resistance to attack by food components and oils.

General Orientation Effects

In general, orientation of polymer films may affect many properties of polymeric materials, particularly in thin-wall plastic films and moldings. In general, the transition of the polymer structure from one containing significant volumes of randomly oriented polymer chains to one that is highly ordered (crystalline) causes the structure to exhibit a higher degree of close-order packing and a higher density. A simplified demonstration of this would be to grab a double handful of randomly oriented string and pull it in opposite directions. The strings would orient themselves in the direction of pull and would most likely be packed much more tightly. The polymer morphology changes that accompany this can include changes in light transmission characteristics (such as a change in clarity), as well as changes in the optical birefringence characteristics, changes in tensile strength as the chains orient themselves in the direction of tensile strain (similar to *work hardening* in other materials), and changes in barrier characteristics as the degree of orientation progresses.

Studies have shown that permeation will actually increase slightly at low degrees of orientation change, possibly due to relaxation of the polymer structure, and then begin to decrease as the polymer chains begin to become more highly ordered and more densely packed. In the case of linear orientation, the overall permeation decrease is significant and is matched by the mechanical orientation of the plastic films, which can have secondary effects, particularly for consumers who find that their package splits open and spills its contents because the manufacturers are trying to increase barrier properties without considering other effects.

Biaxial orientation can have an even higher rate of barrier increase and will often have a balanced change in tear orientation to avoid problems with splitting. The orientation process may result in a stronger but more brittle structure – one that maintains a very high level of strength but will deform little before failing. This is ideal for a beverage bottle that must maintain its shape against high pressurization, but for a package that must be torn open, it often creates problems for the consumer unless a reliably produced tear-notch or other opening feature is provided.

Plasticizers and Additives

Plasticizers are materials that increase the ductility of polymeric materials, usually by allowing the polymer chains greater freedom to move with respect to one another and become an integral part of the overall material structure of the polymeric materials that are used in packaging materials. In the polymer industry, several types of plasticizers are available, though not all of them are suitable for food use. There are, among others, seven major types of plasticizers including: Phthalates, Aliphatics, Epoxidized Vegetable Oils (EPOs), Phosphates, Trimellitates, Citrates, and Polymerics. The simplest sort of plasticizer, and one that illustrates the mode of action (both intentional and unintentional) rather well are petrochemical or plant-based oils. When they are mixed into the polymer, the polymer becomes more ductile and susceptible to flow as well as more permeable, but as previously discussed, ductility produces flexibility as well. Polymers that are very brittle in their pure state, such as PVC, PVDC, and PS, would not be useful in most practical applications without a high level of plasticization to ensure that they do not crack or shatter when used. Unintentional plasticization can occur when the package is made of a material that readily accepts food components that act as plasticizers, the most common being low-viscosity oils. This can have the unintended effect of "softening" the container and causing premature structural instability, in turn resulting in loss of stacking strength or warping or other deformation of the package, as well as increased permeability and decreased shelf life. Early types of plastic packaging for some materials such as motor oil, vegetable oil and products that have high concentrations of oils or volatile plasticizers had difficulty maintaining enough structural integrity to assure that the packages would remain upright in their displays and would not deform extensively, ruining their consumer appeal and delaying their introduction into the marketplace by many years.

Plasticizer extraction from the package into the product is an enormous concern for many types of food items and one that is often hotly debated both in the press and by researchers. From a regulatory perspective, these constitute an indirect food additive and are the subject of specific regulations regarding quantity and type of plasticizer (or other additive) that may be extracted. This is discussed in Chapter 10, but for food packaging applications it must be shown that the amount of plasticizer lost from the food packaging materials into a product simulant is below a specified level, or that a plasticizing material that is already on the FDA's GRAS (Generally Recognized As Safe) list is being used.

Other Additives

There is an enormous variety of components that are added to polymers for any number of different additional purposes. As with plasticizers, it must be shown that other additives are either acceptable as indirect food additives (GRAS substances, for example), do not migrate into the food, or migrate in sufficiently small quantities that their presence is not a matter of concern. Some of the common agents added to plastics used in packaging are colorants, fillers, antioxidants, odorants, stabilizers, and additives used to affect their properties during manufacture.

Colorants: Coloring of plastics usually occurs in one of two ways. It is possible to order plastic resins in specific colors other than those in stock production, but this often requires a very-high-volume order. Additionally, the plastic resin may be colored during manufacture using additives. These are typically inert pigments or dyes added to the polymer resin during manufacture by blending coloring agents with the plastic resin before melting.

Fillers: Fillers are materials that are used as *bulking agents* to reduce the cost of a large-volume molded piece. These are often simple inert materials; in large non-packaging structural moldings, talc or sand has been used. For more involved applications, fillers such as *microballoons* – hollow microscopic spheres – are used to provide a lightweight filler material. Fillers are used sparingly, if at all, in packaging applications due to the relatively low volume of material that is used in each component.

Antioxidants: These are materials that are intended to reduce the effects of exposure to oxygen or degradation during molding, and may be actual food-grade antioxidant additives (ascorbic acid, for example) to eliminate problems with indirect additives in the product.

UV Inhibitors: The "Sunscreen of Plastics," UV inhibitors will reduce the destructive effects of sunlight (or long-term exposure to some types of artificial light) in materials. Typically, these are materials that either convert ultraviolet light to lower-wavelength light, or are sacrificial in nature, degenerating preferentially to save the base materials. There are few applications in the plastic packaging industry that require UV inhibitors for most consumer-grade food packaging, but large bulk containers, inks, paints, industrial coatings, and large structural moldings of materials like fiberglass often require some kind of UV-inhibiting coating to prevent degeneration in sunlight. UV inhibitors can be crucial in labeling applications where the product will be exposed to UV-rich fluorescent light or sunlight, because a faded package can prove to be unsaleable.

Odorants: Although not common in the consumer food packaging industry, odorants are volatile chemicals that are added to the polymer to produce a specific odor (or to mask another). Particular types of plastics that may have a "burnt plastic" smell after manufacture are occasionally treated with odorants, but the large application for this type of additive is type-specific moldings such as those used in children's toys or housewares.

Stabilizers: A more general class of additives than the antioxidants (which are stabilizers), these are typically added to provide protection against attack by a specific agent, such as a solvent in a product or a particular environmental hazard.

Manufacturing Additives: Manufacturing additives are substances that are added to the plastic resin in the manufacturing process to provide the plastic with specific characteristics to aid in proper manufacture. These may include plasticizers, slip agents, and other types of polymers to adjust the melt-flow characteristics or dimensional stability of the final product.

Structural Additives: Although rare in the packaging industry, structural additives are common in other plastics applications. A good example of this type of additive is glass-reinforced nylon. Nylon is a very durable and tough material, particularly when properly hydrated, but lacks a high degree of dimensional stability and overall strength. Manufacturers of structural components may combine nylon with fine glass fibers during molding. The glass fibers contribute their enormous tensile strength and stability, and the nylon component contributes toughness and abrasion resistance, with the final result being a molded piece that is stable, tough, and very durable.

Mold Release Agents (*Parting Agents*) Although not an additive in the strict sense of the word, release agents are used in nearly all plastic-molding operations at some point, and are familiar to most people as the oil used to prevent food sticking to cookware. Release agents are typically organic or silicone pastes, waxes, or oils that prevent the plastic from adhering to the mold surface. This will ensure that the molding can be easily removed from the mold assembly, and may prolong the life of the mold. Release agents may be particularly important if using a polymeric mold to form plastic materials, to prevent bonding. Application of release agents is most often done by either spraying or wiping onto the surface and may be automated to ensure that the mold has a consistent layer of release agent.

Over-application may result in an irregular surface on the final molding, so for continuous products such as chill-roll casting, the casting roll may have a combination of atomized deposition coupled with a wiper assembly to keep the release agent's film thickness to the minimum necessary. Additionally, sprayed mold release agents may represent an inhalation hazard and may contaminate adhesion processes such as gluing or labeling in other parts of a process operation if not properly controlled.

Manufacturing Polymeric Packaging

Unlike nearly all other packaging materials, plastics and polymer-based packaging are relatively simple materials to manufacture once the raw materials have been converted into plastic resin powder, flake, pellets, or beads. The low forming temperatures and durability of plastic packaging has prompted even modest dairy operations to install their own bottle-forming equipment in locations where a source of supply is not available or would be too distant to economically ship in empties. This type of operation, adopted by many producers of food, drug, and cosmetic products, may be owned by the producer company or contracted as a (sometimes literal) "through-the-wall" operation from a supplier situated nearby. It is not unusual to see very large food production facilities ringed with container-manufacturing operations.

Additionally, there is a plethora of intermediate converters of sheet, film, moldings, closures, fitments, and other packaging components that can produce packages at many intermediate stages of manufacture for further modification during manufacturing. For example, it is possible to contract for PET bottle preforms and do the final stretch blow molding in-house to maximize efficiency. The decision point for the "make, contract, or buy" decision is entirely dependent on the individual operation, but as production rates climb into the several million units per year, making or contracting through-the-wall begins to become more and more attractive.

Extrusion Processes

Extrusion processes are one of the simplest and most continuous methods of producing plastic items of somewhat uniform cross section, and nearly all mass production of plastic packaging components involves extrusion at some point. As will be seen later, the extruder has been adopted to more complex methods of manufacturing as well as *hybrid* types of manufacturing, but in its simplest form the extruder can be a simple, high-output means of forming sheet, film, and tubing of various cross sections, as shown in Figure 4.32.

The extruder is a conceptually simple device consisting of a means of melting plastic resin and ejecting it through an orifice or die, something that home hobbyists are capable of building, usually for injection molding. On an industrial scale, the operation becomes more and more complex as the demands for continuous operation, precision, efficiency, and safety increase. The simplest type of extruders are ram extruders that simply have a ram forcing resin through a heated barrel (and perhaps past an annular heater to increase heat penetration). Although these are the simplest and least expensive machines to manufacture, the low thermal conductivity of

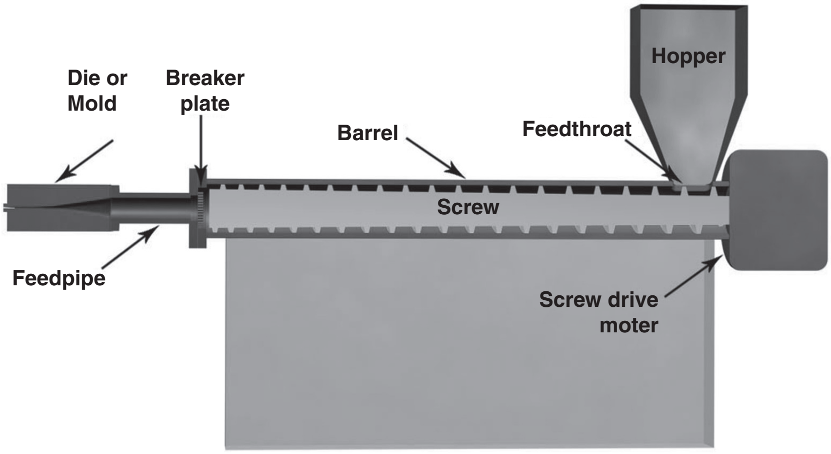


Figure 4.32. Cutaway View of Extruder

plastics, combined with the thick cross section of the resin charge and the lack of circulation of the cold resin, often renders this method inefficient when attempted on any scale.

To increase heat distribution in the resin, a screw-type extruder is used for most high-volume operations. This uses a rotating annular screw (or screws – dual-screw units are available) inside the extruder barrel to circulate the resin past the barrel's heater array and to allow control of temperature profiles in progressive zones as the resin progresses through the melting process from the intake hopper to discharge into a die or accumulator. For extruders that are coupled with large-volume injection-molding operations, the barrel may retract while rotating to provide an accumulated "shot" of resin for the mold, or it may feed an accumulation reservoir that is then discharged into a mold.

For sheet and film and tubing molding, the extruder will run more or less continuously to provide a constant production level, and the melted resin is usually discharged through one or more temperature-controlled dies. It is possible to gang multiple extruders into a single operation to produce co-extruded plastics, with the upper number of layers only limited by expense and the space available to feed the die. Sheet and film can be produced in a number of different methods depending on the characteristics required in the finished product. The most common methods are chill-roll, or water bath, casting and "blown" film.

Film Production

Chill-roll casting extrudes resin through a slit die onto the surface of a water-cooled die. The immediate quenching of the melt causes a very high rate of cooling and interrupts the coalescing of polymer chains into crystalline spherulitic regions, with the result being a less cloudy appearance and different strength characteristics. From there, the film may be taken through printing, coating, lamination, or other processes before final shipment, and may be oriented by stretching in the longitudinal direction by differential-speed take-up reels and laterally by the use of a tenter oven – a process that reheats the film and pulls it laterally using tenter clamps to orient it in the cross-machine direction. This is a complex and troublesome

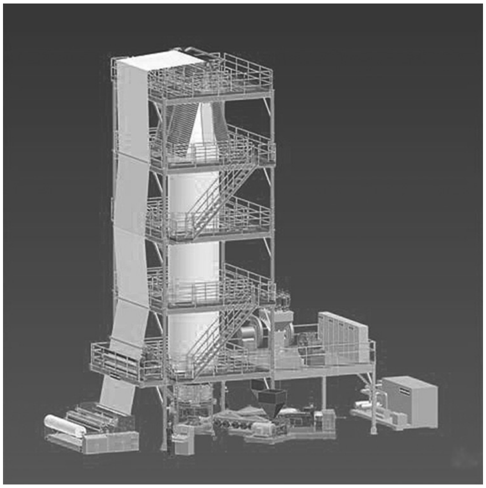


Figure 4.33. Film-Blowing Tower
Source: Alpha Marathon Company, Used with Permission

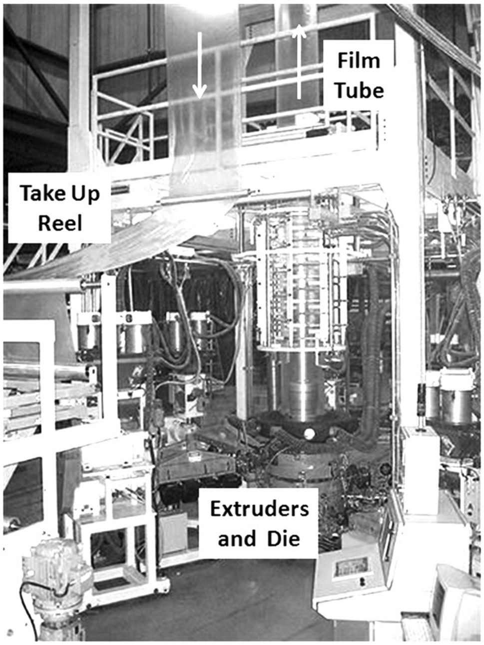


Figure 4.34. Detail of Extruders, Extrusion Die, and Film Bubble
Source: Alpha Marathon Company, Used with Permission

method, particularly for thin films, and has been superseded by blown tubular films in most applications.

Blown film, or tubular film production, is an extension of this process that offers an efficiency improvement for certain types of films because of its high rate of throughput. Blown film is manufactured by extruding film from a ring die that may have several stages to make multilayer films. The tube thus formed is drawn, usually upward into a multistory frame, and inflated with compressed air to form a large "bubble" of rapidly cooling plastic film that is subsequently taken up through a set of guide-frame rollers (Figure 4.34).

By controlling the rate of inflation and the rate of take-up speed, the circumferential and axial orientation may be controlled somewhat to produce a reasonably strong film or thin-wall tube, although the rate of cooling is not nearly as well controlled and so the film is often more cloudy than chill-roll cast films. By slitting one edge of the film as it is taken up, a flat film may be produced to be treated as previously described, or the tube may be left intact for use in bag or pouch making. Nearly all plastic grocery and garbage bags are manufactured in this fashion.

Film Metallization and Microperforation

Although the number and type of coatings and modifications that may be done to films used in packaging are extensive, two in particular should be mentioned here because they are a fundamental modification of the material structure and are quite common in food packaging.

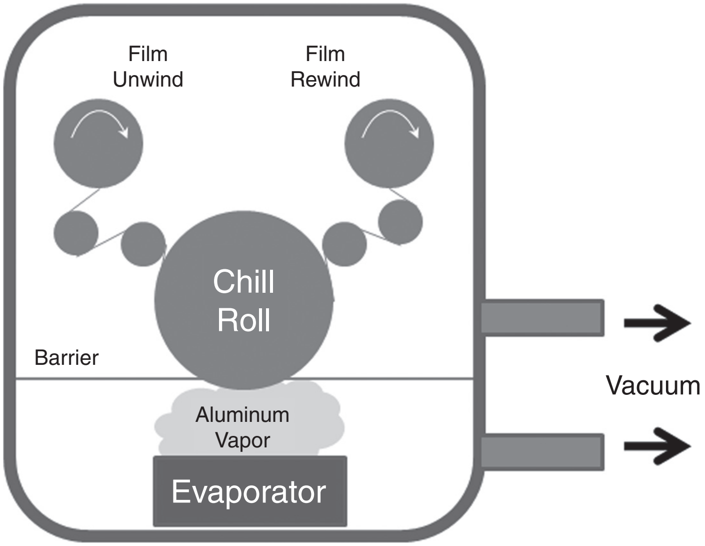


Figure 4.35. Vapor Deposition Metallization Process

Film Metallization

Metallization is the process of applying an extremely thin (ca. 3–10 nm) layer of aluminum in a vacuum evaporation process. The film is placed in a vacuum chamber and spooled through a cloud of electrically charged aluminum vapor that is attracted to and condenses on then bonds to the surface of the film as shown in Figure 4.35.

This process provides two benefits: increased barrier properties without using a laminated material, and an appealingly bright film surface that accentuates any graphics or printing. During metallization, the film may be pre-“printed” with an oil that resists adhesion of the aluminum layer to provide a pattern used in the thicker coatings in microwave susceptors. Problems with film metallization usually are a result of poor film surface condition or poor process control. Deposition may be uneven or have microscopic defects that can cause severe degradation of the barrier properties of the material. Additionally, although aluminum is a fairly stable material, it will oxidize and may change characteristics over time, particularly if there are corrosive elements in the product and if the metallization layer is not protected.

Microperforation

Microperforation causes films to become “breathable” for use with fresh and cut produce containers as well as bread bags and even some types of breathable rainwear. The perforations must be small enough to keep water droplets from penetrating via the droplets’ surface tension but large enough so that gasses and water vapor may be exchanged. Hole sizes using mechanical puncturing systems, laser, or electrostatic discharge equipment may range from 2 to 150 μm (or larger). Gas exchange rates may increase in practical applications by at least an order of magnitude (to more than 1,000 cc/100 in^2-day) to that approximating porous materials such as paper, but retaining waterproof characteristics so that liquids in the product are not lost or spilled. Additionally, some preferential gas transfer may be achieved with CO_2 being retained and oxygen transmission rates being much higher.

Extrusion Blow Molding

Extrusion blow molding of rigid and semi-rigid containers is an extension of tubing extrusion and resembles the manufacture of glass containers in several respects. Blow-molded containers begin as parisons that are extruded as molten tubing that is placed into a mold and inflated. Contact with the coolant chilled surfaces of the die cools the inflated parison and locks the plastic into shape. Extrusion blow-molded containers are common in food and household chemical products, and nearly all plastic dairy containers are manufactured in this manner. Size limitations on blow-molded structures have increased steadily, so it is currently possible to blow mold drums and tanks, as well as boats and vehicle parts. In practical terms, consumer-level packaging is most often limited to large containers of detergent and other household chemicals.

Because of advances in extrusion technology, it is possible to extrude a multilayer parison to incorporate recycled or filler materials, or to incorporate a barrier layer to extend shelf life. Blow-molded bottles, particularly those of polyesters such as PET, are very often layered with an oxygen barrier layer (often polyvinyl alcohol) to reduce discoloration of the surface layer of product that may make the container appear to have been spoiled. A variation on the co-extrusion strategy has allowed container manufacturers to *stripe* the parison – and thus the container – with a line of uncolored resin, producing a container with a visible fill-level indicator that is often used for household and automotive products.

Because of the extension of materials into the far crevices of a mold, it is often necessary to control the thickness of the parison tube via a variable extrusion die to produce a *programmed* parison. This allows the areas that require more resin to extend the molding farther into the mold to be sufficiently supplied.

Injection Blow Molding and Stretch Blow Molding

Injection blow molding resembles glass molding practices in that an injection-molded preform is produced and then inflated, often in a separate step that reheats the original molding as previously described. The advantage offered by this method is most apparent during *stretch blow* molding when the polymer structure is subjected to severe cold-drawing orientation by rapidly inflating the reheated preform. This produces a container that has both an accurately manufactured finish and is highly oriented, resulting in a very-high-barrier package with very good optical properties. It is possible to produce multilayer stretch blow molding using a carefully injection-molded preform, which allows the manufacture of highly accurate high-volume containers as well as those with non-spherical geometries while keeping wall thicknesses intact.

The ability to produce a practical and economical alternative to glass containers has driven both the food and soft-drink industry into using of these containers for their products, and has created the capacity for even small bottlers to manufacture oriented bottles from commercially produced preforms using specialized machinery. One of the hidden benefits of these types of containers is that when failure occurs, they do not disintegrate into a large number of dangerous splintered pieces, the way glass does. This not only provides a lighter and more economical container, but relieves concern (and costs) associated with consumer liability issues. Additionally, the recouped downtime on filling lines has proven to be a bonus. When filling lines are converted to plastic bottles and jars, the need to stop the line and clean a large portion of it out of fear of glass fragment contaminants is eliminated, allowing more continuous production and higher plant efficiencies. This is particularly pressing in the food industry where fears of contamination from broken glass, and the downtime incurred from cleaning up on-line breakage, have driven a widespread industry movement toward plastic containers in many market segments, particularly baby foods.

Surface Treatments of Blow-Molded Containers

The continuing search for low-cost ways to produce a high-barrier container have led to several ways of surface treatment of containers that have shown sufficient commercial potential that their adoption has been growing. Fluorination is a process by which polyolefin containers are subjected to concentrated fluorine gas, which displaces the C-H bonds and generates a C-F structure that approximates polytetrafluoroethylene (Teflon®) at least at the surface level of the material. This in turn creates a high gas barrier layer that can extend the shelf life of products or reduce volatile losses. Because of the toxicity of fluorination, this process is usually contracted through dedicated providers.

Diamond and Silicone Microcoatings

Microcoatings of impermeable materials have been under investigation for some time and work well, but are limited by production speeds in some instances. Coating is done by Plasma Enhanced Chemical Vapor Deposition (PECVD) of oxidized silane or ethane compounds to provide a crystalline carbon or silicone coating. The prospect of a diamond-studded bottle may be appealing, but the layers are typically only a few μm thick and are transparent, although they provide substantially reduced gas and vapor transmission rates and reduced off-flavor and off-odor contamination when used inside the container.

Injection Molding

Injection molding is used to produce precise components that cannot be formed by thermoforming or blow molding. In injection molding, melted resin is forced from the melter/extruder into the mold through a *sprue* and then through runners into the individual mold cavities, as shown in Figure 4.36. Considering that production tooling for injection molding can be very expensive

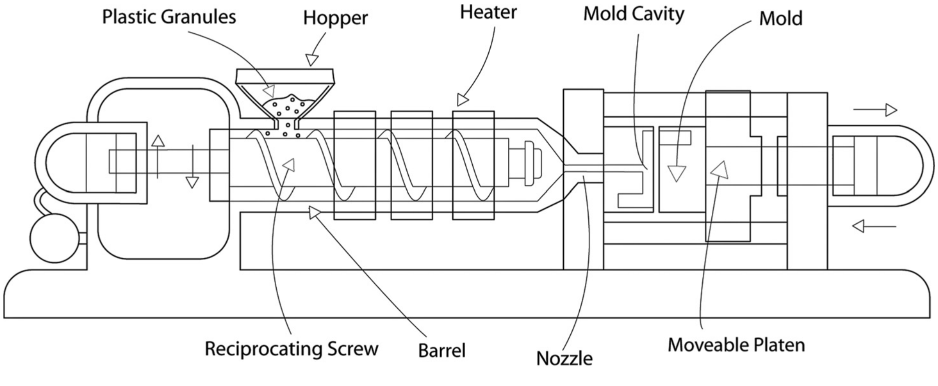


Figure 4.36. Extrusion Injection Molder

and cycle time is at a premium, the molds may be designed to do many simultaneous moldings at once. Dimensional tolerances as well as temperature control requirements are usually exacting in injection molding. For small moldings such as beverage bottle screw caps, a hundred or more caps may be produced in a single cycle, whereas for very large moldings such as tubs and pails, there may be only one molding per cycle, although the molds may be mounted on rotating fixtures to keep the injection equipment moving at full capacity. Very large moldings such as plastic furniture and vehicle parts may require specialized molding machinery and enormous resin reservoirs to manage each "shot."

Rotational Molding

Rotational molding is mostly used for very large and hollow or open structures and operates by tumbling the mold to distribute a thin layer of resin over the interior surface of the cavity. Because there is no interior male component to the molding process, the interior surface remains distinctively unfinished. A variation on the process uses centrifugal force to assist resin distribution during injection molding. Tooling is generally less expensive than for many other types of molding, but good resin distribution during the molding process can require some refinement. This method is also used for other types of specialized molding such as hollow chocolate figures.

Thermoforming

Thermoforming is often used to produce trays and bowls for the food packaging industry, as well as many types of blisters for card-backed packaging and many household and vehicular items. It has been used since the 1930s to form optically clear aircraft canopies from acrylic sheet, although these methods used heated fluid to soften and force acrylic against a mold. The current radiant heat and vacuum system did not appear until 1940 and has been adapted to manufacture many different types of thin-wall structures ever since.

Thermoforming processes, which are simple enough to be often used by hobbyists to form parts and by industrial designers to form prototypes, consists of heating plastic sheeting – most often with radiant heat from gas, infrared, or resistance heaters on one or both sides – draping a mold with the softened sheet, and using a combination of pressure, vacuum, and mechanical assist, as appropriate, to form the film to the contours of the mold. In all cases, the pressure differential – whether mechanical, pneumatic, or hydraulic – forces the sheet to form to the desired shape and with the desired wall thickness.

Packaging applications of thermoforming are typically used for trays, bowls, and blister covers that are used for display packaging, internal supports for consumer electronics, containers for frozen and shelf-stable foods, and as aftermarket food storage containers. Thermoforming containers for food items such as frozen dinners and dairy products are very often done in-house using externally supplied sheet and film stock. In many instances, food items are filled into trays that are formed on line from rolled sheet stock, and then are sealed with film or lidded with a similarly molded cover and trimmed in subsequent steps before retorting or freezing. This has the effect of efficiently compacting an entire forming, filling, and sealing line for relatively complex menu items into a small area, and minimizing the amount of packaging material stored by doing conversions in process. It is easily adapted to changes in tray design and product by changing the dies used in the molding step.

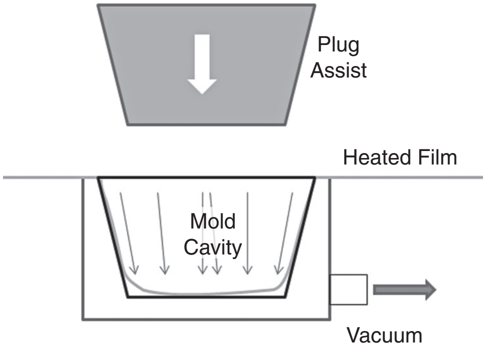


Figure 4.37. Simple Thermoforming Cavity with Plug Assist

Beyond this, there are several different types of thermoforming that are used for different types of plastics. Conventional thermoforming, previously described, forms materials in the melt phase at higher temperatures, but this type of forming makes materials such as polypropylene hard to manage because of the relatively small temperature window and a tendency for poor thickness distribution. In response to this, Solid Phase Pressure Forming was developed, which forces the molding into shape at a temperature below the melt phase but above temperatures approximating its glass transition point. This requires both good mechanical molds with smooth surfaces and careful control of the temperatures (154–158°C for solid-phase molding of a clarified polypropylene homopolymer, as compared to higher temperatures for melt-phase conventional thermoforming) in the molding machinery, as well as usually requiring plug-assist in making the final moldings. The result of this is to allow polypropylene and other materials to be accurately molded using thermoform equipment with good optical qualities and thickness distributions.

As shown in Figure 4.37, thermoforming is conceptually simple, and the molding forms can be built of low-temperature materials such as wood or plastic, if necessary. To control the wall thickness distribution, however, some care must be taken with the mold design to ensure that the plastic sheet or film is not overextended by drawing it too deeply for the method used. This may result in a molding that, although not torn, will be too weak to be useful. Additionally, as with nearly any non-sectional mold, there must be enough draft in the mold design that the finished piece can be easily extracted. Reversing the vacuum with a burst of air pressure may help extract the moldings.

Synthetic Papers

Synthetic papers generally fall into two classes: printing film and *tearproof paper*. Printing film is a thermally stable film that is coated with a stable surface that resembles paper and may be used in thermal printing systems such as laser printers without melting. These are typically used for weatherproof labels, documents, and maps and do not currently have many packaging applications, although they may be used for tagging and labeling machinery and electrical equipment.

Tearproof papers (such as Tyvek®, a high-density PE fiber structure) are actually a non-woven fabric and are typically manufactured from polyethylene, polypropylene, polystyrene, or polyester fibers, which provides the desired flexibility and strength, and that are then formed into non-woven sheets. These provide a very strong, stable structure that resembles paper but is dimensionally stable, resists boiling water, and can be fabricated to be porous enough for gas sterilization while preventing microbial recontamination. Other forms are used as structural vapor barriers, shipping envelopes for overnight delivery services, containers for sharp objects, sailmaking, and other specialty applications that require a very strong, flexible material. Cost considerations are still preventing the use of many of these materials as a replacement for more traditional pouch papers, but the cost is often justified in specialty applications such as boil-in bags and single-pack coffee filters.

Multiple Material Packages

Laminates and Multiple Material Packages

Although the term "Composite Material" conjures up images of aerospace applications involving expensive high-tensile fiber laminations, composite materials have been used for many years in the packaging industry. Often, several materials will be combined to provide a mix of contributions that can be carefully fitted to the most optimal physical and economic properties to suit the particular product application.

There is a distinction between coatings and laminations, in that laminations usually involve the adhesive joining of several (often very different) materials ranging from metallic films to cloth. Although it may be possible to coat paper with a polymer film so that the net effect would be similar to laminating the two materials, it would be impossible to coat paper with aluminum and then with a layer of polymer film on top to protect the foil. Unfortunately, as recycling of materials becomes more and more of an issue, the multiple-material nature of composites may work to their disadvantage because they cannot readily be decomposed into their constituent parts for separate recycling.

Lamination Processes

The simplest lamination processes are those that simply glue two or more layers of material together using an adhesive. This may be done in several ways: either using a contact adhesive that is first applied to each of the layers then dried prior to lamination, or using a liquid adhesive that sets fully after the lamination process. Additionally, a polymer melt may be used as a lamination adhesive, with an extrusion device feeding molten adhesive between layers in the lamination process. Simple glue processes have the advantage of being able to use simple equipment for small runs of materials, but have the disadvantage of requiring water, organic solvent removal or glue polymerization at some point in the manufacture of the laminate. Contact adhesives often require solvent removal during coating, which adds to the complexity of the process, and glues that adhere by solvent removal or polymerization may require time for the proper bonding to be established.

Thermal lamination may rely on heat and pressure to laminate materials together, most often using a thermally activated adhesive *tie layer* to adhere the layers together. This has the advantage of not requiring solvent removal in the lamination step, and providing a nearly instant high-tack bond in the materials. It is not always necessary to have a tie layer if the final effect is to bond a layer of a low-melting-point polymer to the surface of a substrate, but most often, a tie layer has a lower melting point than the laminate materials to reduce thermal distortion in the final materials. For materials such as foil, a bonding layer is necessary, and many foil types require a great deal of care in handling to reduce problems with holing and tearing.

Design Considerations for Laminates

Materials Structures

Laminates can be assembled from many types of materials depending on the requirements of the product. Most types of laminates used for pouches and bags are designed with five basic and somewhat subjective functions in mind: cost, strength, appearance, barrier, and sealability.

Cost optimization of materials is the broader intent of most packaging laminates, so careful attention must be paid to the overall costs of the materials and how well they can integrate into the overall packaging system. False economies occur when a lower-priced material is substituted for the originally specified one if it costs the packaging operation more in defective products, sales losses, or production downtime. Using a spreadsheet, one can construct a simple model for the initial optimization of laminates that considers both the costs of each material and the properties provided by each layer. The consideration of barrier will add to the complexity of this, and will demand a *Pareto optimal* solution – one that balances both strength and barrier when considering the final value of the material – but the solution methods are still quite simple. As with many types of composite materials, it will be necessary to evaluate prototypes of the materials to ensure that their values are as predicted, because the diverse mechanical and barrier characteristics can interact in unusual ways. Strength in simple food product packaging applications has traditionally come from a paper layer, most often a bleached kraft pouch paper, although the current trend in newer types of consumer products are to replace this with a high-strength materials such as polyester to improve the surface appearance when design copy is reverse-printed inside the lamination. It must be remembered that each of the layers in a laminate will contribute something to the overall mechanical strength of the material, so a packaging material that has a critical stress higher or lower than necessary can be modified to adapt to the requirements at hand, but this should be done as a last step when the other functions – particularly barrier properties – are satisfied.

Appearance can be a very subjective term. In the case of a dry-ingredients pouch that is included in a boxed dinner mix, the appearance requirements can be quite minimal, but for newer types of consumer products such as snack foods and retort pouches, it may be necessary to provide an appearance that not only distinguishes it from other similar products, but will overshadow the competition in more traditional types of packaging. Many new types of packages are being produced that take advantage of the bright appearance possible when laminates are printed on the reverse side of the outer layer of film (so that the copy shows through the clear layer), as well as metalized films that add a bright, reflective layer to the package. Other types of surface features such as a microembossed holographic image or clear window can be included in these types of packages, often to good effect.

Barrier characteristics depend on the type of materials used as well as their synergistic interactions. Aluminum foils below 0.001 in. thick with a simple polyethylene film will decrease permeability markedly. Thus, the addition of an extremely fine layer of foil will create an enormous increase in barrier characteristics. Similarly, the combination of several layers of polymer with or without other materials can be tailored to create barrier characteristics that are specifically suited to an application, although this often requires that the prototype material is evaluated because the synergistic effects of lamination and the effect of the adhesive *tie layers* can be difficult to predict with a high degree of accuracy.

In addition to the traditional passive barriers afforded by more traditional materials, it is possible to include *active* materials in laminates, such as an oxygen-scavenging layer, to provide a proactive removal of harmful materials from the product. These types of materials are seeing more use in pouches, composite cans, and other laminate structures.

Sealability of laminates, in this case referring to heat sealing, can be a complex issue when the design requires very-high-speed manufacture or the inclusion of unusual materials. Because there is very little process optimization in sealing processes, with most adjustments being done on a guesswork basis, it can be difficult to predict exact sealing parameters for a single material that may come from several suppliers and be run on many different machines in diverse manufacturing locations. In most cases, an ad hoc knowledge of the sealing requirements is used to specify a layer of sealing material that is adequate, if not optimal. The thermal conductivity of the layers will play an important part in the sealability of the laminates as well, and if one of the internal laminates has a particularly low melting point, it may be problematic in that the pressure of the sealing jaws may cause partial delamination of the film due to melting and cohesive failure near the seal area. Sealability of laminates that use cold or contact adhesives is a much simpler issue provided that the adhesive does not interact with the polymer and has not caused changes in the film during application. Package sealing will be dealt with more comprehensively in Chapter 5.

Multiple Morphology Laminates

The problem with separation of multiple-material laminates for recycling has highlighted an intriguing possibility in laminated polymer films – that of multiple morphology laminates. It is possible to produce a film (polyethylene, for example) that is highly oriented for strength and barrier and another polyethylene film that is largely amorphous for sealability. Combining these materials will a structure that will yield a good mix of characteristics in a structure that can be considered as a single material, and is readily recycled, but that might previously have required effectively unrecyclable sets of different laminated materials.

Laminates for Aseptic Processing

Laminates that are used in aseptic processing operations must both maintain the microbial integrity of the package after formation and filling. These typically have separate layers for strength, barrier, and heat sealing, although it is possible to produce them with fewer. A typical juice box package is usually made of coated or laminated paper, foil, and a heat-sealable inner plastic layer. Many aseptic packages are supplied in ready-to-erect form and are assembled and sterilized as part of the aseptic processing. It is also possible to use simple laminates as part of a form-fill-seal system in the aseptic process, as has been done with many of the early aseptic packaging systems. Other laminates are used as tray and lidding stocks in aseptic filling operations and may be sterilized by radiation, hydrogen peroxide, or ultraviolet light prior to final sealing in an integrated filling-and-sealing line that operates under sterile conditions, as described in Chapter 6.

Laminate and Composite Cans

Composite cans have been a feature of food packaging almost from the beginning, used for dry goods as well as moist products in later years. The ubiquitous oatmeal package is a composite can that has been laminated from paper, although many different types of composites are possible. Multiple layers of paper, foil, plastic film, and even foam are possible, with the structure optimized for the properties required for the product. Composite cans are manufactured by spooling materials onto a cylindrical mandrel in a continuous spiral, so that the formed laminate tube is then cut and fed off the end of mandrel on a continuous basis, allowing for a relatively high-speed production and the absence of a distinct side seam. Convolute cans are formed in a similar manner, with the materials being wound perpendicular to a forming mandrel that rotates in alternating directions to form a layered, seamed can body – this type of equipment must stop forming long enough for the formed blanks to be removed from the mandrel before reforming the next set of materials, which results in lower production speeds.

Composite cans may be produced in any number of geometries ranging from cylindrical to nearly polygonal – slightly rounded corners are a necessary result of the fabrication process – and can be capped at either end with metal, plastic, or paper seals, dispensers, and other types of fitments used to dispense product.

Two-piece cans made from thin aluminum sheet laminated on both sides with PET film have emerged in Japan and Europe in recent years. These have been commercialized most widely in Japan under the names of HiRetoflex® and TULC®, for small trays and beverage cans, respectively. A similar material, Ferrolite®, developed jointly by Carnaud Metalbox and British Steel, is also used in Europe.

Rigid Composite Tubes

Rigid composite tubes are seldom used in the food industry but are quite common for use with construction adhesives and sealants, as well as many other industrial materials. These may be made of rolled paper with or without foil and paper layers in a manner similar to “paper” cans, and incorporate a piston on one end to mate with a dispensing gun that pushes the product out and a molded nozzle on the other. Traditional composite tubes have a membrane seal fitted behind the nozzle that must be punctured before use, whereas molded plastic tubes have sufficient integrity that they are well sealed until the tip of the nozzle is cut off. Current industry trends are toward single-piece tubes of molded plastic because of durability, simplicity, and cost.

Composite Squeeze Tubes

Because of the difficulty of labeling metal tubes, and their tendency to remain wrinkled and crack in everyday use, the development of molded composite tubes has resulted in tubes that are more durable and in many cases can have a great deal of graphic appeal. These are used for frostings, spices, and pastes in the United States, but their use is much larger in Europe and Asia and includes tomato products, chocolates, butter, and sour cream, among other applications. Two-piece plastic and composite tubes are produced by first making the tube that will become the tube body – for a plastic tube, this may be manufactured directly by single or multilayer extrusion. After this, the tube head and shoulder is molded to the body either by heat sealing a preformed molding to the body tube or by compression molding or extrusion molding to the tube. The head and shoulder molding will typically have the complete shoulder, the threaded closure, and orifice. For single-piece tubes, such as those used for cake frosting and construction glues and sealants, the entire structure may be injection-molded in a single injection-molding step. After molding, the tube is printed, usually by offset printing, and has the cap applied before shipping to the filler. When plastic or composite squeeze tubes are filled, the ends are typically heat-sealed rather than being rolled and crimped as with metal tubes, and a date or production code may be incorporated into the sealing machinery.

Endnotes

* The portability and ease of use of paint in tubes also changed the face of art itself, allowing "plein air" (outdoor) painting to flourish among the impressionist and landscape painters of the late 1800s. Previous to this development, any outdoor paintings were typically painted from memory or sketches in part due to the difficulty of handling the pigments and oils and mixing them in the field.

** A Pareto optimal solution is, in the most general terms, a "best mix" solution that provides the most benefits at the lowest cost for all concerned, and cannot be improved in one measure without penalizing another. It is named for Vilfredo Pareto, the Italian economist who is responsible for the 80/20 Rule: that roughly 80% of the effects come from 20% of the causes.

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Chapter 5

Secondary Packaging Components

Secondary packaging components are a somewhat arbitrary definition of devices that are added to the main structure of a package. They are typically added to provide specific functions such as closing and dispensing, communicating product information, ease of use by the consumer, or structural and esthetic enhancement. As packaging systems have developed into more proactive and complex devices, these secondary components have become more important in offering extended product quality, shelf life, and utility.

Secondary packaging components became a necessity the moment that prehistoric people noticed that their gourds and pottery flasks would leak unless they were closed up somehow, and that leaves wrapped around food would spring open unless pinned with a twig. Package closures – the devices that both seal and allow consumer access to the product – are thus arguably the oldest added component in packaging.

Closures

Closures have been made from natural materials since the earliest times. Carved wooden bungs in barrels and natural corks in wines and spirits still exist in this vein, but for most mass-produced applications these have been replaced with closures that are more highly engineered and offer greater functionality. Threaded closures were available on Mason glass jars, patented by John Mason in 1858, from the middle of the 1800s onward, and depended on a shallow thread on the glass jar molded in a multipart mold. This then required a matching, threaded ring with a gasketed plate to form a two-piece lid that is still manufactured for home canning and is used for some commercial products to reinforce a "homemade" image.

The first highly engineered package closure designed for high-speed assembly was arguably the crown cap by William Painter, who patented the design in 1892. This was novel in that it relied on a seal that was formed by bending the edges over the edge bead of the finish on a narrow-neck glass bottle using a pressure die. Previous cap designs relied on a secondary fastening device, usually a strand of wire, to hold the cap in place, and the advent of the crown cap that had a sealing gasket and could be applied at relatively high speeds assisted in the mass production of bottled goods. Neither of these inventions was a particularly precise solution to the sealing problem, and both depended on a gasket material to complete the seal. Twist-off variations of the crown cap were attempted almost immediately after their introduction and finally became widely implemented in the 1970s, although their use is sometimes avoided by bottlers trying to maintain a non-mainstream market image.

As moldable polymers became available, thermoset and then thermoplastic compounds were used to produce threaded closures – one of the few remaining applications of traditional

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thermoset polymers in packaging, although these still relied on an internal liner to complete the seal with the container. With the development of tough thermoplastic compounds, particularly polypropylene, closures began to be responsible for more and more package functionality as these materials would resist repeated opening and flexing of dispenser cap covers without fracturing. These materials also have allowed the development of *linerless* closures that rely on molded sealing ridges in the interior of the cap that compress against the container finish to provide a seal.

Caps

Caps may still be pre-fabricated of stamped metal, but with the exception of the crown closure and large, lug-finish lids for thick products like jams and spreads, many of these markets have largely been given over to molded plastic closures. An exception are rolled-on metal caps supplied as an unthreaded, cup-shaped blank fitted with a liner, which is formed over the finish on the container using rolling dies that use the threads on the container as part of the forming process. These are predominantly used for glass containers, particularly wine and spirits, and have begun to replace corks in the wine market because of their inertness and lack of contaminants, though they still carry a déclassé image with many consumers, despite their better performance.

Thread Profile

Because of the ductile nature of plastic closures, the thread profile for finishes on plastic materials may be different than traditional thread profiles for glass and metal containers. These threads are designed to minimize distortion due to viscoelastic creep of the material, and have mating flat faces between the container thread and the threads on the closure. Use of these types of threaded closures with containers, particularly glass jars and bottles, with the older style of thread will result in cap jamming or premature loosening and leakage. Traditional containers can be specified with a modified thread profile to accommodate the new cap types.

Liners

Liners, when used, are typically composed of two components: a backing, which is made of a compressible, elastic, or viscoelastic material; and a facing that contacts both the product and the sealing edge of the package finish. Facing material must be compatible with the product and must provide the necessary degree of protection against permeation and leakage, because with a metal cap and glass bottle, it is the only path for oxygen or other material to affect the product. Some beer manufacturers have incorporated oxygen scavengers into their crown cap liners because of this. Additionally, since lined caps are often threaded on, the facing must resist tearing or distortion as it rotates onto the finish, although secondary lubricants may be used for this purpose.

Torque loss – the reduction of force needed to unscrew a closure – may occur as the backing material is over-compressed, or exhibits creep or viscoelastic flow over time, and can result in the loss or contamination of product. Generally, torque loss tests are done after conditioning under standard conditions using ASTM D2063 or D3198 protocols or their equivalent, but it may be necessary to do field studies of the post-distribution containers to develop an accurate picture of whether the closures are sealing properly or not.

Child-Resistant Packaging

Child-resistant packaging, which was required for many types of products after Congress passed the Poison Prevention Packaging Act in 1970, relies heavily on specialized closures. The act requires child-resistant (CR) packaging of any household substance that may cause serious injury to children if handled, used, or ingested. Such packaging must be difficult for children under the age of five to open while (contrary to many opinions) still being accessible to adults.

Some substances included in 16 CFR 1700.14 & 1700.20 are: acetaminophen, ibuprofen, prescription and controlled drugs, as well as non-ingested household products such as paint solvents, furniture polish, and certain glue removers. The test protocol to establish a closure as child resistant is rather involved and leads to a limited number of types in production. The protocol requires that 200 children between the ages of 42 and 51 months, working in pairs, are allowed five minutes to open a package. For those who cannot open it the first time, a single non-verbal demonstration is given and they are allowed another five minutes. Effectiveness must be 85% without demonstration and 80% after a demonstration, with a separate adult test having a 90% or better success rate.

Some controversy has occurred with CR packaging as a result of general frustration with difficult-to-open packages, and because handicapped and elderly customers – particularly those with arthritis – often may not be able to open packages of critical medicines. To adapt to this challenge, pharmacies have adopted flip closures that can be either child-proof or not at the discretion of the customer, and manufacturers have begun to include closures with fins or textured surfaces that may be more easily opened by customers with limited manual dexterity.

Glues and Adhesives

Glues and adhesives are typically used as a means of fixing materials together, either as a means of package construction or to attach a feature or product. By definition, glues are derived from natural sources, such as milk or cow hides. Adhesives are based on polymers that are chemically synthesized, but most people use the terms glue and adhesive equivalently, although the distinction may be important in technical standards and specifications.

Simple glues such as waxes, resins, hide glues, and casein (milk protein) based adhesives have been found in many archaeological sites, and recipes for making and using them are mentioned in Greek, Arabic, and Roman texts. Many of these basic types of glue still exist but have been supplemented or superseded by newer adhesive formulations that include synthetic polymers and additives that allow more careful control of properties and retard the aging of the bond. The earliest casein adhesives, manufactured by extracting milk protein from skimmed milk by heat and vinegar, are still available as the "white glue" that is often used for school projects and woodworking, and hide glues rendered from rendered animal bones and hides are still used for the assembly of furniture and musical instruments.

Newer adhesive technology has been driven by the need to bond surfaces without mechanical fasteners in industries such as aerospace structures, automobile assembly, and surface-mount electronics. This has prompted a new generation of bonding methods, some of which have been cost-effective enough to find applications in packaging.

The Role of Surface Chemistry in Adhesion and Printing

Substrate compatibility is a fundamental requirement for any type of printing, coating, or adhesive application, because the ink, coating, or adhesive must bond to the substrate's surface

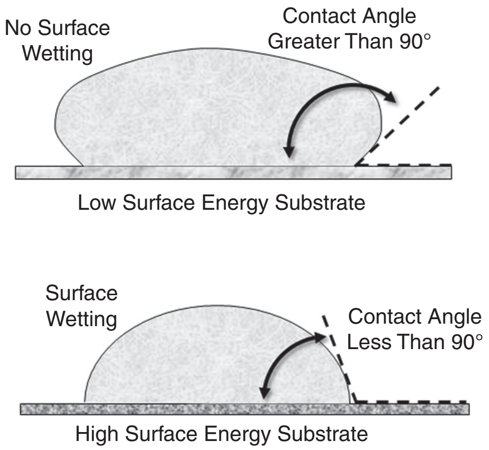

Figure 5.1. Contact Angle and Wetting

in order for the process to be successful. For porous materials, often this is less of an issue than for plastic films that may exhibit a poor match of surface characteristics with the ink, coating, or adhesive. Polyolefins such as polyethylene and polypropylene have traditionally been challenging materials to work with in all types of surface material adhesion applications and usually require surface treatment in order to raise the surface energy of the material enough to overcome the surface tension of the liquid being applied.

This can be illustrated by the concept of *Wetting*, as shown in Figure 5.1. If the contact angle is oblique, the surface energy of the substrate is a good deal less than the surface tension of the liquid, and wetting and adhesion will be very difficult – a principle exploited in car wax and other repellant coatings. On the other hand, if the contact angle is acute, it is an indication that the surface energy is sufficiently larger than the substrate (usually by about 10 dynes/cm). As the contact angle approaches 0°, it is an indication of complete wetting.

To affect the surface energy of films, many treatments may be used, but the two most common are flame ionization and corona discharge treatment. These processes use an open flame or high-voltage discharge, respectively, to achieve this, and each has advantages and disadvantages depending on the material and process. For example, using a thin, flammable film with flame ionization would present a combustion hazard, but corona discharge equipment may create spark-path pinholes in the material in a similar manner to the microperforated films mentioned in Chapter 4.

Both of these methods use a high-energy source to create ionized particles that will partially disrupt surface bonds in the material and create a degree of oxidation and cross-linking that changes the surface chemistry to facilitate improved surface wetting and adhesion. Both treatment effects will dissipate over time as well, so many operations will treat the materials just before use, or have an effective “expiration” date on materials that are treated by contracting suppliers.

Adhesives Terminology

Pot Life: The length of time that a particular adhesive can remain workable. Some adhesives are kept in operating machinery for long periods of time and may degrade due to heat and oxidation.

Open Time: The amounts of time that adhesive bonding surfaces can remain out of contact with one another before a bond will no longer form.

Tack: An initial low-strength bond that is formed upon immediate contact. This is an especially important property in the packaging industry, because high-speed operations require application of a particular component and almost immediate removal of application force.

Hot Tack: The term used for hot-melt adhesives to describe the bonding ability of adhesives that have been applied but have not completely cooled. *Tack agents* are often added to promote this.

Cure: Final forming of a high-strength bond. Cure time is also important in packaging, because packages are often placed in service very quickly after manufacture. In systems where packages are assembled in one operation then used in another, the shipping time between the two operations may be used as curing time for the adhesives used.

Adhesion: A state in which two surfaces are held together by interfacial forces that may consist of valence forces, molecular bonding, or interlocking action.

Mechanical Adhesion: Adhesion between surfaces via interlocking action of fibers, structural features, or adsorbed adhesive components that solidify after joining.

Types of Adhesives

Naturally Derived Adhesives

Naturally derived adhesives are, as previously mentioned, derived from waxes, resins, gums or protein compounds that are subsequently modified to promote stable bonding properties. Although waxes are seldom used except in decorative applications, modified gum structures are quite common.

Starch- and Dextrin-Based Adhesives

Starch, modified starch, and dextrin (an intermediate polysaccharide compound resulting from the hydrolysis of starch to maltose by amylase enzymes [1]) are some of the earliest and still most common packaging adhesives in use. The source of the basic high-quality starches used in adhesives will vary by country (and crop subsidy program), with cornstarch being most common in the United States and potato, wheat, and rice starches most often used in Europe and Asia. Globally, unusual sources of starch such as sago, tapioca, or cassava may be used depending on availability and price [2]. Starch and dextrin adhesives offer the advantages of both high availability and relatively low cost and good adhesion, particularly to porous substrates. Additionally they are non-toxic, biodegradable, and resist heat, oils, and fats, which make them ideal for use with many food products.

Starch suspensions in water do not exhibit useful adhesive properties, so cooked raw starch is seldom used directly as an adhesive in favor of a smaller-chain compounds resulting from acid hydrolysis and modification that produces a more carefully controlled and often thinner starch compound or dextrin, depending on the degree of conversion. Nanoscale starch compounds have shown some applicability as a stable form of raw starch and as a challenger for latex and other laminating adhesives [3].

Starches are composed of two basic molecules, amylose and amylopectin, both with long polysaccharide structures, with amylose typically representing approximately 25% of the total. Amylose is a series of long linear chain structure, whereas amylopectin exhibits a high degree of branching, and only amylopectin is cold-water soluble without further modification. Amylose can be modified by cooking at higher temperatures (typically above 150°F/66°C) in water or water-formaldehyde solutions, or by modification with alkali. This will produce a dispersion that will form a firm gel at concentrations above 2% and a precipitate below that. Amylose gels are prone to *retrogradation*, the formation of a more highly aligned molecular structure that is accompanied by an increase in viscosity and water expulsion, whereas amylopectin is more soluble and less prone to these changes.

Starch adhesives are manufactured by heating starch in water with either caustic soda or metallic chlorides until gelation – the rupturing of naturally occurring starch granules – occurs, forming a colloidal paste of unmodified starch. If the caustic soda method is used, the adhesive is later acid-neutralized. Starch adhesive viscosity varies markedly with concentration and will cause pumping to become impractical above concentrations of approximately 5–8% and impossible as the unmodified starch becomes a solid with higher concentrations.

Modified starches are treated to resist retrogradation and the previously mentioned viscosity problems, making them more suitable for adhesives use. These treatments include alkali treatment and acid modification to change gelation temperature and viscosity, respectively, and hypochlorite-based oxidation that will produce a high-tack adhesive that is used for both adhesives and paper-sizing additives.

Dextrin-based adhesives are manufactured by heat-treating starch with acid to produce a high-solubility branched polymer with good water solubility. The degree of processing can control the extent of conversion and therefore the stability, viscosity, and strength. The three major classifications of dextrin adhesives are white dextrins, yellow dextrins, and British gums, in order of increasing processing temperature and duration, as well as increasing molecular weight, darkness of color, stability, and resistance to retrogradation [4]. British gums are commonly used for high-strength applications such as shipping tapes, whereas the lower molecular weight white and yellow dextrins are often used for gummed papers and envelopes. Additives and modifiers of starch- and dextrin-based adhesives may be added to affect tack, viscosity, brittleness, drying time, and wetting/rewetting properties.

Jelly Gum Adhesives

Jelly gums are formulated by cooking cohesive starches such as cornstarch in alkali, which produces an elastic gel adhesive that is resistant to immersion in cold water and is thus used in many glass beverage container labeling applications. Problems with these labeling applications on glass containers may arise from interaction with the *cold coating* on the glass discussed in Chapter 4, and are often the result of residual coating interfering with the adhesion of the label adhesive. Other uses may include attaching coupons to packages, inclusion of pages in printed materials, and the attachment of cards and flyers in mailing operations.

Other Gum Adhesives

Nearly any plant or microorganism that can exude or otherwise generate a viscous substance has been examined as a source for adhesives. Some of these, such as gum arabic, guar gum, and xanthan gum, are familiar as food-thickening agents, but there are many plant and microbiologically based gums that are available and may be used. In current uses, the naturally occurring gum components are often used as adjuncts to synthetic adhesives to act as property modifiers or extenders, and some are used for non-packaging applications such as denture adhesives.

Bone, Hide, and Fish Glues

These are based on a water solution of gelled collagen derived from animal (usually beef) hides and bones or cod bones and skin. Fish glues are seldom used in applications other than photoengraving, but hide glues are still used both in assembly operations, such as instrument making and bookbinding, and in some limited applications in packaging. Because of the limited pot life and inferior resistance to moisture, the applications are somewhat limited but are included because of their historical impact and potential for specific, niche applications. Additionally, concerns about BSE prions being transmitted from these base materials, as well as the occasional concern about animal products upsetting some customers have curtailed their use.

To recover the collagen from hides or skins, the raw materials (usually taken from meat- or fish-processing plants) are soaked, then treated with weak acid, and finally boiled several times to extract the collagen as *glue liquor* in the final boiling step. The resultant gel is treated to remove impurities and may be evaporated to increase thickness. Bone glues are produced in a similar manner with the exception of a treatment with acid to remove the mineral components of the bones, leaving only the bone proteins for further processing.

Casein (“White”) Glue

Casein glue, commonly known as “white glue” because of its color or “school glue” because it is often used for craft and woodworking projects, is manufactured by precipitating milk casein proteins from milk as a curd using acids, and then neutralizing the acidity to produce a flowable casein glue. Its non-toxic nature and extreme strength for bonding porous structure has made it particularly useful for many types of bonding applications, although the unmodified adhesive may have an unacceptably long bonding time. Many “white glues” that were originally produced from milk proteins have been replaced or supplemented by water-based polyvinyl acetate (PVA) emulsions.

Synthetic Adhesives

Synthetic adhesives in general can be divided into several categories. These would include one- and two-part adhesives as well as anaerobic and moisture-curing adhesives. Although several of these are not used in the packaging industry to any extensive degree, they are mentioned because specialty applications may require their use.

Waterborne Synthetic Adhesives

An emulsion is generally defined as a colloidal mixture of two immiscible substances, and everyday examples include butter (which is a water-in-oil emulsion) and cream (which is an oil-in-water emulsion). Nearly all waterborne synthetic adhesives are emulsions, which are microscopic droplets of the adhesive polymer in water. Generally the emulsions are composed of a dispersed phase (the adhesive) in a continuous phase (water). When these adhesives are supplied as a water-based emulsion, the adhesive can be applied to a substrate, and the subsequent dehydration of the aqueous continuous “breaks” the emulsion particles open, allowing the adhesive bond to form. This has the advantage of allowing complex organic adhesives to be applied without the use of volatile organic compounds (VOC) as solvents that may present a workplace or customer health hazard. The largest part of the market for emulsion-based adhesives are variations on vinyl acetate compounds, predominantly polyvinyl acetate (PVA) and ethylene vinyl acetate (EVA), along with acrylic and styrene-butadiene (SB) latex compounds that are used in pressure-sensitive adhesives for packaging.

Some of the problems that may be encountered with emulsion-based adhesive systems include emulsion instability as the dispersed phase forms clumps or stratifies by density to the top or bottom of the emulsion, or emulsion "breaking" where the dispersed phase separates completely from the continuous phase as a result of freezing, fluid shear during pumping, contamination, or excessive heat.

Other Types of Synthetic Adhesives

Solvent-Based Adhesives: Solvent-based adhesives usually form a bond as the result of loss of a volatile organic solvent leaving behind a binding agent. Rubber cement is a surviving example of this type of adhesive, but many types that were historically used for package assembly have been replaced with lower VOC content types because of workplace regulations or concerns over solvent contamination of the product itself.

PVA (Polyvinyl Acetate Resins): These are formed by polymerization of ethylene with acetic acid and oxygen, and are commonly used as "carpenter's glue" that may be used for paper and other absorbent substrates.

Cyanoacrylate Adhesives ("Super Glue™"): Bond by action of residual moisture in surface or moisture adsorbed from the air. Many types of polymers do not bond well with these adhesives, and the difficulty in handling them makes high-speed application difficult, so they are seldom used in packaging applications.

Polyurethane: These cure on exposure to moisture as well, and are used extensively in vehicular and home assembly, but the expense and difficulty of high-speed automatic application make them unpopular for use in package assembly, although more small-device assembly with these types of adhesives means that packaging applications may be forthcoming.

Hot Melt Adhesives

Hot melt adhesives have a lineage back to the use of naturally occurring waxes to form seals on envelopes and documents. In essence, they are thermoplastic compounds that liquefy when heated, are applied to the bonding surface, and then solidify again after cooling, forming a mechanical bond with the substrate. Unlike most other types of adhesives, hot melts do not rely on a solvent system to carry the adhesive, instead, are systems of thermoplastic resins and additives (typically waxes and *tack agents*) that liquefy when heated. Because of the broad definition of a hot melt adhesive, there is a wide range of formulations available for nearly any application, but most offer the advantage of a high-speed bond and good gap filling without solvent toxicity problems. Because of their capacity to form a quick bond, they are favored for carton and package closing, and it is easily possible to tailor their formulation for a weaker bond for easy opening by the consumer. In some instances, hot melts may be used to provide a temporary bond to secure substrates for other bonding methods, or for temporary positioning bonds for stacked cartons and positioned assemblies.

Hot Melt Blends and Additives

Hot melts may be composed of many types of thermoplastic materials (and there are a few thermoset compounds as well, although they are typically used in non-packaging engineering applications). Polyethylene, EVA, acrylates, and many other compounds can be used depending on the desired properties of the adhesives. Waxes are typically added as extenders, and tack agents, which are often specialized phenolic, polyterpene, rosin, or other compounds, are meant to increase the initial hot bond of the adhesive.

Because of the heat used to liquefy and handle hot melt adhesives, and the usual practice of adding new adhesive to heated storage tanks, which dilutes but does not remove older materials, problems with polymer oxidation are a concern. Antioxidants are a means of preventing the viscosity changes, charring and discoloration, *skinning*, and loss of adhesion that may occur with long exposure to heat and oxygen in production settings.

Cold-Seal Adhesives

Cold-seal adhesives have gained both in popularity and breadth of application, and have replaced heat sealing in many applications. Most cold-seal adhesives are formulated to seal only to themselves (or a treated compatible surface), which is different than a simple pressure adhesive tape-type adhesive, and may provide for accurate bond formation and tamper evidence. Because of the nearly instant seal time (0.5 seconds, compared with several seconds for a heat seal), cold-seal adhesives dominate many sectors of the confectionary, snack, and bakery market by allowing filling machinery to run almost without consideration of bond formation time [5].

Cold-seal adhesives are usually a mix of an elastomers, natural rubber or synthetic elastomers (SBR and similar compounds), and an adhesive component, often vinyl acetate or acrylic compounds. A typical formulation may be made of 60% natural rubber latex with potassium hydroxide solution and zinc diethylcarbamate [6]. Improper formulation of adhesives may result in *blocking* – the tendency of the adhesive to randomly glue the base material together before being pressed together at the seal area. The glass transition temperatures of cold-seal and self-adhesive materials may be a consideration as well, particularly with products that are going to be subjected to low-temperature treatment, exposure, or storage. If the adhesive becomes brittle, it may fracture and cause a loss of adhesion, which can cause packages to open or tags to be lost.

Failure of Adhesives, Inks, and Coatings

Although this section is explicitly concerned with the failure of adhesives used in packaging, the same principles apply to laminations, printing inks, and coatings, all of which must adhere to one or more surfaces and will suffer similar types of failures. When considering a bond or lamination that has failed or never formed properly, it is useful to consider the underlying structure of a glued joint. In all cases, a coating or ink must bond to at least one surface, and a glue or adhesive is an intermediate layer that is used to bond two surfaces together. To accomplish this, it is necessary that the glue adhere both to the surface of each material and to maintain integrity so that it does not fragment or fracture. Failure of adhesives can be broadly grouped into two categories: adhesive and cohesive failure (Figure 5.2). Inks and coatings failures are usually adhesive failures because cohesive failure may result in surface crazing but little loss of the material. Adhesive failure, as its name suggests, is a failure to adhere to one or both surfaces, and is characterized by ink, glue, or coating remaining on one or the other surface or, in rare cases, coming loose in sheets or flakes. In simple terms, the glue bonds to itself preferentially over the surface that has failed to be attached. Cohesive failure occurs when internal strength of the adhesive is less than the strength of the bonds to the surfaces of the joined materials, and is characterized by adhesive sticking to both surfaces and occasionally crumbling into flakes or crystals as well.

The most common forms of adhesive failures stem from surface incompatibility or contamination, improper application methods, or an insufficient hold time before the bond is placed under stress, and hot melt glue joints may fail from improper dispersion or wetting of the surfaces. Cohesive failure may be more complex because the mode of glue bond formation differs among glue types, but most often points to either a quality or formulation problem with the adhesive, or curing conditions that promote a weak internal structure in the adhesive layer, such as temperature or humidity extremes.

Other Bonding Agents

Tapes

Tapes have become an increasingly important part of the industrial engineering world, as improvements in fabrication have produced tapes that are effective for both bonding and shielding in a wide variety of applications. The type of adhesive used divides the tape into two general categories: pressure-sensitive adhesive (PSA) tapes and non-pressure-sensitive tapes that are usually fabricated with a water-activated adhesive. Nearly all tapes are fabricated as wide rolls of material that is then sliced to the desired width during production.

Pressure-Sensitive Tapes

Pressure sensitive tapes may take many forms, from ultra-thin varieties for optical fabrication to thick foams for joining irregular surfaces, and are available in an enormous range of capabilities for more general manufacturing and repair. They are usually fabricated with a four-layer composition: a backing or substrate material, a primer coat to assist the adhesive in adhering to

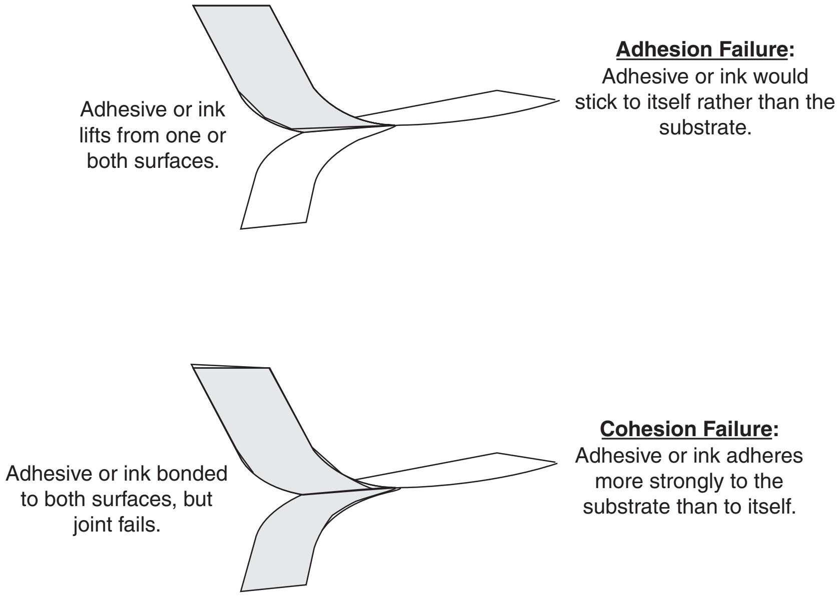

Figure 5.2. Adhesion and Cohesion Failures

the backing, and the adhesive layer itself. The fourth layer may be a release layer on the back of the tape so that the adhesive will not stick to the backing as the tape is spooled up, or it may be a separate release strip that is coated with a release layer that must be removed for the tape to be used. The adhesive layer may be made of many compounds, but historically has been made of dissolved rubber compounds, and more recently the use of acrylic and styrene modifiers as well as tack agents has increased. These newer adhesive systems have found application in cold-seal packages, discussed previously in this chapter, as well as tapes.

Tape Backing Types

Tapes are fabricated of nearly any flexible material that will accept an adhesive. Metal foils, glass fiber strands, cloth, paper, plastic film, and even wood veneers can be formed into tapes for specialized applications. Most packaging applications utilize a single or multiply plastic film, often with a reverse printing security label that indicates if the tape has been torn or tampered with. Although paper tapes continue to be produced, they have been rapidly replaced with plastic film backings because of ease of use and higher tensile strength.

Gummed Tapes

Gummed tapes have been available for as long as paper strips and water-activated glues have been available, but paper tapes with a dry glue layer date back to the early 1900s and still have uses because of their simplicity, ease of recycling, and low cost. The predominant disadvantage is that they will not stick well, if at all, to a hydrophobic surface and take a relatively long time to bond to a surface. This prevents use on most plastic packaging and many high-speed applications.

Solvent, Spin, and Friction and Ultrasonic Welding

Plastic welding includes several methods that may be used in the packaging industry to join packaging assemblies, particularly for specialized applications such as dispenser manufacture or the manufacture of unusual package types. Many of these offer a limited means of joining dissimilar polymer substrates as well. Solvent welding is the simple use of solvents to dissolve materials at their mating surfaces so that they may be joined. This method of fabrication has fallen into disuse because of problems with solvent VOC exposure both to the product and in the production facility, and long setting times, but may have specialty applications if proper ventilation and solvent-handling capabilities exist.

Spin and friction welding systems that include spin welding and vibration welding use the shear friction between two surfaces to heat and fuse structures together, providing a strong, tamper evident bond. Spin welding, a specialized version of this process, spins two circular surfaces together (such as the closure and neck of a bottle) to provide a fused joint, and can provide the method for fabricating a shell structure that could not be molded directly. Careful design of the pieces to be fabricated with correctly mating surfaces allows even relatively thin moldings to be joined into strong, appealing package designs.

Ultrasonic welding is closely related, in that it mechanically generates heat to fuse plastic materials, except that the energy is applied from a high-frequency source (usually in the 15–40 kHz range). The energy is most often directed through a contact *horn* that presses the mating plastic surfaces, and high-frequency compression then fuses the materials together.

Materials that disperse energy, such as foams or laminates with high paper content, may be hard to weld with this method, or may require the application of large amounts of power [7]. The most commonly seen use of ultrasonic welding in the packaging industry is the perimeter sealing of thermoformed packages for electronics and other high-value items. The permanent seal makes it necessary to cut the package open to remove the contents, which is intended to reduce theft (often at the expense of customer annoyance or injury).

Heat Sealing

Heat sealing using melted beeswax is one of the earliest known types of sealing, as well as one of the first tamper-evident sealing methods used for packages, documents, and liquid containers. Although waxed materials are still often sealed with heat, the development of synthetic polymers provides a more dependable material for a heat fusion joint to be used in conjunction with nearly any kind of substrate. Heat sealing can provide a permanent, hermetic seal in many types of flexible packaging, and is the preferred method for many types of films and laminates. Additionally, assembled structures such as pour spouts on pouches and complex aseptic containers are assembled with heat-sealing technology.

Heat sealing may be accomplished either by fusing the package substrate itself, as with a plastic film, or a heat seal layer or coating can be applied to a material so that the mating surfaces will fuse properly when heat is applied. There are many different types of heat-sealing machinery, but all rely on fusing either the substrate or a heat seal coating to join mating surfaces. The major types of thermal heat-sealing devices are hot-bar, impulse, and hot-wire sealing.

Hot-bar sealing, as its name implies, relies on a hot sealing bar, or bars, to compress and heat the layers to be fused. This has the advantage of faster heating of the material, but because the sealing jaws never cool, the surfaces cannot be held while the molten seal area solidifies.

Impulse sealing overcomes this by relying on a thin strip of electrically resistive material to heat the jaws once the materials are clamped. This allows the jaws to hold the surfaces together after the heating current has been turned off, so that the surfaces can be allowed to bond before being released. There is a disadvantage of a slower cycle time, but the trade-off is in more accurately formed joints. Hot-wire sealers rely on a thin, electrically heated wire to both seal and cut material, and are often used to form bags and pouches out of tubular film stock, as well as non-critical overwrapping. This last method is unlikely to provide a leak-proof, much less a hermetic, seal.

Another major type of heat sealing relies on internally generated heat to produce fused surfaces. These sealers may be induction, dielectric, or magnetic sealers depending on the type of materials to be joined and the application, but all use an electromagnetic field to generate heat either by induction currents in a metallic layer, heat from the excitation of a dielectric material, or a magnetic susceptor layer, respectively. These methods of heating are discussed more fully in the section on microwave susceptors and work in a similar manner, though at lower EMF frequencies. The advantage of this type of sealing is the ability to seal materials that are too thick or too susceptible to heat to use conventional methods. The most common example is the tamper-indicating seal under caps of food and household items. This is supplied pre-placed in the cap, and the seal is fused to the container mouth after the cap is applied, by means of an induction-heating chuck containing a toroidal induction antenna that causes the layer to heat.

Still other sealers pre-melt the surfaces to be joined using a variety of heat sources ranging from radiant heat to the application of hot gasses or mechanical friction, and then press the mating surfaces together. These methods have the advantage of providing a seal where the substrate materials are too thick or insulative to permit heat sealing that relies on heat conduction.

Aerosols

Aerosols in their true form are dispersions of liquids or solids in a gas stream, and have been around since the time of cave paintings, and there were many types of aerosol devices in widespread use before the advent of the aerosol “bombs” in the 1940s, which were both manually and mechanically powered. The great advantage that modern aerosol packages have is that they are self-contained and self-powered, requiring neither an external compressor nor a great deal of pumping or effort to use. This is most often achieved by using a two-phase propellant, usually made of a relatively low vapor pressure hydrocarbon that maintains the internal pressure of the container by volatilizing liquid propellant as the pressure is reduced when product is dispensed, as shown in Figure 5.3.

These devices also depend on a precision valving and nozzle system to provide a well-controlled and usable spray or stream, and may rely on the propellant itself to provide a *co-solvency effect*, thinning an otherwise undispensable product such as a thick adhesive enough to allow it to flow freely through the dispensing system and then re-thicken upon rapid vaporization of the propellant after application.

Early aerosols often used highly volatile (high vapor pressure) materials to create internal pressure and to provide a solvent for the product, although these were often quite toxic and occasionally very hazardous. The development and understanding of chlorofluorocarbon

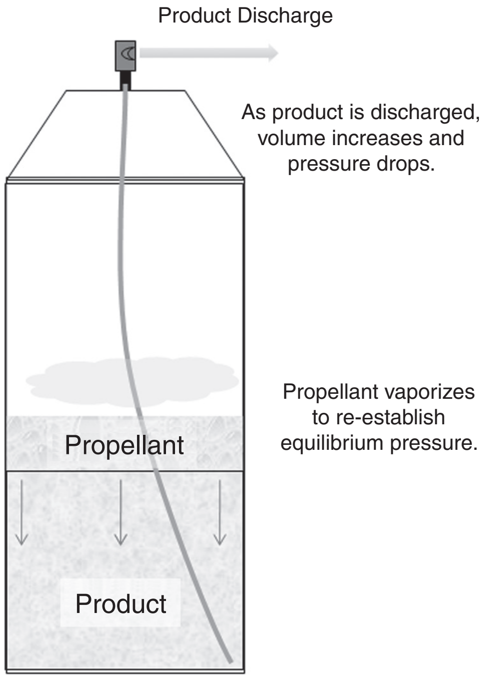

Figure 5.3. Aerosol Can Operation

(CFC) compounds that liquefied at moderate pressures allowed the development of non-toxic and non-flammable propellant alternatives that usually did not react with food, cosmetic, and pharmaceutical compounds. Subsequent discoveries about the environmental hazards of CFCs, coupled with changing market demands and their unprofitability in many markets, led to the implementation of a CFC ban in many countries [8]. Several exceptions were allowed for this ban, the most notable being for Metered Dose Inhaler (MDI) for use by sufferers from asthma and other respiratory conditions. Since CFCs are non-toxic and were able to disperse the 2–5 μm particles of medical aerosols properly into the lungs, they were retained after the initial ban. These were banned at the end of 2008, and substitutes based on hydrofluorinated alkanes (chiefly trifluormonofluoroethane and heptafluoropropane) have been developed, although dispersant and dosage formulations had to be adjusted [9].

Aerosols can be generally classified into general classifications of miscible, immiscible, separated, and alternative propellant systems.

Miscible Systems

Miscible systems are formulated so that the propellant dissolves into the product and volatilizes out of the product during dispensing. This can be assisted by a chemical emulsifier. These systems allow the creation of foams and fine sprays that are dispersed by the expanding propellant, as well as the dispensing of highly viscous materials that require the thinning (co-solvency) effects of the liquid hydrocarbon propellant to be properly utilized. Paints, hair spray, and similar thick coatings may be dispensed through a relatively fine nozzle utilizing this principle.

Immiscible Systems

Immiscible systems, as the name implies, do not exhibit mixing between the propellant and product, which makes it ideal for dispensing streams of product rather than mists or foam, although a moderate degree of dispersion can be achieved with some products with careful design of the nozzle assembly.

Separated Systems

Separated systems have a physical barrier between the propellant and the product and are necessary where reaction with the product or any foaming or dispersion would detract from the product. Physical separation is usually achieved by use of a sliding piston or compressible bag that allows the application of pressure without mixing of the product. These types of systems are most often used with cosmetic gels and creams and other materials such as decorative cake frosting and cheese products.

Multicomponent (2K) Systems

Multicomponent (2K) systems are available for products that must be mixed before use, generally for reactive components such as polyurethane paints, epoxy adhesives, and the like. The container has one or several of the components in frangible internal containers. When the user shakes the container, the agitator ball or the containers themselves will cause breakage, beginning the reaction. The disadvantage to these types of systems is that the product must be used or discarded once the reaction has begun.

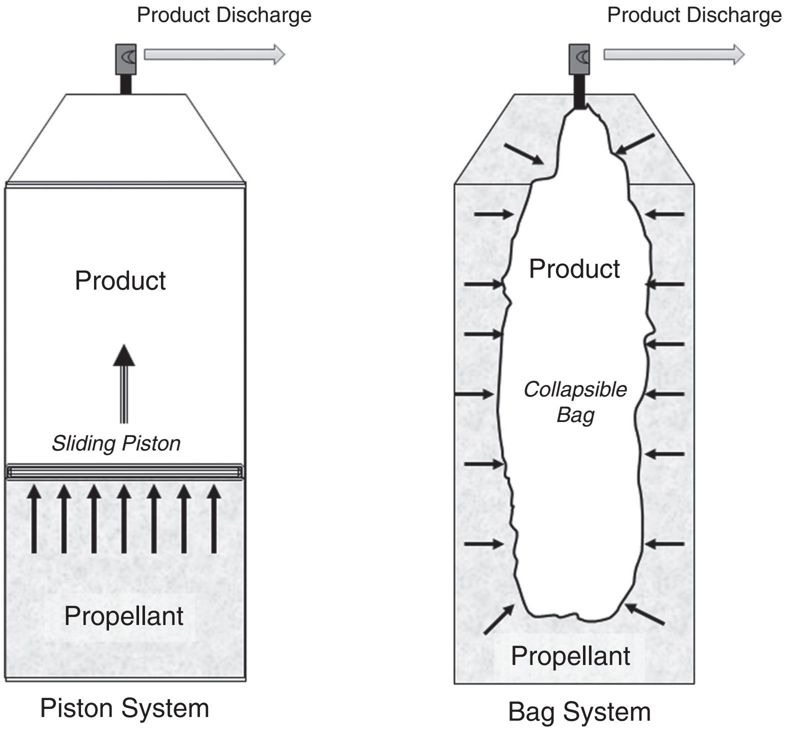

Figure 5.4. Bag- and Piston-Type Aerosol Systems

Alternative Propellant Systems

Alternative propellant systems have been developed at various points and have been intermittently used for products, often in an effort to project an environmentally friendly market image. These usually involve mechanical storage of energy via a rubber enclosure around a flexible bag containing product, or a spring-and-piston arrangement, and are roughly equivalent in effectiveness to manually operated pump spray and dispenser nozzles. Although these have been refined to work reasonably well with some household and cosmetic products, they often do not provide the substantial and consistent pressure required for many aerosol applications, and cannot provide co-solvency for viscous products and may be difficult to recycle.

Air-Powered and Compressed Gas (Single Phase) Aerosols

Air-powered aerosols are extensions of the hand-pumped dispensers mentioned elsewhere in this chapter. These rely on manual operation of an air pump to provide and maintain pressure to the container, and offer the advantages of being available in unpressurized form and using a relatively inert propellant. This allows the customer to add product, then dispense it in aerosol form, and is often used by cosmeticians and for small area applications of pesticides, medical, and paint products. Although these types of aerosols do not maintain pressure at a particularly accurate level, they may be adequate for some types of applications.

Compressed gas (single phase) aerosols rely on simple pressurization of the aerosol container to dispense and disperse product. Although this offers the advantage of using inert propellants such as nitrogen, nitrous oxide, or helium for specialty applications, the pressure will drop in proportion to the expanding volume in keeping with Boyle's Law, PV = k, which states that the pressure times the volume will be constant. Thus, as the product is used and the internal volume increases, the dispensing pressure will drop proportionally, which may affect operation of the aerosol. Although this could be circumvented by the use of a pressure regulator in the valve assembly, no manufacturers currently produce such an item. These gasses are used most often because of their lack of affect on the product. Nitrogen, inherently non-flammable and quite insoluble, may be used with products that are combustible or require pressure without additional foaming action (such as some European beers), and nitrous oxide is often used with whipped cream and other food items because of its high solubility that provides good foaming action, and lack of off-flavor production.

Propellant Types

With the banning of CFC compounds by the Montreal Protocol, many aerosols have resorted to using combinations of hydrocarbon gasses, either HCFC compounds (which themselves will be banned by 2030) or propane and butane blends and variants [10]. Careful selection of the composition of the propellant as well as the mechanical components of the aerosol dispenser will allow the tailoring of pressure characteristics to suit the application. From Table 5.1, one can see that hydrocarbon propellants can be blended to provide nearly any intermediate vapor pressure desired at a particular temperature, and are designated by a letter followed by the pressure at 70°F (21.1°C). Thus, a −50 suffix propellant will provide 50 psig (345 kPa). The letter designation helps describe the mix of ingredients that provides the pressure, and these can overlap considerably because most of these refer to a combination of Propane, Isobutane, and n-Butane. These may be selected for various reasons, and different mixes can provide density and solubility characteristics to match the product and dispensation requirements.

Aerosol Hazards

Aerosol dispensers are unique in that they are one of the few types of packages that may become hazardous regardless of the product they contain. There are many instances of damage or

Table 5.1. Properties of Aerosol Propellants

Propellant Properties. Pressures in psig, (kPa) at STP				
Type	Inert Gasses	Hydrocarbons	Fluorocarbons	Ethers
Compounds	CO_2, N_2, NO	LPG: (Propane, Isobutane, n-Butane mixes), Isopentane, n-Pentane	1,1 Difluorethane (HFC152a), 1,1,1,2 Tetrafluorethane (HFC134a)	Dimethyl Ether
Vapor Pressure at 70°F (21.1°C)	N/A	Propane: 108.0 (744) Isobutane: 31.1 (214) N-butane: 16.9 (117) Isopentane: −3.1 (−21) N-Pentane: −6.2 (−43)	152a: 63 (434) 134a: 71 (490)	63 (434)

injury caused by aerosols being overheated, punctured, or corroded, and all aerosol containers are pressure-tested at levels equivalent to those found at 50°C (121°F) before filling, and cans are tested for leaks or failure by immersion after filling and capping in hot water in the production facility. Although the U.S. Regulations (CFR49§178.33) have been amended to no longer specifically require water bath testing, other regulations on the transport of dangerous goods may still require it, particularly in European countries [11]. There is some objection to this testing based on problems with aluminum and polymeric containers being degraded by the water bath, but alternate test methods have been proposed, and several that are based on gas-leak sampling are available [12].

Because the ban on CFC propellant has driven a trend toward using combustible hydrocarbon propellants, there are instances of cans, particularly those that corrode from storage for long periods in damp environments, leaking combustible gasses and causing catastrophic fires and explosions.

Flashback tests, which indicate the degree of flammability hazard, are based on whether a projected aerosol stream will ignite, if it will create a *flame projection* (ignition of the aerosol stream), as well if there is any kind of *flashback* – flame projection that extends back to the aerosol container at any degree of valve opening (Figure 5.2).

> The flame extension test is conducted by holding the aerosol can 6 inches from a flame and discharging the product across the flame. The extension of any flame from the flame source (typically a candle) in inches is noted and recorded. Any flame extension more than 18 inches or any flashback of flame to the valve at any degree of valve opening would then dictate the proper labeling of the product as either being flammable or extremely flammable. Flashback occurs when the flame is drawn back toward the aerosol can by the stream of propellant. This would indicate an extremely flammable product. [13]

Aerosols (as well as other products) must also be labeled according to flammability:

> 16 CFR 1500.3(c)(6) defines the terms "extremely flammable," "flammable," and "combustible" as extremely flammable if, when tested, it has a flash point at or below 20° Fahrenheit (F), flammable if it has a flash point above 20°F and below 100°F, or combustible if it has a flash point at or above 100°F up to and including 150°F. [14]

Nozzle Design

The success of an aerosol package depends on the careful matching of product, propellant, valve, and nozzle assembly. Typical nozzle assemblies consist of a valve and container neck unit that is crimped after filling and is supplied with a nozzle that is carefully matched to the product and application at hand. Additionally, a *dip tube* may be used to carry the product from the can into the valve assembly, and these may be weighted to allow spraying at any angle, although this is not common. Products such as pavement-marking paint and whipped cream, which are intended to be used with the can inverted, do not require a dip tube.

Microwave Packaging

Microwave heating, described more fully in Chapter 2, has been an increasingly ubiquitous feature of life – microwave ovens are currently in use in nearly all households and many commercial and institutional kitchens. Packaging materials were not a component of microwave

Table 5.2. U.S. EPA Flammability Statements for Aerosols

Criteria	Required Text
Pressurized Containers	
Flash point at or below 20°F, or if there is a flashback at any valve opening, or if the flame extension is greater than 18 inches long with flashback.	**Extremely flammable**. Contents under pressure. Keep away from fire, sparks, and heated surfaces. Do not puncture or incinerate container. Exposure to temperatures above 130°F may cause bursting.
Flash point above 20°F and not over 80°F, or if the flame extension is greater than 18 inches long	**Flammable**. Contents under pressure. Keep away from heat, sparks, and open flame. Do not puncture or incinerate container. Exposure to temperatures above 130°F may cause bursting.
All other pressurized containers	**Contents under pressure**. Do not use or store near heat or open flame. Do not puncture or incinerate container. Exposure to temperatures above 130°F may cause bursting
Non-pressurized Containers	
Flash point at or below 20°F	**Extremely flammable**. Keep away from fire, sparks, and heated surfaces.
Flash point greater than 20°F and not over 80°F	**Flammable**. Keep away from heat and open flame.
Flash point greater than 80°F and not over 150°F	**Combustible**. Do not use or store near heat or open flame.

[40 CFR 156.78)]
Source: United States Environmental Protection Agency (2007), "Label Review Manual Chapter 9 – Physical or Chemical Hazards, September 2007." Op Cit.

heating of foods at the outset of home microwave use. As frozen and refrigerated foods of all types were marketed to meet the increasing demand for ease of preparation in microwave ovens, the use of packaging materials to manage the heating process – and in some instances provide functions such as surface browning that microwave ovens (which do not produce radiant heat) lack – has increased as well.

Because microwave ovens convert electromagnetic energy to heat throughout the body of the product, without the usual heat transfer mechanisms to provide traditional textures and coloring to surfaces, many products were originally thought bland, doughy, or otherwise unpalatable. Much work has been done to provide comparable surface browning and crisping both through product formulations that have high levels of surface sugars and fats as well as packaging materials that are highly lossy and create high temperatures at the surfaces of the foods to provide browning or crisping effects. One of the most widely adopted components in food packaging over the last two decades has been the addition of a microwave *susceptor* to facilitate convenient and effective product heating in microwave ovens. The most commonly seen version of this is with microwave popcorn, which uses a susceptor to melt and heat the fats used to cook popcorn so that the microwave field does not simply incinerate the popcorn. Other common usages are for baked products and pizza, where consumers have learned to expect browning and hard crust formation. Most of these exploit some aspect of induction heating or magnetic oscillation to generate heat from the microwave field, though there are a few that may depend on heating processes that more closely mimic the foods themselves.

Microwave Heating and Interaction with Packaging Materials

The simplest classifications of packaging materials are for “traditional” types of containers: metal that is reflective or opaque to microwaves, and glass and paper that are effectively transparent to them. Despite the folklore that exists regarding the reflection of microwaves back into the magnetron by metallic containers or foil causing violent failure of the oven, little harm is done to microwave ovens by metallic containers, and modern magnetrons are made of ceramic and have thermal cutouts to protect them. Because early magnetron tubes were made of glass, excessive waveform reflection back into the magnetron tube could cause it to overheat and fail, giving rise to the myth that putting metal objects in a microwave oven will cause it to fail or even explode. Given that microwave oven cavities have metal walls, and occasionally metal racks as standard features, this does not make a great deal of sense. Modern microwave ovens have magnetrons that are based on high-temperature ceramics and are protected with thermal shutdown devices to protect them from overheating, so putting metal objects into a microwave is unlikely to cause the problems that the urban legend describes.

Microwave ovens and heaters generate heat by creating a strong electromagnetic field (EMF) near a material that causes molecular agitation and therefore heating. Given that the electric field and the magnetic field operate in opposition to one another in order to satisfy the conservation of energy, there are several heating modes (electric field, magnetic field, and bimodal) available to heat foods. In most food products, the most common mode of heating is caused by polar molecules rotating to try and align themselves with a rapidly alternating electric field, and causing heat from molecular excitation. The most efficient heating in most household microwave ovens will be the result of interactions with water, with decreasing heating rate with fats and sugars as they are less polar. Because the microwave energy that is being applied to the materials to be heated are being absorbed and converted to heat, they are termed lossy materials. Similar technologies are used for stealth coatings on ships and aircraft, relying on absorption by particulate carbon or iron rather than complex food compounds. However, the EMF will generate induction currents in the metal, causing it to heat and generate enough voltage to cause sparking, which may frighten consumers or cause fires or interior damage in the oven cavity. On a much smaller scale, this is exploited in many types of susceptors that utilize metallic inks, fragments, or coatings to generate limited-surface heating. As microwave ovens became popular, it was clear that the traditional foil trays used for frozen foods would have to be replaced because they blocked much of the EMF and caused slow and uneven heating. Early replacements were constructed of coated paper, and subsequently thermoformed plastic trays have come to dominate the industry.

Glass is transparent to microwaves if it does not have a significant metallic component (as many other ceramics do), and is ideal for heating foods apart from its usual limitations of fragility, cost, and weight. Because of this, heating foods in their glass jars or bottles is often suggested by the manufacturer. One of the peculiar hazards of this is flash boiling, where the lid is not loosened to vent excess pressure during heating and either explodes messily in the oven or boils explosively when finally opened by the consumer, often causing severe burns.

Most plastic materials as well as paper are transparent to microwave energy and are well suited to heating frozen and fresh foods. The exceptions are melamine-formaldehyde thermoset resins that will heat and fracture quickly in a microwave field. These resins found their large market in tableware during the 1950s and 1960s, and can still be used for screw-caps in the packaging industry, but are infrequently seen in modern consumer goods, partially due to the unsuitability for microwave use. Additionally, paper or plastic with metallic inks or coatings can arc and heat in an EMF field, which should be considered when designing graphics, labeling, and printing.

Types of Susceptors

Susceptor heating predates microwave heating equipment because it has been used at frequencies ranging from very low frequency AC current to radio frequencies on various sorts of induction furnaces, heat-treating apparatus, and chemical processes. The original microwave susceptors were carbon-particle or metallic inclusions in paint used first on military ships and aircraft in an attempt to defeat radar reflections by converting the incoming radar pulse's electrical component to heat; many of these are still based on ferrous compounds and particles. For the applications typically seen in consumer packaging, the single frequency and relatively high power concentration (and lack of concern about reflection) provide a different set of performance criteria.

Susceptor Formulation

Most common susceptors exploit the shifting magnetic field component of the EMF to generate induction currents in a resistive material, which then are converted to heat. Because metallic objects will produce high-voltage fields and arcing in the microwave field, the object of this is to provide enough current to generate high heat without causing arcing or fire. There are other types of susceptors that utilize the shifting electric field to generate heat in a saline solution, and these offer the benefit of reducing their heating effect as the water is boiled out of solution, but these are not commonly used.

It is possible to construct many sorts of susceptors, but very few of these have seen widespread commercial production, often for reasons of cost, speed of production, or variability in use. By far the most common type of susceptor is constructed from metalized film, either as a patch or as a pattern produced by selective metallization on film. This then produces thermal energy that is transmitted to the product either by conduction in order to firm and brown the product (such as pizza crust), or by infrared radiation to provide a crisp, brown surface, as is done with browning sleeves for pastry products. Similar results may be obtained by coating or printing a surface with metallic inks, although there have been problems with these fragmenting as they heat. The actual mechanism of heating results from the metallic coating or material converting an EMF's magnetic field flux to electrical current (hence, the sparking of metallic labels), and this current then inducing resistance heating, with the thickness and composition of the heating layer affecting the overall impedance and heating efficiency, with a theoretical best square resistivity value of approximately 188.5 Ω/sq. [15]. It is also possible to construct films or coatings that fragment in use, limiting heating, but this is not often done because of the unpredictability of oven type and consumer usage.

Other possibilities include susceptors that may absorb oils or moisture from the food, and may alter their heat generation as these components are sorbed and desorbed from the susceptor. These are seldom used because of the need for very high heat levels for browning and crisping. It is also possible to combine thin film and thick organic coatings to more efficiently utilize both electric and magnetic field components, but this is seldom done with consumer food products for reasons of cost, complexity, and concern with contamination with the coatings.

Patterned Susceptors and Reflectors

Because the wavelength of 2,450 MHz microwave ovens is predictable at 12.24 cm, it is possible to create diffraction patterns by selective metallization of the susceptor, as described in Chapter 4, that act as lenses or shields to concentrate or deflect energy on certain parts of the product by creating artificial nodes, antinodes, or reflecting part of the power input. Although the principles of EMF diffraction have been established for some time in microwave communications and radar applications, the implementation was only explored in microwave cooking after sufficient market penetration occurred to create very large markets for microwaveable foods. Unfortunately, some of these implementations can suffer from the variability of oven types and power, and so they have only been seen on a few specialty products.

Heating Effects and Toxicological Concerns

Recent work has been concerned with the production of unwanted chemical species, either as otherwise entrained materials liberated from polymer structures or as created as pyrolysis or other thermal decomposition by-products under the extremely high temperatures found in some susceptors. It is also of some concern that the very high heats generated in the susceptors may be leading to the thermal decomposition of the polymer film, paper backing, or adhesive used in many food products' susceptors, but there is no currently available definitive data about this potential problem.

For surface temperatures to be hot enough to brown food, point temperatures in the susceptor structure have to be high enough to generate heat in the susceptor material, transmit it to the surface, and then, depending on the product, conduct or radiate the energy to the product. Inspection of a popcorn bag or a pizza tray after use will show distinct browning of the paper fibers, indicating very high temperature generation. Studies have shown that susceptors that achieve 100°C in the product may show internal susceptor temperatures of approximately 200°C [16]. These temperatures can create situations where compounds are liberated into the product, and studies have shown that the susceptors themselves degrade with use [17].

Other studies have shown an increased rate of compounds released over time, ranging from bisphenol-A and volatile organic compounds to fluorocarbons during microwave heating [18–20]. Additionally, there is evidence of microwave energy liberating residual antimony from the original PET polycondensation catalyst process as a result of microwave heating [21].

Both the level of exposure and often the long-term health effects of these indirect food additives are unknown to a certain extent, and because of the extreme variability of exposure conditions, this remains somewhat controversial. The United States Food and Drug Administration has issued a Guidance for Industry document describing test protocols, recommendations, and requirements for materials producers, but these are very limited and are often non-binding. EEU protocols are similarly non-specific, and research is ongoing [22, 23]

Printing and Coding Processes

Printing, marking, identification, and decoration of goods and possessions is one of the oldest processes known. Few if any packages are intentionally shipped without markings of some kind to at least identify the contents, and all consumer products take advantage of the package to identify, market, and comply with labeling requirements.

Traditionally, printing has implied a great deal of setup and a large number of identical items being produced, whereas coding is more closely associated with changeable information such as lot numbers and freshness dates. As printing processes evolve, this distinction is beginning to blur, with digital presses gaining in speed to rival moderate-speed fixed-copy presses, and with the ability to print different copy on each label, carton blank, or tag.

Additionally, the usual model of applying ink to a paper or polymer substrate is changing with the ability to apply adhesive, hot-stamped, microembossed holograms or other decorative graphics, as well as technical devices such as programmable RFID tags.

History

The history of printing is inextricably intertwined with human history, with hand-copied texts, cave paintings, and various palimpsests giving us our view into antiquity. Various forms of mass-printing have been developed, using slate slabs (lithography), carved type and illustrations (letterset), and early engraving-based printing schemes (intaglio). Security seals have been formed of wax or clay, and embossed with unique, carved signet seals, giving us the term “signature” as a description of a unique identifier.

Types of Printing Processes

Traditional printing processes have usually been concerned with transferring a liquid ink from a reservoir to a substrate material in a predetermined pattern. This may be as simple as a rubber stamp or as complex as the precision multicolor presses that are used to print banknotes, stamps, and magazines. To give some order to the vast number of processes and systems available, it is helpful to dissect them into several broad categories: direct and offset printing; and subsurface, planar, and relief printing types.

Direct and Offset Printing

As the name implies, direct printing applies ink directly to the substrate surface. This has the advantage of ensuring precise placement of the image without an intermediate step, but can be unsuitable for irregular surfaces and may wear the printing plate surface down quickly. Offset printing applies the image to an intermediate material, which then prints the image onto the substrate. While this can increase the difficulty of accurate image registration, it also allows the printing process to be tailored to the specific material to be printed, and can reduce wear of the printing plate. Offset printing is almost always used in conjunction with lithographic or letterset printing, although it is possible to use the principle with other methods.

Subsurface Printing

Subsurface printing is almost always done using a gravure method, which is the commercial form of artists’ intaglio printing (in which a smooth plate is carved with an image composed of continuous lines or patterns). Traditional intaglio processes can still be used for high-value items such as banknotes and stamps, but more usually this is a gravure process where the plates are fabricated under intense pressure from a handmade master intaglio design. Gravure (using flat plates) and rotogravure (using engraved cylinders) processes produce high-quality impressions over long production runs by using a regular pattern of *wells* (microscopic indentations) with varying depth as the design requires. Rotogravure printing uses etched ceramic or metal rolls that may be mechanically or laser etched. Mechanical etching produces diamond-shaped wells, whereas laser etching produces rounded wells as the cylinder material is ablated. For either method, once the plate or cylinder is etched, the printing process is one of applying ink to the entire printing surface, scraping off the excess surface ink with a flat *doctor blade* that removes the surface coating, and then impressing the remaining ink that is trapped in the etched design to the substrate, usually under a good deal of pressure. The setup expense for a gravure process is very high, but the durability of the rollers and the accuracy of reproduction often justify its use for very long production runs.

Surface Printing

Lithographic (*lat.* "stone writing") surface printing is historically based on the mutual repellence of water and oil. In its original form, artist's prints were produced by drawing the original design on a slate with wax. The flat sheets of slate were hydrophilic, whereas the wax was hydrophobic. When wetted with water (which would stick to the bare slate), then with oil-based inks (that would not stick to the water film but would adhere to the wax pattern), the ink would remain in "dry," waxed design areas, allowing the image to be reproduced. While still used in fine-arts applications, this method has obvious commercial limitations, but the practice has been expanded, using the same principles, to chemically coated plates and then to the photopolymer plates currently in use.

Surface printing plates are typically sheets treated with a water-repellent polymer that is photopolymerized, often in a laser-scanning device similar to a laser printer that reproduces artwork directly to the printing plate from digital graphics files. The ink transfer area is then retained while the rest of the surface is dissolved away. This leaves a water-repellent transfer area with the required design on a substrate support material. Some advances in method have been developed, including selective irradiation of ceramic surfaces to provide transition from oleophilic to hydrophilic surfaces and back again, but the photopolymeric plate fabrication remains a favorite [24].

Raised Printing

Raised printing depends on ink applied from the raised surface of an image, requiring that the printing plate or roller be constructed in such a way to provide a clear, distinct image. Traditional letterpress methods have relied on cast metal (usually lead) type and images, but have given way to polymeric printing plates and other methods that are less hazardous and more cost- and time-efficient. Raised printing can be made of a range of materials, from metals to rubber, depending on the application. Direct printing is most often done using high-relief letterpress methods, whereas letterset printing uses low-relief printing surfaces in an offset printing process. For direct printing, the processes use reversed images and raised type to transfer ink onto substrate. The plates or rollers are made of metal or polymer, depending on the application. Although letterpress would be an ideal application for a durable ceramic photopolymer, little work has been done in this type of application.

Letterpress plate fabrication is done using a negative image or optical scanner to polymerize low-relief images on the surface in a manner similar to the offset lithographic plates that the technology was derived from. The low-relief plate readily prints to offset blanket in a manner similar to offset lithography, except that the printing plate's surface relief is used to print to the offset blanket rather than oil-water interactions, resulting in it being termed *Dry Offset*.

Flexographic printing, which uses a flexible polymer printing plate, may be used in either direct printing or offset printing, depending on the application. Plates are inexpensive but not as durable as metal letterpress, and are manufactured in a manner very similar to those used in photopolymer letterpress. Cushioning is provided by flexible type and a cushioning layer on the plate cylinder, and the flexible printing surfaces allow the artwork to be transferred to irregular surfaces easily. Because of this, it is the preferred method for printing corrugated board and other very rough surfaces. In flexographic methods, a textured *anilox* roller transfers ink to flexible surface in a manner similar to inking a rubber stamp. The anilox is usually engraved to hold ink, and any excess is removed with a *doctor blade* before inking the printing plate cylinder. Letterpress printing is a common and popular method with packaging because of increasingly good graphics that can be applied to a wide range of surfaces and materials, as well as low costs.

Color Theory and Multicolor Printing

Current printing processes rely on applying several colors in overlapping layers and density to generate intermediate tones and colors. Whereas video displays and most inkjet and laser color printers rely on a standard set of colors (usually RGB or CMYK), printers may use many nonstandard colors to provide the desired effect. The preparation of color plates and cylinders used to be based on very large photographic cameras fitted with specific color filters, but with the broad implementation of digital graphics, color separation can be done directly from the image. The output can then be used to directly generate printing plates or rollers for each color, and will allow for the digital transmission of print job information to many locations via data file.

To better understand how multicolor printing operations can create a full spectrum of colors from a very few basic monochromatic inks, it is necessary to mention some concepts of color addition and subtraction. Color addition and subtraction, so called because addition contributes to make white while subtraction reduces from a basic white state, are commonly used in many items, from printing to display screens of all types and even indicator LED's where red and green are quickly alternated to make yellow.

The basic principle of color addition is that adding basic colors together will produce any intermediate tone required. These are usually RGB – Red, Green, and Blue – in video displays. Printing and photography often use color subtraction, often termed CMYK – Cyan, Magenta, Yellow, and Key (black) – which is often applied in that order during the printing process. Deciphering the combinations can be done with a little real-world experimentation, yielding the following combinations (Table 5.3).

Whereas the overlapping colors of color addition can be somewhat intuitive, understanding color subtraction can be a little more confusing. One way to consider it is to think of the colors as being filters that only allow their particular colors through. Thus, white light "subtracting" magenta transmits only red and blue while blocking green, and cyan, which transmits only blue and green, blocking red, further filters the light, only transmitting the color in common between the two – blue. The practical implications of this are more complex, and are part of the art and

Table 5.3. Color Addition and Subtraction Table

Color Addition	Color Subtraction
Red + Blue = Magenta	White − Yellow & Cyan = Green
Red + Green = Yellow	White − Magenta & Cyan = Blue
Blue + Green = Cyan	White − Yellow & Magenta = Red
R + B + G = White	White − C, M, Y = Black (K)

technology of commercial printing. For example, a transparent blue ink (that only transmits blue light) laid over a yellow substrate (that only reflects red and green combined, while absorbing blue) will not have any light of the proper tone to transmit, appearing black rather than the expected green.

Colors may react to light depending on frequencies absorbed. Red absorbs the high-energy end of the white light spectrum, which often results in the fading of red printing and paints before any other color. For this reason, red pigments are more difficult and expensive to use. Different light sources have different spectra, often described as a *color temperature* relating back to tungsten filament bulbs, with high color temperatures being blue-rich and cooler ones being richer in the yellow and orange spectra. Each temperature will provide different appearances to an item, so printing jobs must be run with the final viewing light in mind, and printing operations may have different light sources for evaluating final copy (Table 5.4). For example, a cosmetics boutique brightly lit with halogen lamps will probably have a different product appearance than in a large discount retailer lit with cool blue fluorescent tubes, even though the product may be the same.

Color Standards

To allow colors to be communicated and included in specifications, sets of color standards are produced with coding systems to give uniformity to printing operations when blending inks. Typically, a set of color standards is printed and circulated that the press operator will use to match a blended patch of ink on the relevant substrate, literally a spot check. In the United States, commercial sources such as E. G. Pantone® color swatches are used, with other similar sources available worldwide. The use of common standards then maintains colors and printing schemes among printing plants and across a series of production runs to ensure that a particular color scheme is maintained accurately. Increasing integration of printing from computer monitor to press run has introduced complications in color matching and has made the calibration of monitors and accurate color continuity an ongoing technical concern in the design and printing industries. As the printing industry changes to digital distribution, the process of matching colors will expand from on-the-shelf products and advertising copy to include online content and video displays, all of which must correspond properly with the intended color schemes.

Halftones and Shading

Resolution – the ability to distinguish closely spaced objects – is limited in the unaided human eye. Printing takes advantage of this to make *halftone* shading and colors by constructing

Table 5.4. Color Temperatures

Some Examples of Color Temperature	
Typical Source	Color Temperature
Incandescent Lamp	2,700–3,300°K
High Temperature Flood Lights	3,500°K
Arc Lighting	4,100°K
Sunlight	5,500–6,000°K
CRT/LCD Screen	Usually Selectable – 9,300°K, 6,500°K and 5,000°K

fields of dots and patterns of varying diameter and density that the eye “runs together” into smooth tones. The same effect is achieved in other visual displays such as computer screens, LCD and plasma televisions, and inkjet and laser printers. Although it is nearly impossible to commercially impress ink in controlled, thin layers to provide shading, printing processes are able to precisely reproduce varying densities of individual discrete color dots of varying size and dot-density to provide shadings and tones. Halftone *screens* were used to segment colored areas for printing, but this has been given over to computer processing of the fine patterns as well, even though the terminology remains. Misalignment of the halftone screens can cause unsightly “Moiré” patterns to appear in solid colors – these are often seen in color supplement printing in newspapers.

Types of Substrates

While nearly anything can be printed or marked in some fashion, the general consideration of substrate types starts with the consideration of whether the material is fed in sheets or in web form (usually taken from large rolls), and if it is cut or rerolled after printing. Beyond that, the type of material surface (paper, polymer, foil, sheet metal, etc.) has to be considered to select the best type of printing process for the application. As previously described, flexography is a good process for small-to-medium runs (unless plate replacement is not a factor) and can provide adequate graphics reproduction, whereas the printing of exact copy on relatively smooth surfaces such as currency and stamps may require an intaglio process.

Types of Inks

Inks are typically composed of a *vehicle* (a liquid carrier component) and a coloring agent that may be a solid pigment, a liquid dye, or a combination of the two. Additionally, there may be a vast array of modifying agents such as surfactants, brightening agents, polymer resins, and the like, depending on the particular application.

The earliest printing inks, intended for use on the first presses, were a mix of black pigment (often from wood or vine charcoal or burnt bones) and oil or animal glue. The oil-based inks are remarkably similar, in principle at least, to the soy-oil-based inks used in newspapers today. They have the disadvantage of requiring time to absorb into the paper fibers, leaving the pigment on the surface. Later developments substituted volatile organic solvents in place of the oils to reduce the drying time. This is particularly important for dye-containing inks because liquid dyes can continue to travel along absorbent fibers, particularly through paper substrates, causing blurring of the copy and images. Problems with volatile organic compounds (VOC) being absorbed by food products, and workplace exposure by printing workers have driven printing inks to rely on differing polymerization processes such as ultraviolet and electron beam curing photopolymers, and other compounds that polymerize or harden with moisture loss or exposure. Polyol-based urethane resins are used as a flexible high-adhesion, low-reactivity vehicle to replace aggressive solvent systems and reduce incompatibility between ink systems that requires press downtime for cleaning [25].

Like any surface coating, the ink must be compatible with the substrate to which it is being applied, as well as any other coatings or printing on the surface. There have been instances of perplexing adhesion failure of single colors of ink on package surfaces because of a mismatch of that particular ink batch to the substrate type. Aggressive solvents may etch or dissolve the surface as well, leading to package failure, and some types of inks may contain chemicals that alter the structure of the packaging material via sorption of organic chemicals, which can affect shelf life or other product quality factors by changing barrier characteristics. Thus careful matching (and testing) of ink-substrate compatibility, as well as consideration of other factors such as exposure to solvents such as alcohol in the product, or heat resistance during package sealing, must be made.

Printing Surface Choices

Surface printing is the simplest and most common type of printing, depositing ink directly on the exposed surface of the material. It may be subject to surface abrasion or other damage unless coated or protected during shipping and handling. Reverse printing is done on the back side of a transparent/translucent material with the copy reversed so that it appears properly through the cover material. When managing this type of printing run, the sequence of application must also be reversed to be sure that large background areas go on last. This has the advantage of providing protection from abrasion or contamination. Because the substrate is also acting as the cover, the texture and optical properties of substrate will affect the final print quality and feel. Thus the surface finish of substrate becomes critical. *Locked-in* printing is surface-printed material that is laminated under another protective layer. This allows changing of copy by changing a relatively inexpensive surface print job without having to throw out a more expensive barrier film. As with reverse printing, the surface finish is critical. Of course, combinations of these are commonly done to achieve a particular design objective.

Printing Production

Graphic Design

Graphic design (the artistic elements of which are beyond the scope of this book) is typically done in conjunction with product marketing and sales. Complex graphics cost more to develop and reproduce, so simple, clever designs can be very cost effective, although the contrary argument is that elegant printing and decoration can push the price point of a particular product up considerably. The world of advertising is full of examples of unprofitable products that have become wildly successful because of clever packaging and marketing. For unusual packages, distortion requirements may be an important factor as well. For example, pre-printing flat sheets to produce metal containers has been successfully used for shallow-draw cans, and shrink sleeves used on glass containers must have printing that will contract to provide the appearance of being printed directly on the container.

Focus groups and consumer test panels are often used to finalize designs, and test-marketing may change the designs even further in an attempt to fine-tune the graphic elements to give the greatest customer appeal.

Once the graphic design is finished, color separation is done so that presses can take the complex color artwork that broken down into basic color components used to create the individual printing plates or rollers, and allow the image to be reassembled on the packaging substrate.

Plate Making

For multicolor press processes (rather than dot matrix or color photocopying), printing plates are made for each of the component colors in the printing process.

Traditional lithography plate making was done with large cameras and photo-etching technology, but plates are now made by direct laser printing onto photopolymer plates that create a differential between hydrophobic and hydrophilic surfaces. Raised surface plates can be cast or produced by photopolymerization, and gravure plates or rollers can be produced by laser pitting, diamond stylus engraving, and chemical etching or, in rare cases, traditional mechanical etching and cutting.

Process Type Selection Criteria

Substrate

The type, composition, quality, and variability of the substrate all have an influence on the process type. Sheets of corrugated board will be handled differently than thin polymer films and metal foils, and each type of process has a useful range of operation. Flexography is well suited to irregular surfaces whereas gravure direct printing will only work with relatively smooth materials.

Number of Colors

Presses are available in any number of colors, but the cost and complexity begins to escalate with increasing numbers of layers. This can also limit the number of suppliers who can do a job if it is extremely specialized.

Quality Requirements

Even though flexographic printing has the capability of doing very precise reproduction, it is most often used for simpler, less accurate printing where the replacement of printing plates is less of an issue. The other extreme, long print runs of highly accurate images such as banknotes and security seals, can justify the high setup costs of intaglio printing.

Size of Printing Run

The length of the printing run and the application will influence the type of printing process used. Very short printing runs might use a photocopier or laser printer, whereas longer runs might use offset. Gravure is most often reserved for very large print jobs because of its high setup cost. Each process has a range of economic feasibility.

Available Equipment and Supplies

Printing process types may also be determined by other factors such as the availability of printing facilities nearby or a specific demand for a particular appearance or texture.

The Preliminary Press Run

Before committing a press facility to high speed runs and consuming enormous amounts of materials, press operators will run test batches of materials through printing (and subsequent cutting and trimming operations, if any) to determine if the copy is being positioned properly, if color registration is correct, and if there are likely to be any significant problems in production. Preliminary runs may be used for consumer preference, marketing review, or final approval purposes as well.

Other Types of Printing

Microembossing and Holographic Films

Microembossing is the use of electroplated relief plates or rollers to create a surface pattern in the surface of a substrate, most commonly a plastic film. Foils and even paper (at larger scales) can be treated this way, although paper will not have the spectacular optical effects of other materials. With reflective or transparent materials, interference patterns can be created, which allows the creation of shifting multicolor graphics as well as static and multiplexed holographic images. Microembossing is also used in the production of cast and stamped MEMS (Micro-Electro-Mechanical Systems) dies and devices for the electronics and medical industry.

To produce microembossed films on a large scale, a traditional laser-based master hologram must be made, either from models or from optical patterns created via an LCD system. From this, a *rainbow* (white light) transmission hologram is produced in a photoresist surface, which polymerizes under the influence of the projected light patterns and is developed in an etching solution to create a raised surface that preserves the projected interference patterns. This surface is then coated with silver or other electrically conductive material, creating a *mother shim*. These are electroplated with nickel used to create electroformed *child shims*, which are peeled off, attached to rollers, and used for the actual film embossing process.

Microembossed films may be used in transmission mode for other color effects, but for the holographic image to be realized, it usually must be printed or laminated onto a reflective film so that light transmission from the rear of the image can reproduce the original pattern. Although the cost of the initial setup for these processes can be quite high, subsequent production can bring the price down significantly. Additionally, the technical complexity of creating a holographic image has provided a ready market for security seals, ID badge features, and the like, because casual counterfeiting is thought to be difficult.

Screen Printing

Screen printing, which is usually associated with the printing of designs on fabrics, is used to produce images on irregular surfaces of nearly every type. The basic principle involves pushing viscous inks, coatings, or adhesives through a mesh that is blocked to allow an image to be formed from the remaining open-meshed areas. Although artisan-level production is troublesome, and requires frequent screen cleaning, it is possible to use automated screen printing in manufacturing situations to the extent that elegant bottle decorations for wines and spirits may be done by screen printing, as are the decorations on compact disks and wooden surfaces as well as patterned adhesive and coating application for specialty processes.

Transfer Printing and Labeling

Transfer printing is a general class of printing that blurs the distinction between labeling and printing, as it usually does not rely on liquid inks or printing materials. Instead, material is *hot stamped* to the surface using a heated silicone rubber plate that adheres material to the substrate in a desired pattern via heat-activated adhesive. This is often used to transfer metalized films to packages to create glossy and shiny images, or to supplement printing on labels and substrates. Therimage® is a trade name that is often used to describe a general class of labeling that resembles decal application. The label consists of a laminated paper carrier with multiprocess color labels, usually on a transparent carrier, that are transferred onto a package that has first been pre-heated by open flames to warm and oxidize the surface. A final heat treatment "cures" the inks and covering carrier film to the package.

Thermal Printing

Thermal printing can be broken down into two broad classes: thermal transfer and thermal paper-based printing. In thermal transfer printing, "ink" – actually a tinted thermoplastic film – is transferred onto surface with thermal dot-matrix print head. It has the advantages of no "drying" time and does not smudge easily, but it is slow. Print resolution is quite good, smudging is low, and the printing is well suited to optical readers. Airline operations use thermal transfer printers for tickets, boarding passes, and similar documents that require good resolution. Thermal paper-based printer uses paper containing thermally activated dyes and is commonly seen in use as credit-card slips, receipts, and on-demand labeling for delicatessens. These are good for short-term consumer use, but they are susceptible to degeneration and darkening by exposure to heat, sunlight, and organic solvents.

Ink Jet

Ink jet printers, which are commonly used as low-cost computer printers, operate by spraying microscopic ink droplets from a print head into dot-matrix pattern on surface of material, often at extremely high speeds. The print will smudge as they require a small amount of time for ink to dry or set, and high-speed resolution may be poor, though acceptable for simple alphanumeric coding. Because the printer never has to contact the printed surface, this method is well suited for very irregular items such as beverage bottles and cans during filling, building materials, and irregular bags. Additionally, very-large-scale equipment is available that achieves the same effect using pressurized ink lines and large nozzles to create large patterns, typically on shipping cases and larger packages.

Laser Debossing

Laser debossing, which is different than laser printing that deposits toner on surface, operates by using an industrial laser to burn a pattern into the surface of a material. This can work either by ablating the material or by removing ink on a specific part of the package, providing white lettering on a dark background. As laser power has increased and the debossing equipment has made the transition from simple metal pattern masks to LCD-based gating, the range of materials that can be directly marked has increased to include metals and even diamonds, and the ability to change code copy at nearly any speed is available. Although very capable, this equipment is among the most expensive because of the necessity of high-powered lasers and optical equipment.

Dot-Matrix Printing

Substrate material is printed with a ribbon/print-head system similar to dot-matrix computer printer. Because of the proliferation of inexpensive inkjet and laser printers, this method of printing has fallen by the wayside with the exception of processes where the physical impingement of the printing head wires is useful, such as the creation of multicopy documents like invoices and receipts.

Laser Printing

Laser printing exploits the photoelectric effect to directly print an image from an optical image or laser-scanning pattern. The photoelectric effect, for which Albert Einstein won his Nobel prize in 1921, is the result of impinging photons knocking electrons from a charged surface, and is exploited in laser printers by a scanning laser causing electrostatically charged drums to pick up and reject finely powdered toner in an image, which is subsequently fused to the printed surface with a hot roller. It is well suited to applications like document printing on paper, but less so on materials that are susceptible to thermal effects. Laser printing of unsuitable plastic films can lead to printer damage. It offers extremely accurate printing with resolutions in excess of 9,600 dots per inch, but is limited in the types of material it can print.

Package Printing Versus Labeling

In the same way that different types of printing processes seek to establish larger market shares, the competition between package printing and package labeling is also an ongoing struggle for market share. A good example is the growth of clear-backed self-adhesive labels on glass bottles that replaces screen printing on glass while providing excellent graphics. The precision printing and speed of application, as well as the elimination of pre-printed inventory (which allows several products to use a standard bottle by changing the labeling) has driven this change. Labeling has the general advantage of allowing the use of a manageable inventory of standardized packages – the primary example being standardized metal cans with paper labels – with the disadvantage of having an extra step in the production process.

Many processes that assemble packages in the production line, for example a cereal-packaging line, would be poorly served by labeling operations because the outer packages themselves are little more than labels, and changeover times would not be shortened. Labeling has the advantage of providing an additional surface layer on the package to provide some degree of protection against abrasion or damage, as with glass containers. Finally, many types of labels are simple enough that they may be printed in-house, whereas the container itself (a glass bottle, for example) requires an enormous capital investment to produce, so one may be manufactured elsewhere while the label printing can be handled locally.

Coding, Scanning, and Identification Methods

Coding differs from more traditional printing in that it is used to carry changeable information, such as batch numbers, expiration dates, and formulations. More usually, a small area on the package is devoted to production information. This may be in *closed code*, encoded so that the customer cannot read it directly but still useful to production personnel and useful in the case of a product recall. Open codes are becoming more common, as well as the inclusion of “use by” and “sell by” dates on perishable products. Coding can be used to indicate variable weights, quantities, and colors on a standard package as well. The distinction between label printing and coding is becoming blurred as printing processes are developed that can generate hundreds of meters of custom text per minute, essentially allowing a different package on every product.

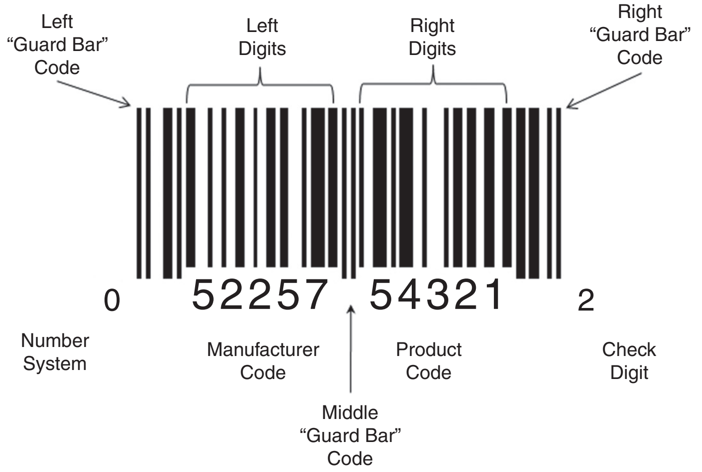

Figure 5.5. Parts of a United States Retail (UPC-A) Bar Code

Coding Methods

Coding methods range from the simplest method, such as a worker writing on a package, to the extremely sophisticated, such as laser debossing and ink jet labeling on high-speed bottling lines. In general, the idea is to mark the package with changeable data as simply, clearly, and accurately as possible. Some of the oldest automated methods are rubber stamps and automatically inked stamp wheels that use rubber type and roll along the top of the package. Similarly, embossing stamps and debossing dies (that cut or remove material rather than pushing designs into it) can be changed for a production run or day's shift, but are not as well suited for information that changes quickly. Debossed codes of all types are very common in the pharmaceutical industry and are often present on cartons and the sealed ends of squeeze tubes, though the proliferation of heat-sealed laminate tubes has required the use of dies in the heated sealing head, or second coding operations using a heated stamp.

Cut Codes

Cut coding is a simple method of coding batches of product, and is still used in the brewing and wine industries. Codes are simply slits cut down the edges of a stack of labels with a sharp blade before they are loaded into the magazines of bottling labelers. By knowing the pattern (which is sometimes explicitly printed on the edge of the label), batch, date, and other information may be read. This method has the advantage of requiring no special equipment, although the ragged edge of the label may be problematic in some labeling operations.

Machine-Readable Codes: Bar Codes and Matrices

Machine-readable codes have become the most important part of the information cycle discussed in the Chapter 1, allowing the use of networked computers to manage and track items throughout their life cycle. It allows a fast scan of product at checkout, during manufacturing and distribution, and during use. Code systems drive store inventory systems and are used for automotive applications from Vehicle Identification Number (VIN) coding to coding of license plates in some countries. Hospital patients may have a patient code as part of their identification bracelet, and medications, devices, and procedures may be similarly coded to prevent misapplication. Because devices and products must "speak the same language," there is a broad range of coding standards, depending on the particular application. One of the earliest and most prevalent is the Uniform Product Code (UPC) standard that is used on nearly all consumer goods, as shown in Figure 5.5, and other standard, have evolved for different application, including two-dimensional data matrix coding that can store a much larger amount of data in a small area, and is used in applications such as package delivery services and order tracking.

Another basic consideration in printing bar codes is that in all bar codes, optical contrast must be maintained for them to remain machine-readable. A black line on a blue ink background will not be scanned by a red laser, nor will a frozen package that is frosted over. Metallized packages present a particular problem, often requiring the printing of a white background behind the code. Nearly all codes have common features, including left and right codes that prevent "backward" reading of codes by scanners, a "check digit" that compares with the sum of the digits in the code, such that if the last digit in the sum and the check digit do not match, the scan is rejected.

RFID Coding

Radio Frequency Identification Device (RFID) coding, an outgrowth of powered (*active*) radar aircraft recognition systems in the World War II, uses embedded radio-respondent chips to transmit data when queried by external reader. First versions of modern, microchip methods powered solely by the reader's interrogatory radio signal (*passive* tags) were used by zoologist Michael Beigel to identify otherwise indistinguishable penguins in the Antarctic. RFID coding is used as a low-labor means of tracking inventory that cannot be accessed for bar-code scanning or manual recording, verifying security of items, and providing an alternate means of retail checkout. It enables *Electronic Point of Sale* (EPOS) operations, first implemented in South Africa in the 1990s.

These have been adapted to other high-value assets of all types using both passive and active tags. Frequencies range from under 135 kHz to over 2MHz, and tags are available in nearly any size needed, from roughly 1 mm^2 to large self-powered units on shipping containers and construction equipment. Implementation is severely limited by interrogation signal's ability to penetrate layers of stacked product because interrogation transceiver power is limited to 500 mW in Europe and 4,000 mW (4W) in the United States. Currently, consumer-level RFID tags only carry UPC-level information plus a serial number (typically 64 bits). Demands by large retailers in the mid-2000s drove a rush to implement RFID-tagging systems for products, but the effort stalled at the pallet-tag level because of problems with penetrating large quantities of goods and the persistently high cost of tags. It is inevitable that this system or something offering similar features will be implemented so that not only checkout and inventorying operations can be rendered nearly automatic, but that *smart shelves* can track goods movement within stores. This final – and in some sense invisible – type of "printing" (or information conveyance) is likely to have enormous implications as marketing, distribution, and retail systems become faster, smarter, and more diverse.

Additional Resources

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Chapter 6

Processes Calculations and Their Applications

The preservation of foods is a basic mechanism for survival by most cultures because Earth's seasonal variations can prevent continuous supplies of particular crops in many regions, and food supplies that are constantly available either for consumption or trade have always been a critical aspect of day-to-day life. Historically, in more environmentally severe areas, it has been critical to store the results of a short growing season for use throughout the year as well as drying or preserving meat and fish that may have an undependable supply.

Traditional methods such as drying, pickling, fermenting, and salting are still used for many products, but with the advent of more modern processing methods in the early nineteenth century, as well as the subsequent understanding of the microbial processes involved, thermally processed foods heated in durable, hermetically sealed containers found an expanding market. Relatively inexpensive refrigeration systems and temperature-controlled supply chains that began with naturally occurring ice and expanded with the development of mechanical refrigeration allowed the development and distribution of frozen and chilled foods as well as wide distribution of fresh produce, which led, in turn, to the development of specialized crop-growing regions such as the vegetable farms and citrus groves of the American West.

Because of the simplicity, reliability, and ubiquity of thermal preservation either by heat or cold, so-called non-thermal preservation methods that use alternate forms of energy input to achieve industrial sterility have been under investigation for more than a century, but few have gained a significant market share. Nonetheless, they offer particular benefits for niche markets that may include flavor, texture, and nutrient retention.

Thermal Processing

Foods have been thermally processed since prehistory, with sun drying and cooking over open fires common wherever possible. Because of the long history of these terms (and their variability among various cuisines), food processing is often filled with simple and inelegant terminology. For the purposes of this book, thermal processing will refer to commercial processing, for the purposes of enzymatic or biological action reduction or inactivation in the product. Thermal processing in general can be broken down into a progression of general categories as follows:

Cooking

Cooking is traditionally considered to be the exposure of the food material to a temperature of at least that of the standard boiling point of water (100°C). It may include an entire cookbook's

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Food and Package Engineering, First Edition. Scott A. Morris.

worth of terminology, depending on the method of heat application and the media in which the food product is cooked. For instance, heating food in boiling water may be stewing or poaching whereas heating the same food in hot oil might be sautéing or frying, and heating it in air might be baking.

Blanching

Blanching is done to reduce or destroy naturally occurring enzymes that can degrade food products, most often fresh fruits or vegetables or their juices. The process may be done with indirect heat, boiling water, or applied steam depending on the requirements of the food product and the scale of the operation. Blanching is almost always included as a step in the canning of fruits and vegetables to avoid color and quality degradation.

Pasteurization

Pasteurization is a process that will reduce the microbiological population of a food to a low level, and can incorporate blanching processes. While this can be done with several types of basic mechanisms, it usually involves an exposure of the product to a heating process. Pasteurization is typically used by itself for food products that are either consumed quickly or are kept in a temperature-controlled environment that further reduces the growth of microorganisms with off-odor and flavor development as an indicator of spoilage before significant levels of pathogen growth can occur. One of the most common processes is the thermal pasteurization of milk that is used to reduce or eliminate the incidence of *M. tuberculosis* and *C. burnetti*, which are responsible for tuberculosis and Q fever, respectively. Although the milk may be heated to reduce the number of pathogens to a minimal level, the continued refrigeration of the product is an essential part of maintaining an acceptably low level of contamination. Pasteurization may also be applied to products such as fruit juices and beer to remove spoilage organisms and reduce pathogen risk.

Sterilization

Sterilization is a process that will render all spoilage organisms – bacterial, yeast, or fungus – completely inactive. Because the energy input required for this is often either impractical or destructive to the product, the term *commercial sterility* is used to denote that no viable organisms can be detected with standard methods, or that the number of survivors is insignificant under usual conditions of canning and storage, or that the acidity (Ph), oxidation-reduction potential (Eh), or temperature will restrict growth [1].

Although the historical methods of food pasteurization and sterilization are most often thermally based, other types of energy input have been successfully exploited for nearly a century, ranging from simple electrical discharge to complex irradiation technologies and physical means such as ultrasound and ultra-high pressure.

Calculation of Thermal Process Times

The condition under which foods must be thermally processed to reduce or effectively eliminate the necessary number of microbes is a function of:

- The product type: pH, salt or sugar content, preservatives, water availability, fat, carbohydrates, and other composition factors.

- The microbe type, age, and number: resistance to heat, affinity for growth in the food product, and initial number of organisms present.
- The heat transfer characteristics of the package, the food product, and the heating source media.

Product Type

For extremely acidic products such as lemon juice (pH $\approx$ 2.3) or sauerkraut (pH $\approx$ 3.6), the processing requirements are very different than for a pH-neutral (pH $\approx$ 7.0) growth media such as beef broth. The primary reason for this is that *Clostridium botulinum* organisms, which are responsible for botulism poisoning and thus of great concern to processors, do not grow below a pH of slightly less than 4.6. For this reason, the dividing line between low-acid foods that require thermal treatment to achieve commercial sterility and inactivate spore forming bacteria and high-acid foods that generally only require pasteurization processing to inactivate molds and yeasts is set at a pH value of 4.6. Fermented, low-Ph foods such as sauerkraut are considered in the same category as high-acid foods. An additional category, *acidified foods*, includes low-acid foods that have had acids or acid foods added, and have a final, equilibrium pH of less than 4.6 and a water activity above 0.85. These require thermal processing to kill the vegetative cells of pathogens and spoilage organisms, but unlike low-acid foods, spore activation is considered to be controlled by pH. Low-water-activity ($A_w < 0.85$), high-acid foods such as jams and jellies are also not considered an acidified food provided criteria for acid, brix (sugar content), and other conditions are met.

Microbe Type, Age, and Number

Given the extraordinary number of bacteria, molds, and yeast that love to share our food with us, it would be difficult to discuss each of them in the space of this book, but concentrating on a few will give a general indication of the nature of the organisms and their growth preferences, as shown in Figure 6.1 [2].

Research beginning in the 1920s has indicated that the age of the particular colony may have some effect on the viability of some organisms, with thermal resistance at its lowest during the logarithmic growth phase and highest during the stationary phase, but the mechanism is not well understood and the organism should be treated as if it were at its most resistant period in order to provide a margin of safety [3].

Common sense would argue against subjecting the processing facilities and equipment to intentional contamination by a deadly pathogen such as *C. botulinum* for the purposes of testing whether or not thermal processes are adequate to the task of eliminating that particular organism. For this reason, a closely associated non-pathogenic organism such as *C. sporogenes* PA3679 is used because it is slightly less thermally susceptible (giving a safety margin in the thermal process) and can be easily assayed.

Thermal processing causes an exponential reduction in microbial activity that never exactly reaches zero even though it can attain infinitesimally small numbers, with a corresponding improbability of illness. For this reason, thermal processes are established on a probabilistic basis that seeks to produce an extraordinarily low probability of contamination. For example, for *C. Botulinum*, the standard end point for thermal processing is to provide a 10^{12} reduction in population, presuming an initial population of 1 spore per gram of product. This is often taken to be one (or fewer) surviving organism per 1,000,000,000,000 containers, neglecting

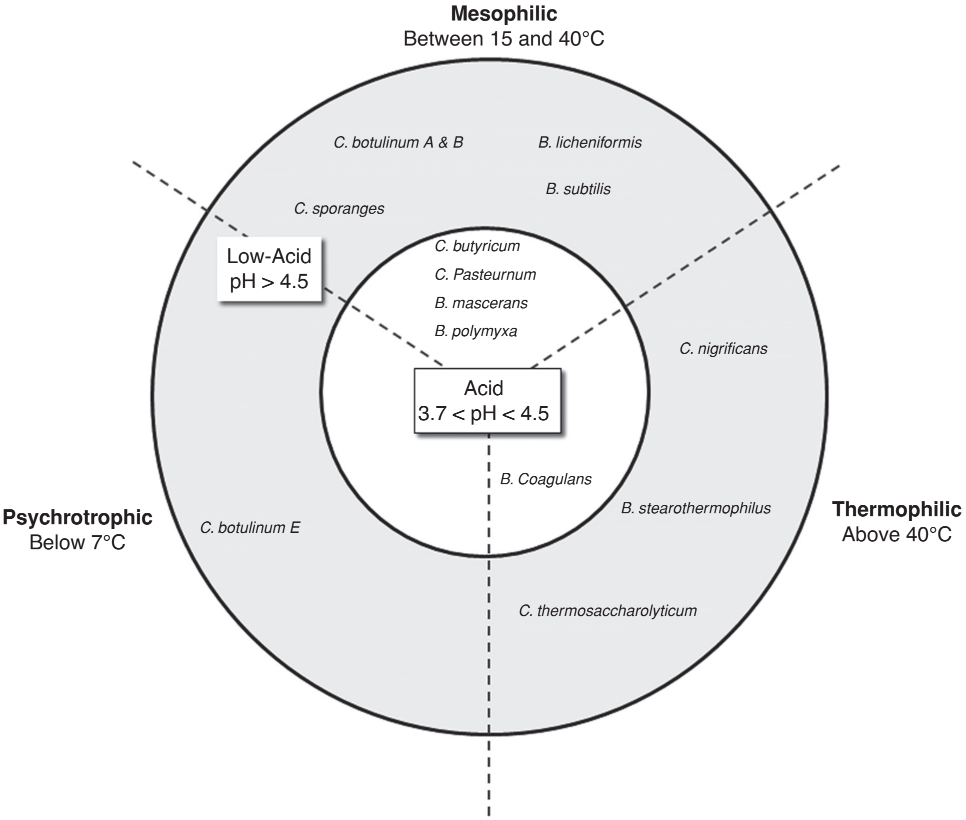


Figure 6.1. Thermal and pH Conditions for Spore-Forming Spoilage Bacteria

the size of the container in the calculation. Nevertheless, the processing industry practices rigorous controls, and outbreaks of botulism poisoning due to under-processing are extremely rare (estimated at four cases and two deaths between 1942 and 1980 after producing more than 30 billion cans of food) [4].

Heat Transfer Characteristics

Heat transfer, previously discussed in Chapter 2, is a critical part of thermal processing. For heat to kill organisms, it has to be applied to the media containing the organisms at sufficient level and for sufficient time to ensure commercial sterility. This can be a simple arrangement, such as in-home canning where the product is treated in boiling water for long periods, or a complex system such as in-flow microwave processing where microbial reduction occurs from heat being created in the product itself by an EMF field.

For simpler types of thermal processing, the basic type of processing (canning, in-line pasteurization, and the like) as well as the type of heat source (most often, steam) and heat transfer regime (conductive, convective, or a composite means) used will affect the processing variables such as time and temperature involved in achieving a particular level of pasteurization or commercial sterilization.

Microbial Destruction, Thermal Death Time, D, and z values

Thermal Death Time (TDT) is a measurement of the time a particular process requires to kill a given number of organisms at a specific set of operating conditions. These are usually temperature and operating pressure for traditional canning processes that hold containers for treatment or may be related to temperature and heating-section residence times in pasteurization and aseptic processing lines where the product flows continuously through the system. These requirements are usually determined by both calculation and test-operation using indicator organisms. It is critical to understand that although many examples and a great deal of literature is based on the assumption of a simple logarithmic death curve, the actual death time and death rate is more likely to be a statistically uncertain function and must always be checked against trials of the actual system to ensure adequate microbial reduction. Decimal Reduction Time, usually termed *D*-Value, and abbreviated as simply *D*, is the amount of time that a thermal treatment process, operating under a particular set of process parameters, requires to kill 90% of the pathogen population present at the start of the time interval. Processes are often specified in terms of the *D*-value and, as previously discussed, most commercial sterilization procedures require a *12-D* reduction in a particular organism (usually *C. botulinum*), producing the probability of contamination to be 1: 1.0×10^{-12} per gram of product. Note the effect of pH on the *D* value for an idealized product shown in Figure 6.2 [5].

The *z*-value is the temperature change required to shift the process microbial destruction curve by one log cycle, as shown in Figure 6.3. Thus, if a process has a 12-*D* value of 20 minutes,

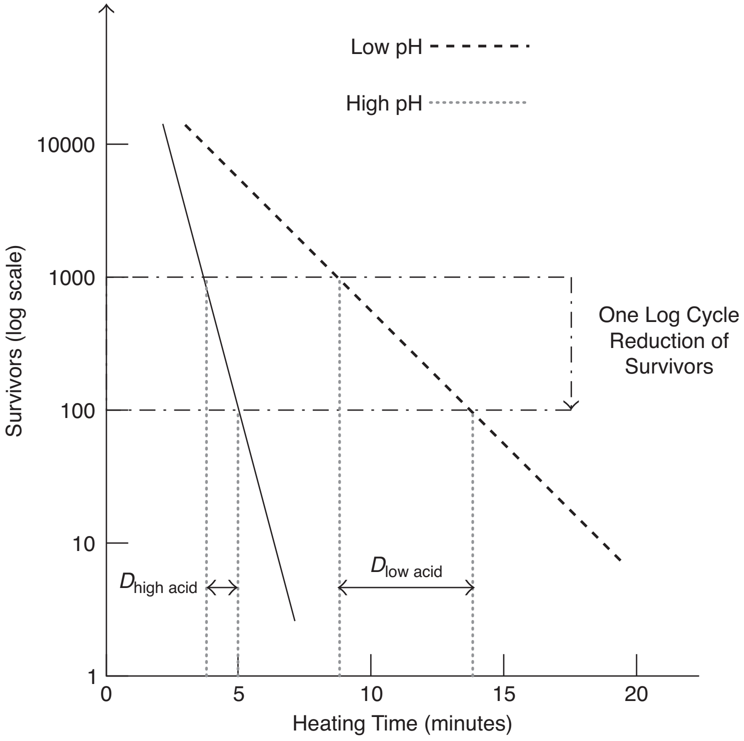


Figure 6.2. Calculation of *D* Values in Thermal Processing

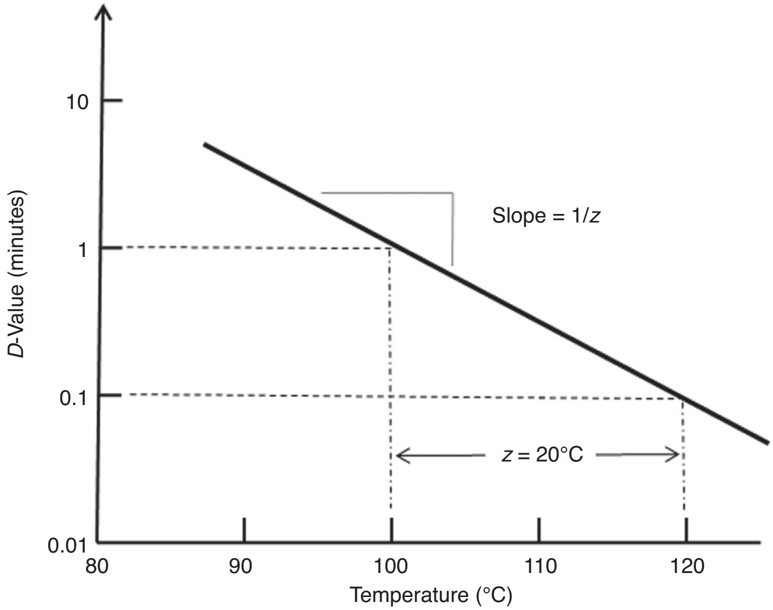


Figure 6.3. Calculation of *z* Values in Thermal Processing

and a *z*-value of 10°C, a 10-degree increase in temperature will result in the process time being shifted to 2.0 minutes, and a 10-degree decrease from the original starting temperature will result in the process time being shifted to 200 minutes. Of course, these figures have practical limits. *z*-values should be confined to known useful values for the microbial destruction curve – extrapolating the above figures by cooling the process by 50 degrees from the original starting temperature would extend the process time to 2,000,000 minutes – about 3.8 years!!

To evaluate and compare processes using a relatively standard reference point, the F-value represents the total time to achieve a desired *D*-value (E.g. 12-*D* for *C. botulinum*), and is frequently referenced at a standard temperature of 121°C (250°F), and thus is abbreviated as D_{121}. The simplest value for F is an F_0 value that assumes an instantaneous and homogenous temperature change throughout the product and will provide a calculation of the ideal-case for processing.

$$F_0 = D\,(\log N_{\mathrm{i}} - \log N_{\mathrm{f}}) \qquad (6.1)$$

N_{i}: initial microbial load
N_{f}: final microbial load

Because of the realities of heat transfer and the economics and mechanics of real-world processing operations, neither the amount of thermal input will be instant, nor the temperature profile homogeneous. Thus, a number of methods have been devised for calculating the overall F value that integrates the thermal energy input and resultant lethality.

The usual notation for F values has the z value as the superscript and the temperature as the subscript, where both are expressed in the same units system. Thus, for a standard temperature of 121°C (250°F) and a z value of 15°C (27°F), the F value would be expressed as ${F_{121}}^{15}$ or ${F_{250}}^{27}$ in Fahrenheit units.

F-Values that represent the logarithmic-linear (first-order) reduction curve of the traditional literature must be modified with the realization that the assumption that microbial populations are homogeneous is as unlikely as the assumption that the human population is homogeneous. Research has shown that the thermal death kinetics of actual microbial populations are more often a higher-order function and may be described by several different mathematical functions.

For example, rather than a simple Arrhenius curve, the death curve may be a concave logarithmic function described either by

$$(Log\ N(t)/N_0) = -kt^p \tag{6.2}$$

$N(t)$: Population at time(t)
N_0: Population at time$(t = 0)$
k: Population curve constant
t: Time, s
p: Process Constant

or by several other functions involving Weibull frequency distribution models that, although both literally and figuratively complex at times, can incorporate information about non-Arrhenius death curves and accurately describes nearly any real-world time-temperature death time correlations [6,7]. Most of all, given that there is a likely degree of uncertainty about the exactness of the thermal death curves, it is important that validation studies are done to ensure adequate processing.

Thermal Process Calculations

Commercial Sterilization

Calculating accurate and useful operational parameters for thermal processing is the subject of a great deal of engineering effort and literature. Although there are formulas and tabular systems that are commonly used in determining process parameters, there is also a growing array of computational tools ranging from spreadsheets to complex neural network systems to provide accurate, safe process lethality parameters [8].

The General Method and its variants use the fact that within limits, time and temperature can be traded off to provide the desired lethality for a process. Thus, the sterilizing effect as the temperature profile changes in the food material is accommodated by factoring its equivalent value at a reference temperature (usually 250°F/121°C) and summing the values. The *lethal rate* can be calculated as shown in Equation 6.3.

$$\text{Lethal Rate} = 1/10^{(121^\circ C - T)/z} \tag{6.3}$$

Thus, for a z value of 20, the values for lethal rate are shown in Table 6.1.

These can be used to “accumulate” lethal rate value as the area under a lethal rate curve, as shown in Figure 6.4, which links temperature and time to lethality via translation through the lethal rate values (which, of course, can be automated in actual use).

This effect can accommodate both the heating and cooling profiles in the container, which are measured by placing a thermocouple or similar temperature recording device in the *cold spot* of the container and monitoring the temperature during the process operation. Summing the

Table 6.1. Lethal Rate Values for $z = 20$

Temperature	Minutes at 121°C	Temperature	Minutes at 121°C
100	0.089	119	0.794
101	0.100	120	0.891
102	0.112	121	1.000
103	0.126	122	1.122
104	0.141	123	1.259
105	0.158	124	1.413
106	0.178	125	1.585
107	0.200	126	1.778
108	0.224	127	1.995
109	0.251	128	2.239
110	0.282	129	2.512
111	0.316	130	2.818
112	0.355	131	3.162
113	0.398	132	3.548
114	0.447	133	3.981
115	0.501	134	4.467
116	0.562	135	5.012
117	0.631	136	5.623
118	0.708	137	6.310

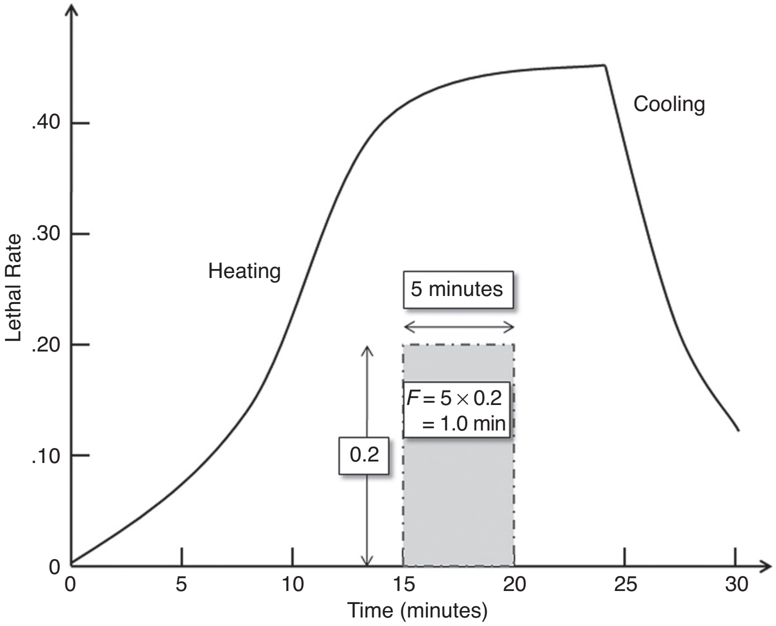


Figure 6.4. Lethal Rate Curve for Process Calculation

equivalent lethality values over the total process will give an equivalent lethality value ($F_{250/121}$) for the organism in question. This will have particular applications in calculating the lethality of pasteurization and aseptic processes where temperature lag is considered to be minimal. The general method and its variations have the limitation of only indirectly returning operating parameters such as retort shutoff time, and may require trial-and-error calculations to converge on a working answer.

The Formula Method, first published by Ball in 1923 [9] and subsequently refined [10], uses knowledge of the heating and cooling lag in the product as well as operating conditions in combination with tabular calculation coefficients to provide a good approximation of the operating time required by a particular process to achieve commercial sterilization. In its simplest variation, to calculate the value for the thermal process time, t_B, the general formula

$$t_B = f_h \log\left[\frac{j_h(T_M - T_i)}{g}\right] \tag{6.4}$$

f_h: the heating rate constant, the slope of the steady − state heating curve.

$$j_h = \frac{T_M - T_1}{T_M - T_0}$$

$$j_c = \frac{T_1 - T_M}{T_0 - T_M}$$

$$g = T_M - T_B$$

j_h: heating lag constant
j_c: cooling lag constant
T_M: The temperature of the heating media
T_i: The initial temperature of the product
T_B: The reference point (usually the "cold point") temperature in the container
g: The product temperature difference between the heating media and the reference point in the material at the end of the product heating

can be used where j_h, the heating lag constant, accounts for the nonlinear temperature change when heating begins and has not yet achieved a linear rate of increase, and j_c, the cooling lag constant, as defined by accounts for the nonlinear temperature change when cooling begins and has not yet achieved a linear rate of decrease.

It is most usual to use Ball's calculation method in conjunction with graphs (or their digital equivalent) of (f_h/U) versus log (g), where U is the Thermal Death Time for a particular z temperature value, which will allow rapid estimation of the thermal processing times.

The general and formula methods, as well as many variants that have been developed over the years, are rapidly being supplemented with computer-based heat transfer modeling that will allow not only a more accurate estimation of the heat penetration into the product and the resulting deaths of populations of microbes whose response to heat may be non-linear, but can help understand materials that undergo phase changes or other substantial thermodynamic effects in order to create the proper balance between product over-processing and inadequate sterilization. Additionally, these newer methods can be used to analyze less severe treatment methods such as pasteurization and sterilization using HTST/UHT processing. No matter which methods are used, however, it must be re-emphasized that process verification tests

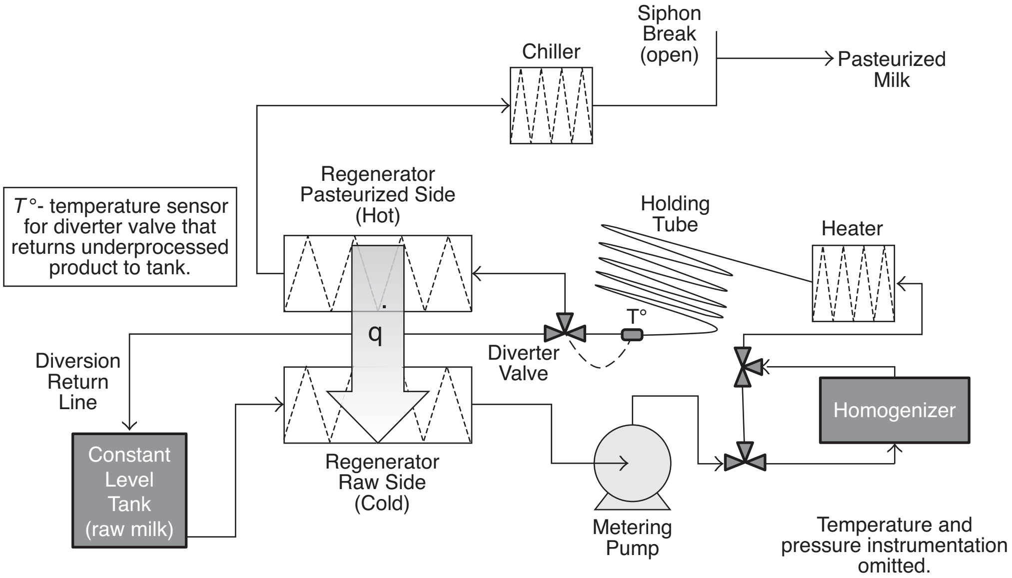


Figure 6.5. Basic Pasteurizer Flow Diagram

must be conducted to verify that calculations have resulted in the required degree of microbial destruction.

Pasteurization is a less severe form of heat treatment, generally applied to destroy particular organisms of interest in a particular food product. The most common form of pasteurization is applied to milk in order to destroy *Mycobacterium tuberculosis* and *Coxiella burnetii*. For milk products, the rate of destruction of phosphatase is used as the evaluation criteria because it is destroyed at a slightly higher temperature but approximately the same rate as the two organisms, and is easily assayed; presence of the enzyme is a simple indication of inadequate treatment.

The schematic for a pasteurizer is shown in Figure 6.5. Although there are a number of variations depending on manufacturer, all share several common safety features. In all designs, pressure gradients are incorporated to ensure that any leakage forces processed product back into the unprocessed stream (particularly through regenerator heat exchangers), thermal sensors return under-processed product to the process intake, and vacuum/siphon breaks are incorporated to prevent the system from drawing processed product back through the system.

UHT processing is an extension of this technology with higher temperatures and shorter residence times. Standard pasteurization schemes for milk can be any of several time and temperature combinations, as shown in Table 6.2 [11], with the resulting shelf life and intermediate processes such as ESL processes discussed in Chapter 7.

Although the HTST processing criteria presents the temptation to construct a *flash* process that heats milk to the boiling point for a fraction of a second, the realities of heat transfer and fluid flow usually provide a discouraging counterpoint in that it may be very difficult to create enough mixing and heat transfer to guarantee proper heating of every part of the product in such a short time without destroying product quality. As a result, the slower processes are more common in order to ensure both proper processing and a safety margin in the response capability of the pasteurization equipment.

Table 6.2. Pasteurization Times and Temperatures

Type of Pasteurization Process	Time	Temperature
Low Temperature, Low Time (LTLT)	63°C/145°F	30 minutes
High Temperature, Short Time (HTST)	72°C/161°F	15 seconds
	89°C/191°F	1.0 second
	90°C/194°F	0.5 second
	94°C/201°F	0.1 second
	100°C/212°F	0.01 second

Other types of products such as fruit juice are pasteurized both to extend shelf life under refrigerated storage and to reduce or eliminate the presence of certain microorganisms such as *E. coli* 0157:h7 that have been associated with unpasteurized cider [12]. Non-thermal methods such as ultraviolet pasteurization have been investigated for some of these applications in order to provide a low-cost means for small processors to meet standards. Other non-thermal and thermal-supplementing types of pasteurization such as ozone use or thermosonication have been investigated for some time and are discussed later in the chapter, but cost and dependability issues usually restrict widespread implementation [13]. Chemical additives can be used as an adjunct, but may interfere with flavor characteristics or prevent an "organic" label claim.

Hot Fill Processes

As the name implies, hot fill processing involves heating the product to a temperature below its boiling point, often 90–95°C, holding it at that temperature for up to 30 seconds, and then filling the container at a temperature up to approximately 85°C (185°F) when used with plastic containers, or possibly higher with glass and paper-based cartons. This offers the advantage of using the product itself to reduce or eliminate microbial activity on the packaging material, as well as providing a shelf-stable product for low-pH, high-acid foods and an extended shelf life for higher-pH products. This process is commonly used with juices, teas, and other drinks, and when combined with a properly stable or preserved product can provide ease of filling as well as thermal treatment to viscous food product such as jams and fillings. The packaging challenge has been to provide plastic containers that will withstand elevated filling temperatures, and PET, PBT, and its variants dominate this market for consumer applications, often with vacuum panel design features to disguise the vacuum collapse that occurs after cooling the sealed product. Hot filling for bulk ingredients may use any number of thermally stable containers including pails and aseptically lined intermediate bulk containers.

Degradation of Product During Thermal Processing

Many types of degradation may occur in products as a result of thermal treatment, even though the treatment may not be excessive. Thermolabile components may include enzymes, vitamins, starches, proteins, color, and flavor compounds all of which will have a thermal destruction profile similar in concept to those previously discussed for microorganisms (Table 6.3). In general, the balance that must be achieved trades degradation of the food product against microbial safety, and the impetus is to provide processing methods that reduce the former without compromising the latter. Because microorganisms are often much more thermally

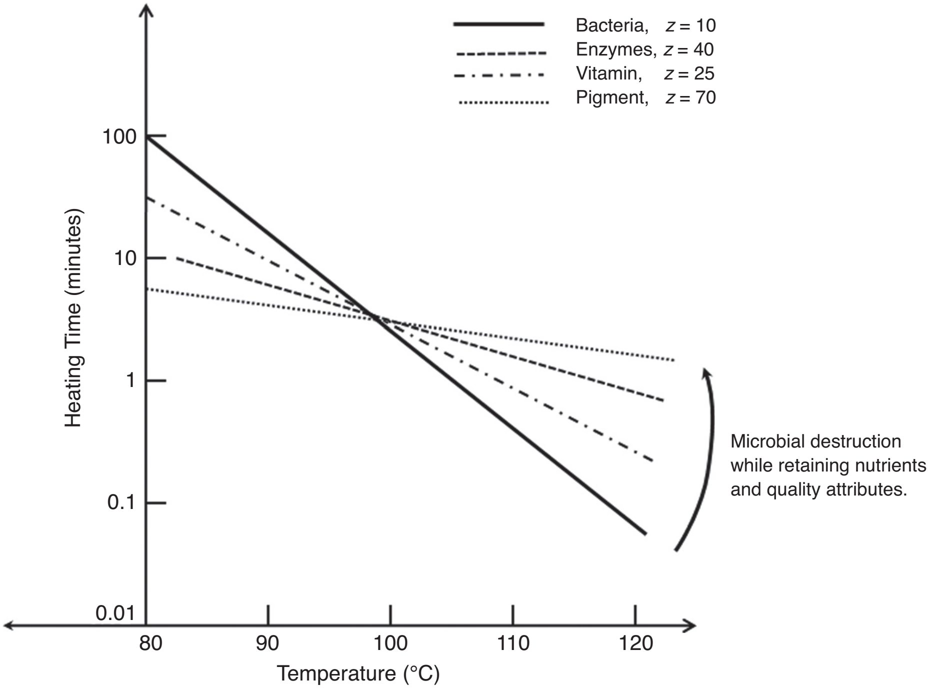
Table 6.3. *z* and *D* Values for Bacteria and Food Components

	z-value (°C)	D_{121} (min)
Bacteria	5–10	1–5
Enzymes	30–40	1–5
Vitamins	20–25	150–200
Pigments	40–70	15–50

Source: University of Guelph. "Thermal Destruction of Microorganisms." http://www.foodsci.uoguelph.ca/dairyedu/TDT.html

susceptible than vitamins and pigments, the destruction rate per unit time may be much higher and the application of a short-term heat impulse can result in microbial destruction and enzymatic inactivation with minimal loss of other desirable components, as shown in Figure 6.6.

This difference in reaction time again leads to the development of Ultra High Temperature (UHT) processes that typically will hold the product for 1–3 seconds at temperatures well above boiling (typically, 135°C/275°F). This will retain many of the characteristics of the food product and lead to a shelf-stable product such as UHT milk and many soups, broths, and sauces currently on the market. The temperatures used may present other problems, such as the caramelization of sugars that gives UHT milk its distinctive taste, but many products previously sold in cans have shown a notable quality increase with the adoption of UHT processing combined with aseptic packaging operations.



Approximate Scale Only

Figure 6.6. Relative *z* Values for Bacteria and Food Components

Aseptic Packaging

Aseptic packaging in and of itself is nothing new. Early canning experiments involved out-of-package sterilization and canning under steam or ultraviolet light, but the common current usage refers to a combination of UHT or HTST processing as previously described, hermetically sealed packaging to prevent recontamination of the product, and a fabrication and assembly system that operates under sterile conditions in order to fill and seal the package after processing the product such that further processing will not be necessary to provide an extended shelf life or commercial sterility.

The initial markets for early experimentation with aseptic processing and packaging systems were typically regional milk producers who needed to extend shelf lives of product, and various development efforts led to the production of the first tetrahedral milk packages formed from chemically sterilized barrier material in a modified TetraPak® machine in the early 1960s. Although the unusual original tetrahedral packages were never widely accepted by the American consumer who had ready access to quantities of refrigerated fresh milk, large quantities were successfully distributed to the military and to school lunch programs.

Subsequent production of more conventional rectangular and semi-rectangular packages followed in tandem with the growth of technical knowledge, improved barriers for packaging materials, and the inevitably slow regulatory approval, particularly for low-acid food products that are ideal bacterial growth media. Although the technology is much more energy and material efficient, as shown in Figure 6.7, the enormous infrastructure for the manufacture, distribution, and storage of canned, frozen, and refrigerated products in developed countries as well as regulatory concerns over process safety have slowed the adoption of many aseptic products on a widespread basis.

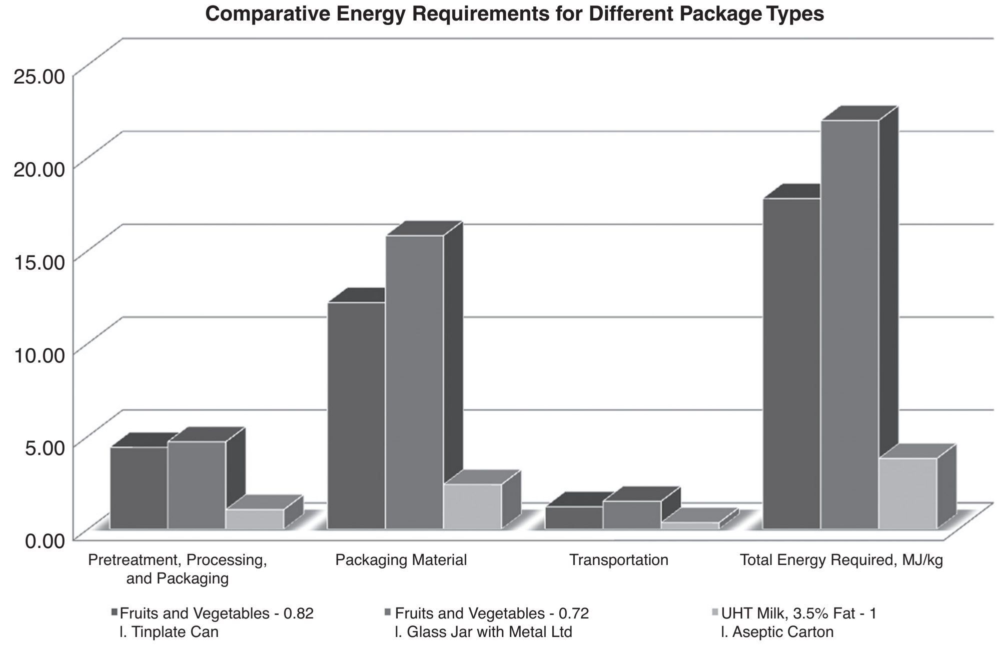


Figure 6.7. Energy Use in Aseptic and Traditional Processing Methods
Source: Derived from: Reuter, H. (1980) Verpackung von Lebensmitteln, 31, 132–6

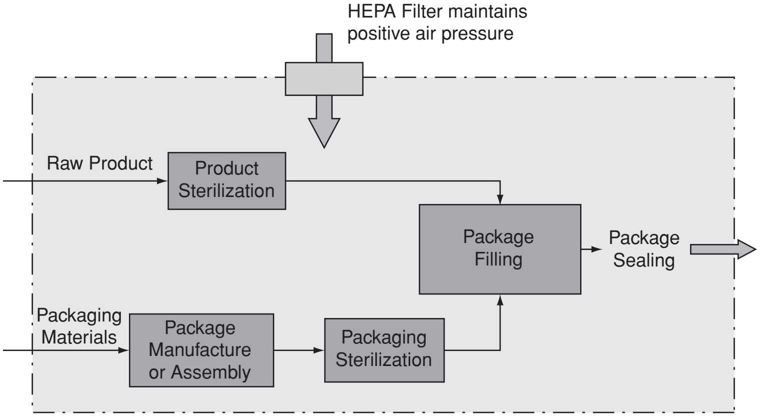


Figure 6.8. Aseptic Processing Line Diagram

Niche products such as soups, broths, cheese sauces, and the like have seen a high degree of success for particular applications by reducing empty container disposal costs, reducing injuries from cans, and often improving product quality for the consumer, and inroads are being made in traditional markets for processed whole tomato products, meat stews, and fish.

General Layout of Aseptic Processing Lines

As shown in Figure 6.8, the general layout of the aseptic process involves constructing and sterilizing the food package and treating the product, then combining them both under sterile conditions to provide a shelf-stable product. This is most often done in a sealed enclosure, under a positive air pressure environment provided by a HEPA (High Efficiency Particulate Air) filter and blower assembly. Given that there are a variety of package types, products, sterilants, and other variables, there are some general principles that are at work, but the larger process must be developed individually.

Product Sterilization

Product sterilization for non-particulate liquid products is a relatively straightforward process based on existing UHT technology, and the same simple heat exchangers may often be used. For products containing small particulates (<10 mm), the retardation of heat transmission to the center of the particles may require scraped-surface heat exchangers to ensure that proper heat transmission occurs, and may increase equipment costs and maintenance problems. Larger particulates (>10 mm) may require sterilization of the liquid and solid components in separate stages, then recombination in order to ensure adequate processing [14].

Packaging Material Sterilization

Material sterilization is an essential part of the aseptic packaging process and may be achieved by many means, although fewer are actually useful or effective because of material degradation, toxicity, workplace hazard, or cost. Many of the potential sterilizing methods and materials may be toxic, or may degrade or contaminate the packaging material or affect its ability to perform over long periods of time. Thus, ethylene oxide, hydrogen peroxide, heat, or steam may remain the process of choice for some time. Electron beam or gamma radiation suggest themselves if the installation, operation, and safety concerns can be managed.

Equipment Concerns

Establishing and keeping a sterile environment within the operating machinery is one of the most difficult facets of making the transition to aseptic packaging operations. Training personnel to avoid accidental contamination is a critical facet of maintaining high production levels, because simply reaching inside to make an adjustment requires complete re-sterilization of the entire production line. Some newer installations are built with access glove boxes and tunnel-entry protective suits to allow workers "hands-on" access to equipment and operations. Additional considerations such as the maintenance of a sterile environment in the event of power fluctuation or HEPA airflow pressure variations are an additional concern.

Commercial Microwave Processing

"Commercial" microwave devices, whose principles of operation have been discussed in Chapter 2, have come to mean microwave ovens that are similar to home ovens but used in commercial facilities, most often restaurants and cafeterias, and these may use the 915 MHz frequency that was allocated (along with 2,450 MHz) for microwave use. Although various companies have worked with different types of microwave technology to produce competitors to current thermal methods of processing, the effectiveness of these against spore-forming bacteria have not been proven [15]. In addition, the cost and complexity of installed equipment, potential operator safety hazards, and the relatively low thermal efficiency relative to direct combustion or even resistance heating has always been a barrier for mainstream applications such as simple food processing, freeze drying, and grain drying, although microwave furnaces are used for critical applications in ceramics and composite materials processing. One paradoxical use that the food industry has found for microwave heating is for "tempering" frozen foods, particularly frozen meat carcasses and cuts – warming them to temperatures near the melting point so that additional operations such as slicing, grinding, and forming can be performed.

Alternate Processing Technologies

Other technologies being investigated for commercial use as sterilization or pasteurization techniques are often derived from technologies that have existed for some time but have been resurrected because of new developments such as advanced control systems or new refinements in methodology. As with many of the previously discussed methods, the refinements and developments for applications for food were originally developed for other industries and have been subsequently adapted to food processing uses. Some of these methods include light-based processing, pulsed electric field and electric discharge, ultrasound, ultra-high-pressure, and various *multiple-hurdle* processing methods that may combine several of these methods and include conventional thermal heating or chemical additives. Most of these new processing technologies are being tested on an experimental basis for use with fluid and semi-fluid food products [16].

Light-Based Processing

Light-based processing has existed for decades, with some of the original processes for pasteurization of milk dating back to the 1930s, but light offers a potentially good source of energy transfer for the proper product. Ultraviolet light processing using equipment originally designed for UV curing of coatings and adhesives has been tested as a means for modest cider processors to achieve an approximately 5-log reduction in bacterial count and to reduce the risk from *e. coli 017:H7*. Although there is a risk of photolysis of flavor and nutritional compounds, the microbial contamination risk in these products is great enough that the small changes that might occur are considered acceptable. Research on very-high-intensity light, typically from a gas discharge tube or arc source, is still being done in an effort to reduce thermal degradation of flavor and odor during processing, particularly of UHT milk and similar products.

Because the transfer of energy to microbial contaminants is hampered by the opacity of a material or by the *shadowing* of organisms by particulates, light-based processing methods have limited usefulness in many products except for surface treatments and relatively transparent products. For this reason, most light and pulsed-light systems are systems for the pasteurization of clear or translucent fluids. Ultraviolet systems using short-wavelength, high-energy light typically comprise a flow cell and light source, typically of annular design that allows the product to flow in the space between an inner light tube and an outer shell. Pulsed-light systems are more often for "flash" treatment of both products and material surfaces, including packaging materials and medical devices and materials. Because pulsed-light systems operate intermittently by creating broad spectrum, high-energy discharges, they are typically constructed as treatment chambers, holding the product in static position temporarily allowing the light pulse to occur, although several in-flow systems have been licensed. The pulsed-light method has not proven to be a commercial success, however, and as of this writing is not being manufactured.

Pulsed and Oscillating EMF Treatments

Several variations of pulsed electric fields, oscillating or pulsed magnetic fields, and electric arc discharge have been used on an experimented basis, with only the pulsed electric field systems yielding a large body of promising research results. Arc discharge, which can produce any number of electrolytic breakdown compounds, works by producing both electrolysis compounds – particularly free radicals – and hydraulic shock phenomena that are similar to the ultrasonic methods discussed elsewhere. The breakdown compounds may cause problems with textures or flavors in food products, and have made the process one that is unlikely to be used in its current state for food products. Although the Electropure Process milk processing system dates back to the 1920s, current implementations claim that they can be more energy efficient than other electrically based systems. These can combine to lyse cells and produce pasteurization or sterilization effects, but current research is sparse and more work needs to be done for large-scale processing to be widely adopted.

High-intensity and oscillating magnetic field technology uses either an oscillating magnetic field where the polar orientation switches periodically or a static magnetic field where the polar orientation remains constant to attempt to reduce or eliminate microbial contamination. Results of these treatments are mixed, with different types of organisms exhibiting various reactions ranging from population reduction to increases in colony formation, depending on the type of organism. To further complicate the problem, generation of a high-intensity magnetic field typically requires a high-energy discharge from a capacitor bank, or other technology such as superconducting magnetic coils, which implies that large-scale processing would be complex and energy-intensive, although the magnetohydrodynamic induction effect on the ionic compounds implies that a properly constructed device could both treat and pump liquid materials simultaneously.

Pulsed electric field (PEF) technology has seen the most research focus, and various implementations have shown some promise for the pasteurization or sterilization of liquid materials. The chief mechanism for pathogen destruction appears to by electroporation or electrical breakdown of the cell wall. Both of these proposed mechanisms lead to the eventual destruction of the cell wall and loss of cell contents, killing the pathogen, although electroporation will allow the uptake of external material, and is a common laboratory technique for the introduction of external DNA into a cell culture. The effectiveness of PEF treatments is a multivariate effect of field intensity, number and duration of pulses, pulse waveform, temperature during treatment, and various product factors such as dielectric strength, pH, and composition, as well as the type and concentration of specific organism being treated. Current experimental methods involve using equipment that incorporates the discharge electrodes into a flow cell that will allow continuous flow of relatively low-viscosity material.

Ultrasonic Methods

Ultrasonic treatment of foods is a technology currently being studied both as a stand-alone technology and in combination with other treatments to provide a multiple-hurdle approach to microbial reduction. Ultrasonic treatment has been shown to act by disrupting the cell wall and allowing the cell contents to escape, and with the increased durability of piezoceramic transducers may provide an efficient method of energy transfer into microorganisms, unaffected by opacity or electrical properties. Because ultrasound is a periodic function, and is subject to loss factors in some types of materials where the energy is converted to heat and dissipated rather than being transmitted – a so-called *lossy* material – there would be some few limitations placed on materials that have a high percentage of entrained air such as foams. Microencapsulated materials might suffer product quality loss because of micellar rupture, essentially rupturing the microencapsulation system in a manner similar to that which provides destruction of the cellular membranes. Although ultrasound technologies have been shown to be moderately effective in reducing microbial populations, due largely to cavitation effects, the incorporation of ultrasound into multiple-hurdle technologies such as heat, reduced pressure, and the use of additional sterilants such as ozone and hydrogen peroxide and ultrasound shows promise for energy-efficient processing methods. Additionally, exploratory uses of multifrequency and multimode systems have been shown to increase the effectiveness of sterilization methods.

High-Pressure Processing

As previously discussed in Chapter 2, high-pressure processing (typically up to approximately 600 MPa) shows promise for the reduction or elimination of microbial populations of vegetative *E. Coli*, *Salmonella*, and *Listeria* in moist, air-free foods, and for the creation of extended shelf-life foods, although the resistance of spores to pressures in excess of 1 GPa has thus far limited applications to pasteurization [17]. These methods have shown great promise for the enhancement of traditional thermal processing methods but have seen the largest growth for use with products where the texture changes do not detract from perceived product quality, and the retention of flavor and shelf life justifies the high equipment costs.

Although many of these processes show promise to complement thermal processing, without the clear advantage of equivalent processing capabilities and safety at modest cost, their greatest use may be to supplement or enhance existing process systems, although this will negate many of the low-temperature benefits. Improvements, standardization, and an understanding of the specific modes of action of these methods and others will be a critical factor in any potential replacement of thermal or radiation processing [18].

Refrigeration and Freezing of Foods

Foods have been frozen or preserved by low temperatures for as long as any kind of cold environment has been available. However, the modern variety of refrigerated and frozen foods has only come into its own since the World War II, assisted by home refrigeration and distribution and warehousing systems that allow relatively accurate temperature control throughout the product's pre-consumer existence.

Refrigerated distribution of commercial foods began with Swifts's early experiments with boxcars for carcasses bound from the Chicago slaughterhouses to eastern U.S. markets. These railcars were packed with ice in various configurations and early versions had problems either as a result of discoloring the carcasses or not adequately controlling the temperature. Later varieties solved these problems as well as load instability damage, although implementation by railroads was slow because of the threat to the railroads' existing live-animal handling infrastructure. Despite this, refrigerated carcasses steadily replaced live animal shipments throughout the 1880s, with the trend continuing until live-animal shipments became a rarity. When Chicago's rail lines were extended to nearby Milwaukee, Wisconsin, the beer manufacturers located there used the new technology to return-ship chilled, unpasteurized beer in the empty cars to Chicago's much larger markets.

Additionally, refrigerated and cooled railcars (*reefers*) allowed the development of the now-enormous national citrus and vegetable industries in areas of the American Southeast [19]. Iced reefers, initially dependent on regular loading with natural snow and ice, were in service until the 1970s but were all eventually replaced by cars with mechanically driven refrigeration, which allowed better temperature control and essentially unlimited use provided the compressor was refueled.

At the same time that reefers were being developed in the United States, mechanically refrigerated loads of mutton and beef were being shipped from Australia to Britain and Europe on freezer ships with compressors driven from the ships' steam engines, allowing both a needed supply of meat to those countries and a boost to the Australian economy. Japanese railroad systems were similarly reported to use cooled, ventilated, and occasionally iced shipments for the shorter-distance transport of seafood, fruit, and vegetables.

Current distribution methods include refrigerated truck trailers that typically have a diesel-driven compressor, as well as intermodal containers that can be run from a ship's central electric source so that unitized shipments can be maintained for very large distances.

Frozen foods were first commercialized in the United States by Clarence Birdseye who, while working as a naturalist to pay college expenses, observed that fish caught by the Inuit froze very quickly in arctic temperatures while maintaining their flavor and texture. Although foods were commercially frozen at higher temperatures, Birdseye's contribution was to flash-freeze foods so that ice crystals would have little time to grow and disrupt the cellular structure of the fruit, meats, and vegetables being processed, resulting in a higher-quality product. Birdseye's first continuous freezing system involved pressing waxed containers of food product between brine-chilled belts, which reduced air voids and increased heat transfer [20] – a method still in use in modified form using chilled plates.

Types of Freezing Systems

Freezing systems all seek to remove heat from the product as efficiently as possible. To this end, several varieties of refrigeration systems have been developed, which can be broadly grouped into three categories: non-contact, indirect contact, and direct-contact immersion/spray systems. All of these rely on large installations of refrigeration equipment that operate in a manner similar to the vapor compression refrigeration processes described in Chapter 5.

Non-contact *air blast* freezers rely on a high-velocity stream of refrigerated air to remove heat from the product, and are used for products that have shapes or configuration that do not allow contact-freezing to work well. Because of the insulating effects of packaging materials (if present) and the lower efficiency of heat removal using this method, the residence time in the freezer may be longer. Fluidized bed airflow freezers may allow quick freezing of granular or particulate materials in a manner similar to the fluidized bed dryers discussed later in this chapter, because the product will be suspended in the freezing air blast with good circulation around the product.

Indirect contact systems rely on conductive heat transfer away from the product, typically into chilled plates that may contain circulating coolant. Although conductive heat transfer may be more effective than other types, plate freezers may compress foods into unpalatable bricks, and single-surface plate freezers may not freeze foods rapidly enough. Liquid products are typically chilled to near-freezing in indirect heat exchangers before final freezing either in packages, as with fruit-juice concentrates, or in forms and molds as may be done with juice bars. Final freezing (*hardening*) can be done with an air-blast freezer.

Direct-contact freezing depends on the circulation of liquid or sprayed refrigerant on the product either before or after packaging. This may be even more effective than indirect-contact freezers, because the product can be sprayed or immersed directly in refrigerant, often carbon dioxide or nitrogen, as required. Brine-based immersion systems may be used as well, although the brine must be removed from the product after immersion, which may be difficult for unpackaged products.

Frozen Food Properties and Processes

Because the thermal properties of foods change as they change phase into a frozen state, the prediction of specific properties of frozen foods have been the subject of a good deal of research. A good example is simple water ice, which has a thermal conductivity approximately 3.8 times that of liquid water and a density of about 0.92. As one might expect, a freezing process will therefore be nonlinear as the *freezing front* – the boundary of the frozen region – progresses inward through the product. Similarly, the latent and sensible heat given up by the product as it freezes will both affect the freezing time and may produce profound effects in the product, because the extracted heat must be conducted outward through the already frozen material and may cause product degradation as it does so. Numerical analysis of freezing fronts have provided some insight into the nature of the thermal properties of food during freezing, but broad estimation and trial-and-error persist as the usual method of determining process time [21]. Degradation of frozen products is often termed *freezer burn* because of the browned, dehydrated state of the product. This has been shown to be a function not only of temperature but of the state of water in foods, with browning and other processes dependent on whether the food material is above or below the glass transition temperature, T_g covered in Chapter 7, which may be well below the observed *frozen solid* point for many foods [22]. The product may be above its T_g point yet still appear to be thoroughly frozen, and with moisture more free to migrate through and out of the product, the shelf life will be severely reduced. Unfortunately, many consumer freezers are not capable of maintaining the extremely cold (−23°C [−10°F] to −32°C [−25°F]) conditions required to lower most foods below their T_g and achieve very stable storage conditions, so shelf life may be limited even with good protective packaging.

Refrigerated Foods

Refrigeration using natural ice, cold water, or mechanical means has been used to extend the shelf life of products throughout history. This typically occurs by reducing the growth rate of spoilage microorganisms for products such as meats and dairy, as well as reducing the growth and ripening rate of fresh fruit and vegetables. When combined with pasteurization to reduce the initial microbial load, products such as milk and lunch meats can be kept fresh for at least two weeks, allowing wide distribution and home consumption [23]. Most refrigerated products represent an early form of multiple-hurdle preservation in the sense that they are typically treated either with chemical preservatives, pasteurization, or other physical means to reduce the microbial count, and then the temperature is held as close as possible to freezing to reduce the microbial growth rate. This process has been extended to include multiple-technology extended shelf life products such as bagged salads, which use a chlorine-based wash to reduce microbial loads and then refrigeration and controlled-atmosphere packaging to stabilize the product for long periods of time. Fresh pasta products have seen similar success by using oxygen-absorbent packets, and dairy products such as cottage cheese are kept fresh by refrigeration and the addition of carbon dioxide [24].

One of the major concerns with refrigerated foods is *temperature abuse* in the supply chain – conditions that expose the product to destructive temperature rises and fluctuations. A malfunctioning refrigeration system can cause the temperature to rise and microbial growth to achieve an unacceptable rate without outward indication, but careless handling is usually the predominant cause of the problem. Many devices have been developed to track the temperature profile during storage, and most suffer from the lack of ability to record anything but surface temperatures, which can give a misleading impression of the internal temperature of a product. Newer devices that include sufficient data storage and computing power are doing a better job of estimating shelf life based on simple Arrhenius curves, but simple chemical and physical indicators will usually only give surface indications and may be error-prone for all but the most sensitive products [25]. The surface data collected by temperature loggers is useful for estimating product damage if the thermal properties of the product are known and *dummy* products (or genuine ones with embedded data collection) are occasionally used.

Temperature abuse beyond the supply chain is a major concern with regard to food safety – the inability of consumers to store foods in appropriate ways should never be doubted, and packaging should be clearly labeled if refrigeration or freezing is required, even if it seems obvious. Additionally, many consumers have poorly regulated refrigerators either because of mis-set thermostats, mechanical problems, or the refrigerator used in a house with children that can have the door opening and closing much of the day. Finally, it may not be possible for consumers to transport refrigerated or frozen foods any distance without special measures. Consumers in the American South and Southwest have been observed carrying frozen foods home from grocery stores in ice chests, even while travelling in air-conditioned cars, because of the extreme heat.

Drying of Foods

Another historical method of food preservation is drying, which effectively reduces moisture availability for spoilage and often provides a more compact means of food storage by eliminating excess water. The general process of adiabatic drying has been discussed in Chapter 2, but the practical application of drying processes can take many forms.

The earliest types of consumer food drying were simple air-circulation racks and drying trays that were used to dry fish, meats, and vegetables, some of which are still in use in remote areas both for crops such as dates and coffee as well as for locally consumed fish, meats, fruit, and vegetables. Because these are subject to both contamination by dirt, insects, and vermin as well as the vagaries of the weather, they are generally not accepted for many products that must meet an exact production schedule or strict cleanliness standards.

Because drying methods rely on the ability of moisture to be removed through the product cross-section, it is usually a common sense step to reduce this distance as much as possible to increase the speed and efficiency of drying and reduce the possibility of scorching or cracking the outer surface of the product. Thus, traditionally dried meats are cut into thin strips first, and in commercial operations fruit is typically cut in thin slices or chunks, while particulates, fluid films, and fluid drops are kept as small as practicable in most drying.

Generalized Drying Mechanisms

There are several distinct types of simple drying that occur, and these may occur sequentially during many types of drying processes. These have been segmented by mechanism into a constant rate and two falling rate curves that will occur when moisture content and drying rate are compared as shown in Figure 6.9.

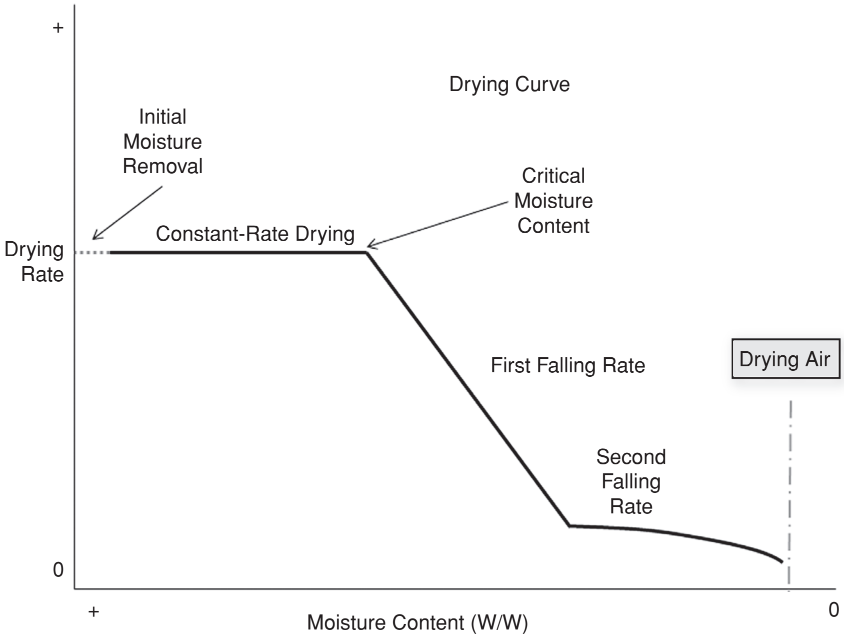


Figure 6.9. Generalized Drying Curve

Initial Moisture Removal (Warming Stage)

In this stage, surface moisture and moisture lying very near the surface will be removed by direct evaporation into the air stream for as long as there is moisture available, and the product may exhibit a temperature rise limited to that of the wet-bulb temperature of the air.

Constant Rate

Constant-rate drying usually occurs at a constant temperature, and is only limited by the heat-transfer rate into the product and moisture, and the mass-transfer rate into the air stream. When the easily removed moisture is completely removed – the so-called Critical Moisture Content – moisture removal will continue at a decreasing rate.

First Falling Rate

In the first falling rate, product drying is limited by the ability of moisture to diffuse from the center of the product to the surface for removal and is limited by heat transfer and the diffusion characteristics of water in the material.

Second Falling Rate

The second falling rate is the point at which the A_w of the product begins to decrease below 1.0 (the bound water capacity of the product), and the rate of moisture removal is limited by a complex set of factors such as thermal conductivity of the product because the moisture must be vaporized within the product before it can diffuse outward to the surface for removal. During this second rate, the moisture-binding mechanism may shift to a system that may appear as another falling rate, where the moisture is held in low-order molecular layers by capillary condensation* and is usually quite stable.

Termination

Termination of the drying process is usually determined by the desired moisture content of the product, because excess drying is costly, requiring both energy and time with diminishing returns near the termination point. Drying is usually terminated in the stable region described in the previous paragraph in order to provide a shelf-stable product, but if run indefinitely will produce a product that is in equilibrium with the drying airflow. For contact-drying (non-airflow) operations, more moisture may be driven out.

Prediction of Drying Times

Prediction of drying times may be taken from trial data and extrapolated graphically using a simple chart of time versus moisture content once the final drying rate has been established, or can be done algebraically using the slope of the experimentally determined drying curves, although this is usually unnecessary. In either case, the variability among product batches and drying machinery requires verification of drying times until the consistency of the process can be assured.

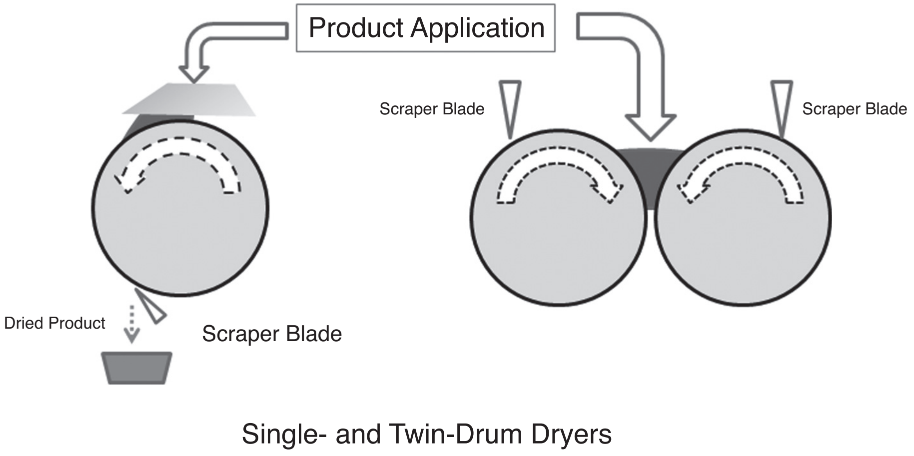


Figure 6.10. Drum Dryer Diagram

Drying Methods

Drum Drying

Drum drying is one of the few direct-heat-conduction-based drying methods, and is used to evaporate solvents from a thin film of material that is spread on the surface of a heated rotating drum as shown in Figure 6.10. Typical food products that are produced with drum drying include many powdered products such as cornstarch, dried yeasts, dried soups, milk and fruit pulps, and mashed potato flakes. Although the product is usually composed of solids contained in a liquid or slurry of some sort, it is possible to use a rolling hot drum to dry other products (as is done in the paper industry as described in Chapter 3). Cereals may be produced by heated rollers "ironing" blobs of cooked grain into dried flakes in a single process, and product feed is often very similar to the coating methods described in Chapter 5, with product either being fed directly to the heated steel drum, applied via a transfer roller or spray, or applied between two closely spaced drums. The surface finish of the drum may be important because application doctor blades may control the applied film thickness, and there may be scraper blades assisting in the removal of the dried product. Highly polished surfaces or nonstick plating may assist in removal of some products.

The rate of moisture removal is a function of the product's film thickness and thermal conductivity, the drum's heat differential between the drum surface, the product, and the outside air, the relative humidity of the air, the useful fraction of the drum that the product is in contact with, and the time that the film is in contact with the heated drum, which is a function of the product's feed rate and the drum rotation speed. Other factors such as the gelatinization region in starch feeds may also figure in some operations [26].

While it is possible to construct a general equation describing the heat transfer characteristics of particular machinery, these ballpark figures inevitably are used as a starting point for adjusting the process operations to a more optimal state. More importantly, recent developments in sensors and controls can allow a process operation to self-tune to match the product and any changes in the process while it is in operation.

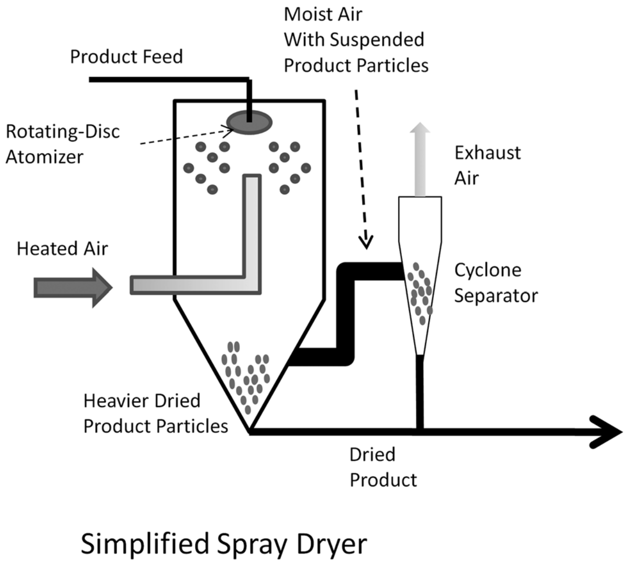


Figure 6.11. Spray Dryer Diagram

Spray Drying

Spray drying is used to dry liquid materials such as instant beverages and other food components. It relies on a stream of liquid particles produced by a spinning disc, which are descending into an upward-flowing stream of heated air (Figure 6.11). As the liquid particles lose moisture and collapse into granular particles, they fall to the bottom of the dryer and are collected. Because of the small particle size, drying is accomplished quickly and the product is somewhat protected by the evaporative cooling that occurs in the dryer. Product spray must be kept in suspension long enough so that it will dry to particles that do not have enough moisture to clump or cake when collected, typically below 5%. There is also a limitation on the types of materials that may be processed in a spray dryer because, for example, extremely high sugar contents will cause the droplets to spin outward as long threads, effectively converting the dryer into a cotton-candy machine. Because of problems with particle adhesion either because of inadequate drying or static charge, cleaning devices such as sonic horns may be fitted to dryer cavities to force accumulations loose.

Spray drying calculations are often based on mass-transfer principles derived from idealized droplet sizes, airflow, and operating conditions, and are largely derived from coefficients based on drying curve data and psychrometric data for the airflow. Many of the calculations do not account for the changing nature of the droplets both in terms of physical dimension and thermodynamic properties, nor do they account for humidification of the airflow while in the dryer. Because of this, manufacturer's operating information and experience are critical in optimizing practical performance of spray dryers.

Fluidized Bed Drying

Fluidized bed drying suspends a moving horizontal flow of particulate material in an upward-flowing stream of air. This allows air to forcibly circulate around the product and, if designed

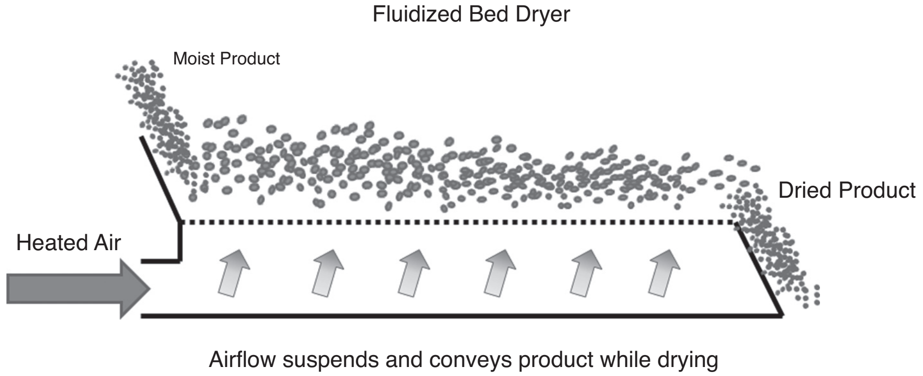


Figure 6.12. Fluidized Bed Dryer

properly, will cause the product pieces to rotate and tumble somewhat (preferably without being ejected), leading to more uniform drying, as shown in Figure 6.12. Proper design and adjustment of the dryer is important because the product will lose mass as it moves to the end of the process, so there is a risk of the product lifting out of the dryer stream as it progresses. Design parameters for fluidized bed drying are similar to spray drying in that moisture loss is governed by similar mechanisms, and a force balance between the downward force of gravity and the lifting force of the aerodynamic drag on the particles must be considered (similar to the force balance considerations for the Stokes Equation shown in Figure 6.18). Lighter products are more readily accommodated by this method because high velocities of airflow will be needed for heavy materials, but for very specific applications, such as fluidized-bed combustion systems in furnaces used to efficiently burn fuels such as coal and municipal waste, it is possible to develop an appropriate heavy-materials process.

Tray, Belt, and Tunnel Dryers

Tray and tunnel dryers, and their continuous-feed counterpart, belt dryers, all work on the principle of simple airflow around a product that is mechanically suspended in the drying airstream, usually on mesh belts or ventilated sheet metal trays. For some types of dryers, drying is conducted under reduced pressure in order to facilitate moisture removal at lower temperatures to preserve flavor, although the operating costs of this type of process can be higher. Larger tunnel systems may accommodate stacked cars of trays that travel through the airflow in the drying tunnel.

Belt and tunnel systems may be operated in either a concurrent or countercurrent mode with the movement of the product either opposing or coinciding with the airflow, depending on product quality requirements. Countercurrent operation offers the advantage of having the wettest product exposed to the hottest and driest airflow with an attendant efficiency increase (as with heat exchangers, discussed in Chapter 2), but at a risk of damaging the product from overheating resulting in surface cracking, caramelization, or an undesirable texture change.

Infrared, Geothermal, Solar, and Microwave-Assisted Dryers

Radiant heat may be used for drying, as it always has been for earlier civilizations, but the undependability of weather and security of power networks makes a strong argument for exposure to artificial drying energy, even if the initial source of the power is from a solar installation. Some processing plants are intentionally located near sources of geothermal heat or in areas where there is a predominantly sunny climate or the climate is dominated by hot, low humidity air to increase the efficiency and reduce energy consumption in the processing plant. Infrared drying may be done with electric or fueled burners built behind radiant plates.

Microwave-assisted drying has been an experimental subject for many years, but the inefficiency of energy conversion and expense and hazards associated with high-energy microwave generation have restricted practical implementation. The singular advantage of microwave heating has – efficient energy penetration – makes it useful for very specific types of drying such as pharmaceutical products, and it has been incorporated to a certain extent in freeze-drying operations.

Freeze-Drying

Freeze-drying, first used as an atmospheric-pressure sublimation process by Incas in the cold, dry Peruvian Andes mountains, was industrially developed as an extension of the lyophilization process developed in the early part of the twentieth century to dry chemicals in the laboratory. Although freeze-drying is most usually applied in the pharmaceutical industry and comprises a relatively small portion of the entire food-drying industry, it can offer many advantages for specific applications such as light weight, long shelf life, and high product quality.

The general process path of freeze-drying exploits the direct sublimation of solid ice to vapor under a moderate vacuum. Although the process is fairly simple, there are some limitations inherent in the heat and mass-transfer that can cause problems with a high quality product.

General Freeze-Drying Procedure

The general process path for freeze-drying is shown in Figure 6.13 and usually consists of:

1. Loading of frozen foods into vacuum chamber: The foods are typically frozen to a temperature below the eutectic point (the lowest temperature point where liquid and solid coexist, and in the case of water the triple point). Materials with indistinct phases may use a *critical point* similar to the eutectic.
2. Reduction of pressure to below the eutectic: This guarantees that water will sublimate directly to vapor rather than going through a liquid phase.
3. Heating Stages: After this point is reached, heat is supplied under vacuum to the material in order to drive the water into the vapor where it is removed by vacuum pumps and condensed or adsorbed out of the system. There may be several heating stages to liberate not only free water but adsorbed water and possibly other volatiles. The ability of the system to remove water is often practically limited by the ability of the material to conduct heat from the heated surfaces. Because the material is desiccated at the region nearest the heat source first as moisture is driven out, the thermal conductivity of that layer of product decreases rapidly as the drying process occurs – it becomes self-insulating in a sense – and can cause insufficient drying in layers of product that are too thick. Similarly, moisture that is sublimated away from the heating surface can remain in the surface regions of the product, causing quality and texture problems as shown in Figure 6.14.

   Experiments have been conducted with microwave heating of food during freeze-drying [27], but although this method overcomes many of the heat conduction problems exhibited by tray-type heaters in freeze-drying, practical implementation has been slow.

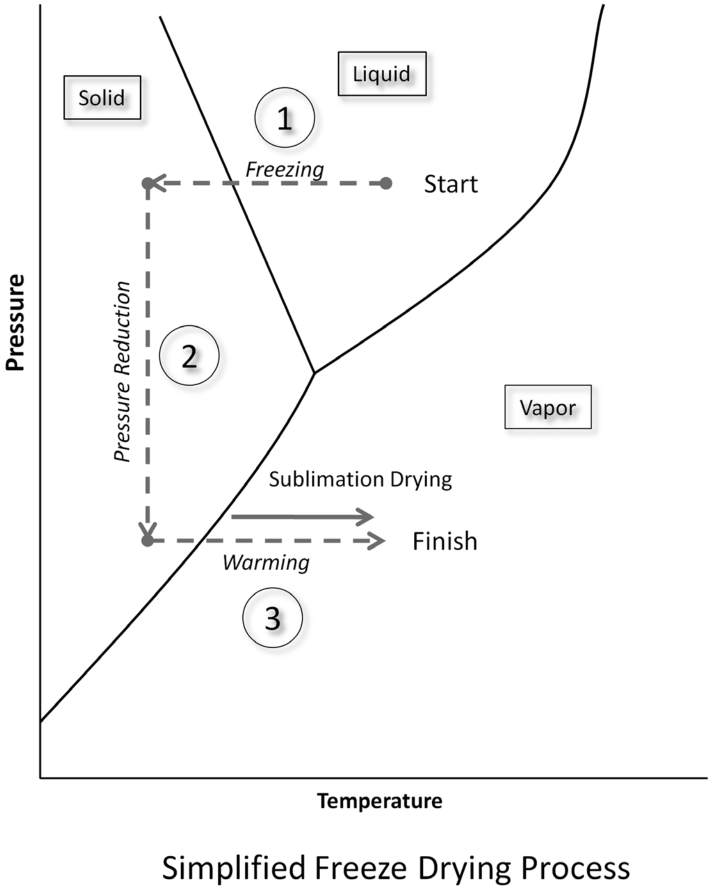


Figure 6.13. Freeze-Drying Process Path

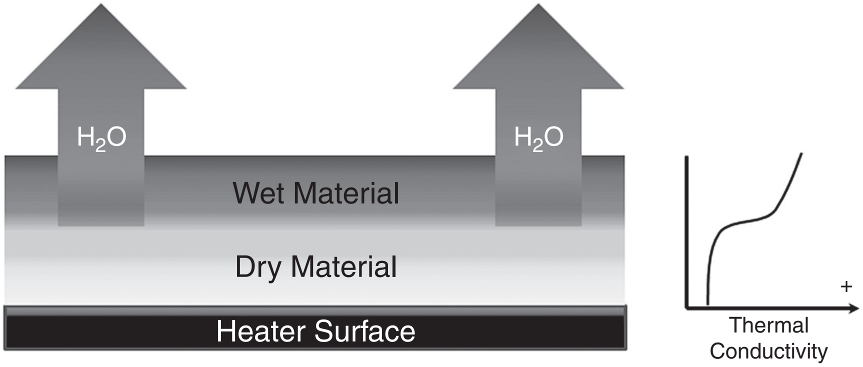


Figure 6.14. Insulation and Mass-Transfer Effects During Freeze Drying

4. The process is ended by returning the system back to atmospheric pressure either with a simple venting or by backflushing with inert gas to protect the product, although the latter is more common with freeze-drying in the pharmaceutical industry.

One of the product limitations inherent in freeze-drying is that the region nearest the heat will sublimate moisture first, which has two effects. The first of these is that the product will usually become porous as ice is removed, which reduces its thermal conductivity enormously – in effect creating its own "foam" insulating layer and disrupting the ability of the product to be heated further. The second of these effects occurs because the moisture must travel through the remaining product as it vaporizes, which may over-humidify the rest of the product. The result of too-fast drying may be scorched or collapsed product that is unappealing, or a *stalled* process that has a moist surface that cannot be easily removed. Because of the reduced pressure, convective heat transfer may be difficult, so radiant and/or conductive heat with carefully controlled operational parameters is most often used. Microwave heating is an appealing addition to this because it is not dependent on conduction and can provide a uniform heat profile in the product, but the expense and hazards associated with this have restricted its large-scale implementation in bulk food processing [28].

Drying time estimation can be expressed as [29]:

$$t_{\mathrm{d}} = \frac{L^2 \rho (m_{\mathrm{i}} - m_{\mathrm{f}}) \Delta H_{\mathrm{s}}}{8 k_{\mathrm{d}} (T_{\mathrm{s}} - T_{\mathrm{i}})} \tag{6.5}$$

t_{d}: drying time, s
L: slab thickness, m
ρ: density, kg/m^3
$(m_{\mathrm{i}} - m_{\mathrm{f}})$: moisture content difference at dry/frozen interface, kg/kg
H_{s}: latent heat of sublimation, kj/kg
k_{d}: thermal conductivity of dry layer, $\frac{\mathrm{W}}{\mathrm{m} \cdot {}^\circ\mathrm{K}}$
T_{s}: surface temperature, °K
T_{i}: internal temperature at dry/frozen interface, °K

In general, freeze-dried and lyophilized products are processed in thin cross-sections of solid or liquid product to minimize the heat transfer and moisture diffusion problems. Often, a great deal of trial and error is involved in this, particularly with oily or high-sugar-content products, to avoid the collapse of the structure and loss of organoleptic properties while efficiently transferring heat into and moisture out of the product.

Irradiation

Irradiation using radioactive substances or charged particles is one of the newer types of food preservation techniques, and is an outgrowth of radiation research that began in earnest before World War II, although the concept of preservation with radiation was considered in 1905 with the idea of embedding food with thorium in order to render it sterile (fortunately, the Pure Food and Drug Act of 1906 intervened)[30]. The National Food Irradiation Program that spanned the period from 1953 to 1980 provided the largest impetus for developing food irradiation processes and techniques, with that function being assumed by the USDA in 1980. Since then, irradiation has been approved for use with pork, spices, vegetables, poultry, shell eggs, and various meat products. All of these approvals are at very specific dosage ranges and are intended to extend shelf life and to control foodborne pathogens [31]. Additionally many other items from medical supplies to cosmetics may be irradiated at high levels for the purposes of sterilization.

Irradiation Background

When accelerated electrons, X-rays from scattered electron beams, or charged particles (typically gamma rays) interact with both food and packaging materials, radical species are formed that damage the DNA and metabolic structure of microorganisms, causing both death and the inability to reproduce, as well as potentially causing radiolysis products and chain interactions in the polymers of packaging materials.

Three types of irradiation are typically used: electron beam, X-ray, and gamma radiation. The first two are based on electron accelerators and require substantial electric supplies but do not contain any permanently radioactive materials – turning off the power removes any charged particles. Both of these rely on the acceleration of electrons; however, the electron beam (*E-beam*) systems produce a stream of electrons that have a limited ability to penetrate targets (typically to a depth of approximately 3–6 cm.), and requires only modest shielding. X-ray systems generate more energetic X-rays by directing the electron beam at a highly electron-dense plate (often of gold, tungsten, or tantalum) where the impinging electrons knock orbital electrons out of the plate material's inner orbits, cascading replacement electrons from higher-energy orbits to fill the orbital shell and causing the emission of their excess energy as X-rays. This latter process is very inefficient and requires heavy shielding, but offers the advantage of much greater penetration depth (in excess of 120 cm).

The last method, gamma irradiation, relies on an isotope (most commonly, ^{60}Co, although ^{137}Cs may be used in some countries) that emit high-energy photons but do not emit neutrons, which effectively eliminates the formation of radioactive species in the target. These installations require an extensive infrastructure both for handling materials to be irradiated and for the storage of isotopes and protection of personnel, but offer the advantage of very good penetration and very-high-energy irradiation.

Levels of total absorbed irradiation are regulated in kilograys (kGy) and are typically used at the following levels given in (Table 6.4), although not all are approved for commercial food processing use in the United States (Table 6.5) [32–34].

Effects on Packaging Materials

One of the great advantages of food irradiation is that it can penetrate a finished and sealed package, so the effects of radiation on packaging materials are of concern both from the standpoint of public perception and of safety regulations. A list of approved materials was originally produced during the initial period of intense irradiation research in the early 1960s, but as the preservation method went out of favor, new approvals were not sought because there was insufficient demand to justify the time and expense of getting full approval. With the resurgence of interest in irradiation, materials manufacturers and regulators were caught off-guard by the demand for approval of materials that had been developed in the interim. Fortunately, there are currently Threshold of Regulation (TOR) exemptions in the United States for low-dosage packaging systems using approved food contact polymers and adjuvants that

Table 6.4. General Irradiation Levels for Foods and Other Applications

Levels of Absorbed Radiation for Various Applications*

1 kGy = 100 kilorad, where the kilorad (krad) is an older unit of measure. Both are the equivalent of 1 kilojoule of energy per kilogram of material.

Dose Level	Application
"Low" doses (up to 1 kGy)	
0.15–0.5 kGy	Control insects in grains
0.05–0.15	Inhibit sprouting in white potatoes, onions, garlic, ginger, etc.
0.15–0.5	Control trichinae in pork, insect infestation in dried fruits and dried fish.
0.15–1.0	Inhibit ripening and decay and control insects in fruits and vegetables.
"Medium" doses (1–10 kGy)	
1.0–3.0	Control *Salmonella*, *Shigella*, *Campylobacter, Yersinia*, and *E. Coli* in meat, poultry, and fish; delay mold growth on strawberries and other fruits.
1.0–7.0	Eliminate spoilage of fresh, frozen, and pathogenic seafood, and of raw or frozen poultry and meat.
2.0–7.0	Improve technological grapes (increasing properties of food juice yield), dehydrated vegetables (reduced cooking time), etc.
"High" doses (greater than 10 kGy)	
10–30	Kill microorganisms and insects in spices, enzyme food additives, ingredients preparations, etc.
30–50	Commercially sterilized foods. The only US approval for this dosage level is for food products for immune-compromised patients.
25–40	Complete sterilization of implants, sutures, drapes, syringes, and neurosurgery devices.

*Generalized figures – not all of these are approved by all regulatory agencies in the US or other countries.

operate at doses of 3 kGy or less and either under an oxygen-free environment or under vacuum while frozen. Current U.S. Approval Levels for irradiation of packaging material are given in Table 6.6.

Polymeric packaging materials will exhibit simultaneous radiation-induced cross-linking and chain-scission, with the final effect being the result of the dosage and conversion efficiency of each process. Secondary factors such as oxygen availability, secondary compounds, type, dose, and dose rate, among others, will affect the final results of the materials treatment. E-beam and X-ray treatments have been shown to produce fewer volatiles such as aldehydes, ketones, and carboxylic acids than gamma irradiation in polymeric packaging materials [35]. Mechanical changes will follow with the scission/cross-linking competition, with an increase in cross-linking increasing the modulus of the materials and beyond a certain level causing embrittlement and failure. Paper, which is composed of cellulose chains, will show radiolytic reactions similar to synthetic polymers, with scission of the cellulose chains, darkening of the paper structure, and an increased susceptibility to acid hydrolysis and alkali solubility [36]. Metals and glass are sufficiently stable for irradiation, but secondary compounds associated with them, such as coatings, linings, and sealants, may show degradation.

Food products for retail to consumers that have been irradiated must display the radura emblem on the packaging, as well as a label statement indicating processing by irradiation,

Table 6.5. U.S. Food Irradiation Levels

Current US Approval Levels for Irradiation of Food Products[i]		
Food Type	Purpose	Dose Level
Fresh, non-heated processed pork	Control of *Trichinella spiralis*	0.3 kGy min. to 1 kGy max.
Fresh foods	Growth and maturation inhibition	1 kGy max.
All foods	Arthropod disinfestation	1 kGy max.
Dry or dehydrated enzyme preparations	Microbial disinfection	10 kGy max.
Dry or dehydrated spices/seasonings	Microbial disinfection	30 kGy max.
Fresh or frozen uncooked poultry products	Pathogen control	3 kGy max.
Frozen packaged meats (solely NASA)	Sterilization	44 kGy min.
Refrigerated uncooked meat products	Pathogen control	4.5 kGy max.
Frozen uncooked meat products	Pathogen control	7 kGy max.
Fresh shell eggs	Control of *Salmonella*	3.0 kGy max.
Seeds for sprouting	Control of microbial pathogens	8.0 kGy max.
Fresh or frozen molluscan shellfish	Control of *Vibrio* species and other food-borne pathogens	5.5 kGy max.
Fresh Fruit	Delay Maturation	1.0 kGy

[i] "US FDA/CFSAN–REGULATORY REPORT–Irradiation of Food Packaging Materials." http://www.cfsan.fda.gov/~dms/irradrpt.html.

Table 6.6. U.S. Approved Packaging Materials for Irradiation

Packaging Materials Listed in 21 CFR 179.45 for Use During Irradiation of Prepackaged Foods.		
Section	Material	Max. Dose (kGy)
179.45(b)	Nitrocellulose-coated cellophane	10
	Glassine paper	10
	Wax-coated paperboard	10
	Polyolefin film	10
	Kraft paper	0.5
	Polyethylene terephthalate film	10
	Polystyrene film	10
	Rubber hydrochloride film	10
	Vinylidene chloride-vinyl chloride copolymer film	10
	Nylon 11 [polyamide-11]	10
179.45(c)		
	Ethylene-vinyl acetate copolymer	30
179.45(d)		
	Vegetable parchment	60
	Polyethylene film	60
	Polyethylene terephthalate film	60
	Nylon 6 [polyamide-6]	60
	Vinyl chloride–vinyl acetate copolymer film	60

Note: Additional packaging materials for use during irradiation of prepackaged food are listed in the Threshold of Regulation Exemptions or Inventory of Effective Food Contact Substances.

Figure 6.15. FDA Radura Symbols for Irradiated Foods

both to inform the consumer and to prevent re-irradiation during subsequent use or processing. Many other irradiated products such as ingredients in multicomponent foods and foods for food service operations do not require that the final product be labeled as irradiated. There has been some effort to reduce these labeling requirements because of resistance by consumers to irradiated products. Current regulations require a radura emblem (Figure 6.15) and a statement regarding irradiation for whole foods that have been irradiated. Foods containing irradiated ingredients such as spices are not required to be labeled. Public perception of irradiated foods has been affected by both the historical association with military testing and irradiation research and by concerns with both radioactivity of the foods and secondary species of compounds and pathogens that might be created by the process. While the process has been shown to be safe when used carefully and sparingly, it is a developing technology that offers both the promise of improved safety and some risk of unintended consequences.

Food Safety, Quality, and Irradiation

Irradiation has continued to be a contentious issue, although many medical products and spices have been irradiated for years. Concern about the development of novel radiolytic species, or accelerating the rate of mutation of pathogens and insects as well as providing an uncontested growth environment for organisms such as aflatoxin-producing molds all have been raised as potential objections. Studies have also shown that although for the most part, spoilage organisms survive irradiation better than pathogens (causing food to spoil before becoming toxic), the survival of spore-forming organisms such as *C. Botulinum* type E under low radiation doses demands careful post-process handling [37]. While some of these issues remain a matter of debate, concerns expressed about using radiation in place of good sanitation practices are worth considering when irradiation is suggested as a final safety treatment for products, because the temptation to rely on the single, final treatment may create poor practice in other parts of the operation.

Food quality may be affected by extreme doses of radiation, to the point where early experiments on meat products at doses in excess of 70 kGy would reduce them to badly oxidized and

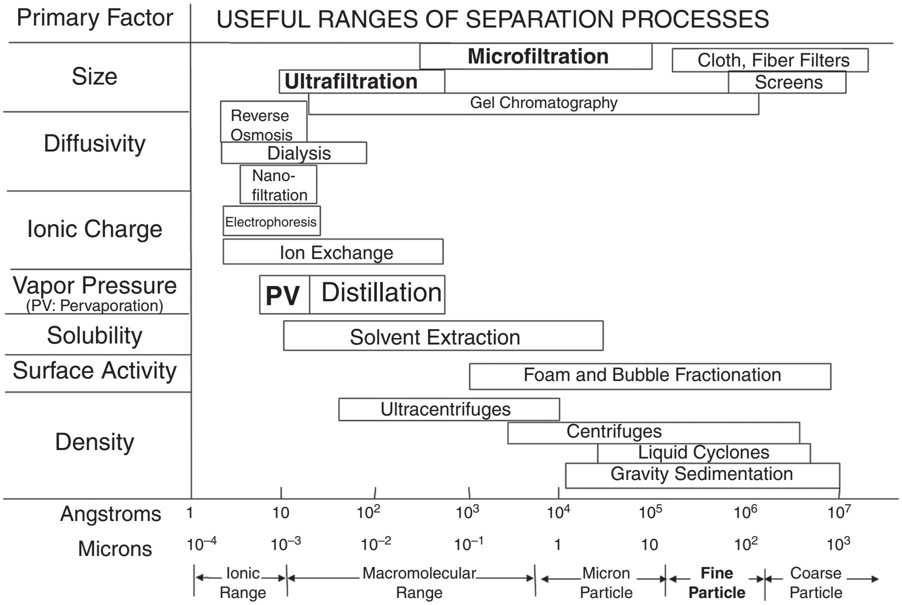


Figure 6.16. Range of Separation Processes
Source: M. Cheryan, (1989) "Ultrafiltration Handbook". Used with permission of the author.

inedible waste. At lower, approved doses, effects on food quality are similar to those produced by thermal processing, with water-soluble vitamins being oxidized most readily. Fats and oils may begin oxidizing more rapidly because of the direct energy input initiating oxidation reactions, and so control of oxygen availability may be an important step in preserving product quality, and oily foods such as fresh avocados that have been reported as generating off flavors with as little as 0.15 kGy may have to be minimally processed or given an alternative treatment.

Concentration and Separation of Food Products

Many processing systems rely on changing the concentration of particular components in a material. For food materials, there is a plethora of separation methods based on differentiating characteristics that are well described by Figure 6.16.

Most separation and concentration technologies may look intimidating in an industrial application because of the scale and secondary complexity. Despite this, nearly all of them are scaled-up versions of very simple ideas, typically using a particular (and preferably unique) differential in some physical property to separate materials.

Separation and Concentration by Size Differential

Size separation depends on both a useful size distinction and a method for passing (or not passing) materials of a particular size through a process. The oldest method of this type is simple sifting through a screen or grid that will separate materials or objects by size, allowing smaller units to pass and retaining larger ones. This has long been standardized using the gap in a wire mesh to allow both single and progressive sifting of materials under mechanical agitation. The

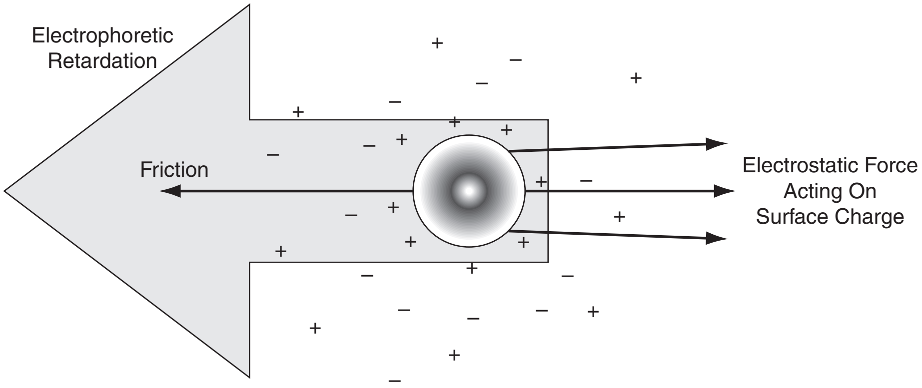


Figure 6.17. Eletrophoresis Forces on a Particle

agitation serves to reorient materials that may be lying across the screen in an effort to pass any material that is smaller in any of its dimensions than the opening in the mesh. As particulate components get smaller, the separation method becomes more reliant on a statistical average of pore sizes in a filter structure because these are often produced of fibrous mats or perforated sheets of solid material, and the exclusion size may be a function of both pore size and the orientation of the material in the filtrate. A good example of this would be a long, thin structure such as a protein strand that will pass end-on through an opening but is retained when it lies across the pore structure. Because of this, many filtration methods are very dependent on the particulars of the media, particulates, and the filter membrane itself, and will require evaluation for suitability before large-scale use is undertaken. Additionally, at the micro and ultra-filtration levels, it is possible to have surface chemistry interactions between the filtrate and the filter structure, which can affect the accuracy of the filtration. Nanofiltration exploits this in the separation of dairy by-products by allowing non-valent ions, water, and low-molecular-weight solids through and rejecting higher-molecular-weight solids and divalent and multivalent ions [38, 39].

Electrophoresis (Figure 6.17) takes this to the molecular level by driving the constituents through a fluid material via a uniformly applied electrical field. In this case, the materials are driven by electrostatic force and finally separated by the friction they exert, as well as their electrophoretic retardation force (a countervailing force that occurs due to a diffuse layer of opposite-charge ions about the material particle), as they move through the viscous fluids.

Separation and Concentration by Density Differential

Simple separation by density differential has also been done since prehistory with the separation of fatty components in dairy products and oil-water mixtures during the secondary olive pressings that use hot water to liberate oil from the ground olive paste. Simple settling of particulate matter in fluids is usually accomplished by giving the material a quiescent place (a settling tank or storage bin) to settle, but demands for higher-speed processing of materials that may have smaller density differences (and therefore longer settling times) can demand that the settling and separation rate be artificially enhanced either by agitation to accelerate the rate of particulate stratification, or by cyclone or centrifuge separation that provides artificial acceleration to the particles, in turn increasing the force of separation between the disparate masses. Additionally, it is often useful to add material of a particular density to assist in separation, or to induce a flocculation process (described under surface activity separation).

Separation time in a simplified settling scenario that assumes a roughly spherical fluid particulate, as shown in Figure 6.18, in a two-part fluid system can be calculated using the Stokes equation, which is valid for small Reynolds number values ($\mathrm{Re} < 1.0$), although attention must be paid to the direction of travel, as dictated by the density difference between the fluid and particle:

$$v_\mathrm{p} = \frac{D^2 a(\rho_\mathrm{p} - \rho_\mathrm{f})}{18\mu} \tag{6.6}$$

v_p: velocity of particle or droplet, m/s

D: diameter of spherical particle or droplet, m

a: applied acceleration, $\mathrm{m/s^2}$

This is usually (g) gravitational force, $9.81\ \mathrm{m/s^2}$

ρ_p: density of particle, $\mathrm{kg/m^3}$

ρ_f: density of fluid, $\mathrm{kg/m^3}$

μ: viscosity, $\dfrac{\mathrm{kg}}{\mathrm{m \cdot s}}$ or $\mathrm{Pa \cdot s}$

Thus, for the fat and non-fat components in whole milk (which is an oil-in-water emulsion) under the existing force of gravity, the separation time can be calculated as

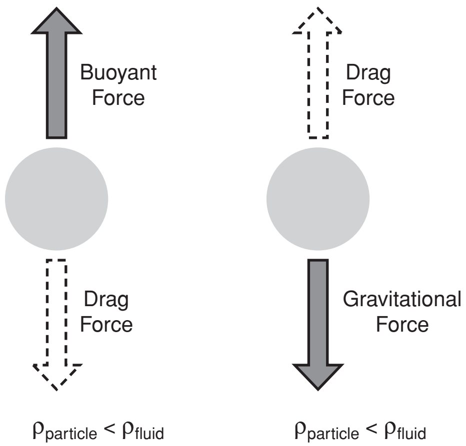


Figure 6.18. Stokes Equation Force Balances

From the extraordinary amount of time required for the fat components to separate in milk, one can see why early European estates had milk settling rooms where shallow pans of milk would be put out to reduce the distance that the fat component had to travel before being poured off.

A much simpler (and more sanitary) solution was eventually devised – a milk separator, which is effectively one of the first continuous-flow centrifuges, as shown in Figure 6.19. Centrifuges are mechanical devices that induce a high outward force by mechanical rotation of materials, one of which is usually a fluid. This creates an artificially high value for g, and proportionally reduces the separation time and overcomes the effects of Brownian motion on very small ($< 0.1\ \mu\mathrm{m}$) spherical particles:

$$a_c = r(2\pi N_r)^2$$

$$F_{\mathrm{rc}} = \frac{r(2\pi N_{\mathrm{r}})^2}{g} = \frac{a_{\mathrm{c}}}{g} \tag{6.7}$$

a_{c}: centrifugal acceleration, $\mathrm{m/s^2}$

F_{rc}: relative centrifugal force, expressed in “g’s” or multiples of the force of gravity (g)

r: rotational radius, m

N_{r}: number of rotations, $\frac{\text{revolutions}}{\text{second}} = \frac{\text{RPM}}{60}$

g: gravitational acceleration, 9.81 $\frac{\mathrm{m}}{\mathrm{s}^2}$

Thus, from the Stokes equation

$$v_{\mathrm{p}} = \frac{D^2 a(\rho_{\mathrm{p}} - \rho_{\mathrm{f}})}{18\mu}$$

v_p: particle velocity, $\frac{\mathrm{m}}{\mathrm{s}}$

under the acceleration generated by a centrifuge

$$a = a_c = r(2\pi N_r)^2$$

$$v_p = \frac{D^2 a_c(\rho_p - \rho_f)}{18\mu} = \frac{D^2(r(2\pi N_r)^2)(\rho_p - \rho_f)}{18\mu}$$

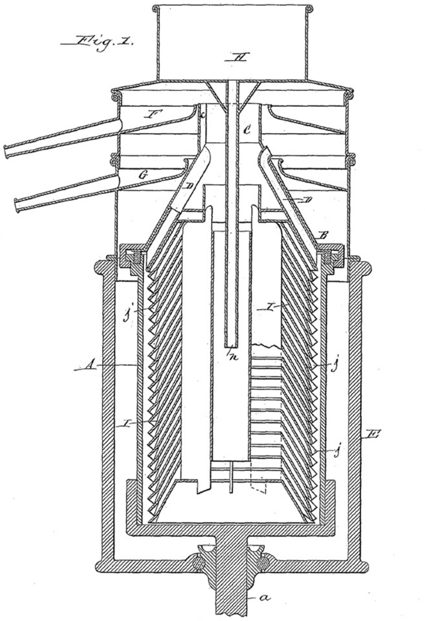


Figure 6.19. Cream Separator Patent Drawing
Source: US Patent 463794

Laboratory centrifuges are capable of creating millions of **g** in specially constructed static tubes that are mechanically rotated around a central driveshaft. Milk separators and continuous-flow extractors of this type operate similarly except that they depend on a series of closely spaced plates to reduce the "rising" distance, and to both rotate the components and to channel them either to the center or the radial edge of the rotor depending on density. Because the net *g* force is outward (roughly corresponding to "down"), the lighter fraction will be extracted up through the central axis ("*F*") while the heavier fraction is expelled along the edge ("*G*").

The time for a fat globule to travel to the "top" of the fluid is reduced significantly by increasing the effective force of gravity in a centrifuge. By closely spacing the plates, and reducing the distance, the "rising" time can be reduced to seconds rather than many hours, ensuring a useful throughput. Because this is a continuous flow device, the separation time is usually considered to be a *residence time* – the time that the fluid remains within the extractor – rather than a more intuitive *settling time*. Also, because of some small degree of mixing and other factors, the separation will not be complete in the sense that a careful centrifugation in a laboratory might produce, but will produce an acceptable product.

Homogenization

The Stokes equation also describes the necessary parameters for many kinds of homogenization, which is the converse of accelerated separation processes. Most often, a homogenizer will be designed to reduce globule or particle sizes below the point where they can aggregate or separate. For milk homogenization, the whole milk, which has fat globules that are both large (mean diameter ca. 2 μm) and buoyant enough ($\rho^{20^\circ\mathrm{C}} = 915\ \mathrm{kg/m^3}$) to cluster and separate readily over a few hours, is forced under high pressure (ca. 15 MPa) through a series of valves that exert a great deal of fluid shear and force the mean particle size to approximately 0.5 μm and nearly eliminates clustering.

For other types of homogenization, such as that applied to peanut butter to prevent oil separation, an additional component – higher-melting-point saturated fat – is added to bind the oil droplets in place at room temperatures.

Cyclone and Hydrocyclone Separation

Cyclones are a type of extractor that rely on fluid flow to create rotation in the fluid column and to extract the heavier fraction or particulates from ports on the outer radius or a settling area at the bottom, while allowing the lighter component to escape through the central axis, as shown in Figure 6.20. Cyclones are limited by the kinetic energy of the fluid flow and can suffer from the inability to cleanly separate materials with very similar densities, but offer the advantages of simplicity and durability. Nearly every industrial process that creates a great deal of dust, shavings, or other waste will have an air cyclone in the air exhaust from its dust and particulate extraction systems, and consumer appliances such as vacuum cleaners have been designed to operate on the same principle.

Cyclones for liquids, called *hydrocyclones*, are used to separate liquids or liquid/solid combinations in the same manner, although the different density will require much stronger construction. Hydrocyclones can be manufactured to create radial forces thousands of times that of gravity, allowing separation of oil and water, agricultural processing components such as starch, removal of waste material in mining waterflow, and the removal of contaminants such as staples and sand in recycled paper pulping operations. Additionally, *air-sparging*

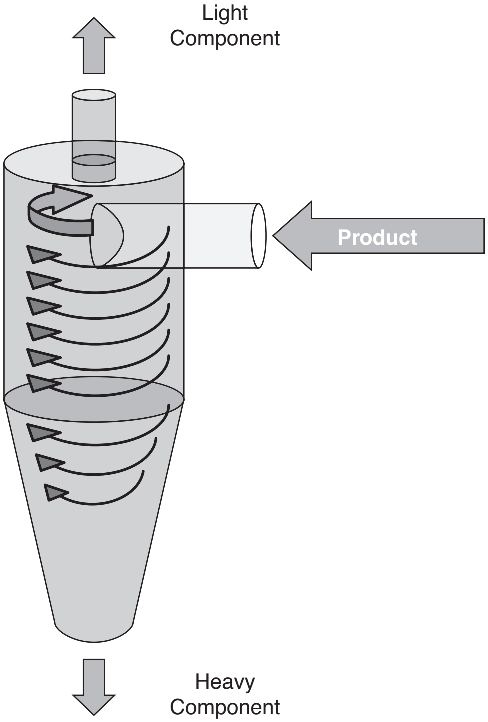


Figure 6.20. Cyclone Separator Diagram

hydrocyclones inject fine air bubbles into the fluid system, which attach to a particular component as a flocculent and aid in completeness of separation by creating a distinct density boundary layer between fluid and extracted material.

Separation and Concentration by Vapor Pressure

Separation of fluids from solids and oils by simply letting water evaporate is a traditional method that was augmented by adding heat to boil away water. This is a basic recovery method for sugar and salt, and has been enhanced by using multiple-effect evaporators that recover the heat of condensation in successive stages to improve energy efficiency in a series of staged evaporator pans.

When applied to water-alcohol mixtures, it was observed that a flammable vapor was produced at relatively low temperatures, which is possibly the source of the original Arabic term *al-ġawl* (roughly, “spirit”), although the intoxicating effects may also be the source of the name. This process was first isolated and extensively studied by the chemist Razis (Muhammad ibn Zakariya al-Razi) in the ninth century. Distillation is simply the heating of a mixture of components and then causing the condensation of the vapors of the lower boiling point fraction using chilled surfaces (often cold water circulating in pipes) to recover the low vapor pressure fraction. Although the process is simple, the engineering of optimized distillation and separation systems can be quite involved.

Distillation systems are typically constructed to allow multiple layers of vapor and increasingly concentrated distillate to interact via *plates* or *trays* in a manner similar to the

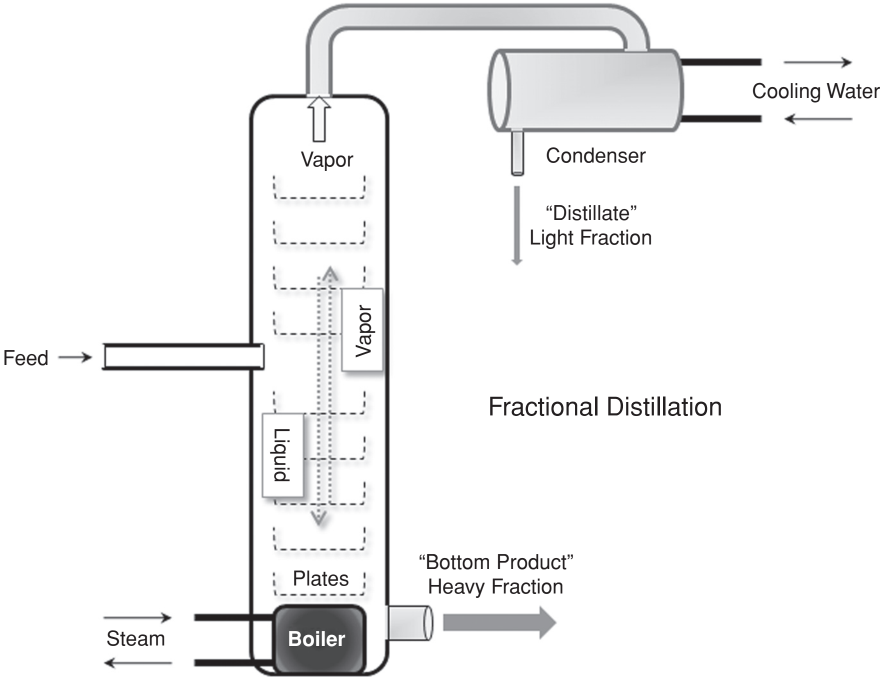


Figure 6.21. Fractional Distillation Diagram

multiple-effect evaporators, as shown in Figure 6.21, so that the efficiency of the separation process is maximized. As the heated vapors of the light fraction rise, they are forced upward through a downward-cascading flow of liquid heavy fraction, enabling simultaneous mass and heat transfer that enriches the vapor with more light fraction contained in the liquid and the heavy fraction with any residual heavy components in the vapor.

The result of a well-run distillation operation will be a purified *Top Product* and a *Bottom Product* made of the concentrated feedstock materials in the process. For desalination and water purification, the installation is quite simple, and newer installations have been devised that exploit the vapor pressure of water in a near-vacuum and use waste heat for domestic water treatment.

Figure 6.22 shows a McCabe-Thiele diagram of the operating curves of an ethanol-water distillation process. This provides a useful way of visualizing the exchange of top and bottom products as the vapors rise and liquids settle, although the number of *theoretical plates* must be translated into actual design data by correlating with actual plate or tray efficiencies [40]. From this diagram one can gather that there are limitations on the process that restrict the purity of the final products. The equilibrium curve in the example suggests that there is a so-called *pinch-point* where the extraction process is no longer practically feasible. This is the case because ethanol-water systems form lowered-boiling-point azeotropes at concentrations of 96% ethanol, and any further processing will actually start enriching the azeotropic mix with water.

Steam Distillation

Steam distillation, or steam stripping, relies on the principle that an immiscible mixture of two compounds will boil at a temperature that is often well below that of the high-boiling-point

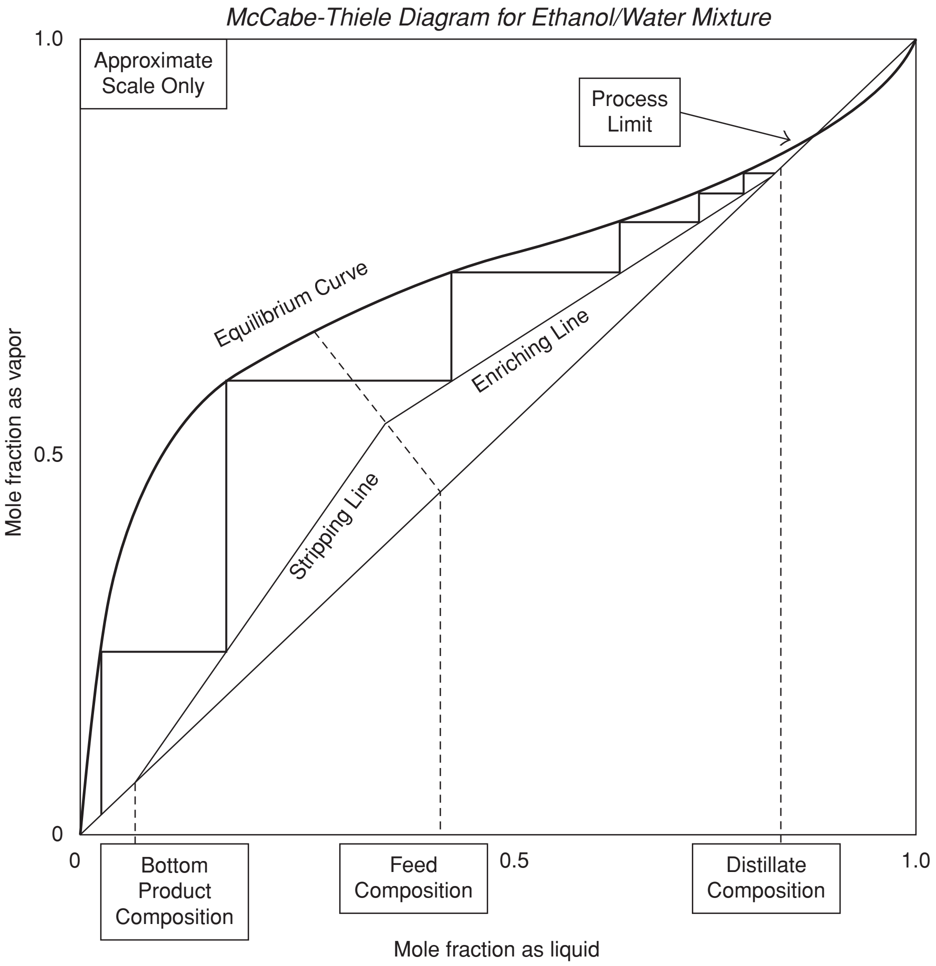


Figure 6.22. McCabe-Thiele Process Diagram

compound. This process is often used for the purification of essential oils that may be susceptible to decomposition from heat. It relies on the principle that immiscible compounds will each make a partial contribution to the total vapor pressure in the system as if the other compounds were not present, with the final effect being that the mixture will vaporize at a temperature that is lower than the highest-boiling-point fraction. Additional inducement to vaporize the desired compounds may be introduced by lowering the system operating pressure, amplifying the effect by creating a *vacuum distillation* system that can operate at reduced temperatures either alone or in conjunction with other distillation systems.

Separation by Crystallization

Extraction by crystallization is closely related to evaporative techniques in many parts of the world, very often those involved in sugar production and salt harvesting. Although these are most often simple evaporation processes that are allowed to run until the solvent is completely removed, it is also possible to operate them on a continuous basis by forcing the solvent to become supersaturated and then harvesting the crystals as they appear. Another version of this is freeze concentration, which allows a highly concentrated solution to cross into supersaturation by reducing the temperature.

Freeze concentration stems from the observation that quiescent freezing will allow one fraction of a compound to preferentially crystallize while the other remains liquid. The most common example of this is in the inadvertent freezing of soft drinks in home refrigerators, which results in the syrup remaining liquid while the water component crystallizes.

This may be a preferred method of separation and concentration in operations that are severely restricted in temperature range because of the delicacy of the components, or in geographic regions where freezing product is a relatively simple process. The costs of installing and operating mechanical refrigeration systems makes the economics of this type of separation questionable where simpler or less expensive alternatives might be used.

Separation and Concentration by Solubility Differential

Solubility differential separation and concentration is another old technology that began with the simple removal of flavor components, minerals and sugar by water, and has been steadily refined and improved to use solvents to extract any manner of flavor and aroma compounds as well as specific constituents in the food manufacturing process. Water and ethanol are obvious solvent choices for many products, yet the use of more complex organic solvents is often more efficient. This in turn creates the problem of residual solvents in the final product, which have become less and less acceptable as the health risks associated with many formerly common solvents such as benzene used in decaffeination have come to light. Even if still-accepted solvents such as ethyl acetate are used, the product must often be heated or steamed for a long period to remove the residual solvents.

Phase-based solubility differential extraction may be used, utilizing steam as an extraction agent as previously described in order to remove particular components. An extension of this exploits very high pressures to create a solvent out of an otherwise innocuous material such as carbon dioxide.

Supercritical Fluid Extraction

Supercritical Fluid Extraction (SFE) exploits the differential solubility of organic compounds in liquefied gasses. These can be nearly any kind of gas, but is most often CO_2 that is above the *critical point*, as shown in Figure 6.23, where it can only exist as a liquid [41].

Because this requires very high pressures (in excess of 7.38 MPa/1070 psig) at temperatures above 31°C, the equipment for large-scale handling may be cumbersome and expensive, but the advantages of an organic-solvent-free product that is modified without heat can provide an enormous advantage for particular processes such as the decaffeination of coffee.

Because of CO_2 having a limited degree of polarity, it may be modified with the addition of ethanol or methanol in order to broaden the range of materials that can be extracted. Once the extraction process has been completed, the solvent is moved to a reduced-pressure system that exploits the pressure dependency of the solvents' dissolving power and precipitates the extracted materials. The gas can then be recycled or vented off depending on the type and size of the process operation.

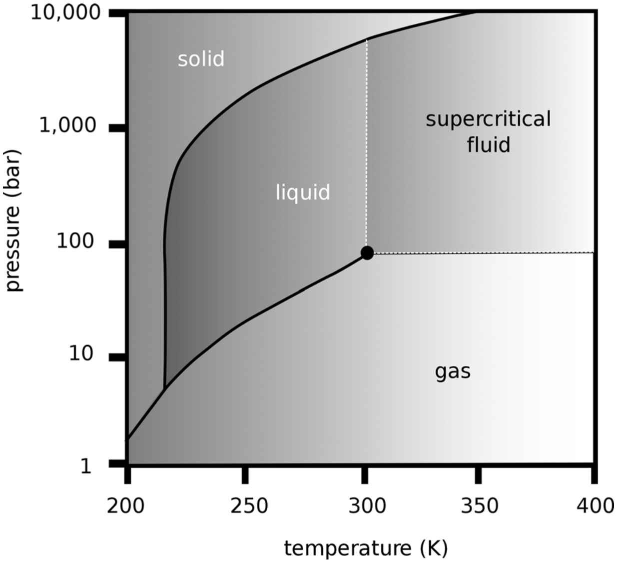


Figure 6.23. CO_2 Pressure – Temperature Chart

Separation and Concentration by Diffusivity

Diffusivity of a material through another material – an essential component of permeation that has been discussed in the context of packaging – can be exploited as a separation methodology. Osmosis, a naturally occurring type of diffusion, moves solvent from a region of low solute concentration to a region of high solute concentration across a *semi-permeable* membrane, as shown in Figure 6.24. These membranes are capable of passing solvent, but restrict solute movement and can range in size from cell walls in living organisms to large-scale desalination systems used for drinking and process water.

Osmotic pressure can be approximated with the Morse Equation:

$$\Pi = iMRT \tag{6.8}$$

Π: osmotic pressure
i: van't Hoff factor
M: molarity of solute, moles/liter
R: ideal gas constant
T: absolute temperature

Some examples of the van't Hoff factor are given in Table 6.7.

Because the object of most extraction processes is to remove pure solvent rather than add it – something that could usually be done more directly – reversing these processes becomes of more interest than their "forward" operation. Reverse osmosis depends on the ability of externally applied hydrostatic pressure to reverse the movement of solvent that produces osmotic pressure.

Because the osmotic pressure created can be quite large, the largest cost of desalination is usually due to the high pumping costs associated with pressurizing the osmotic membrane

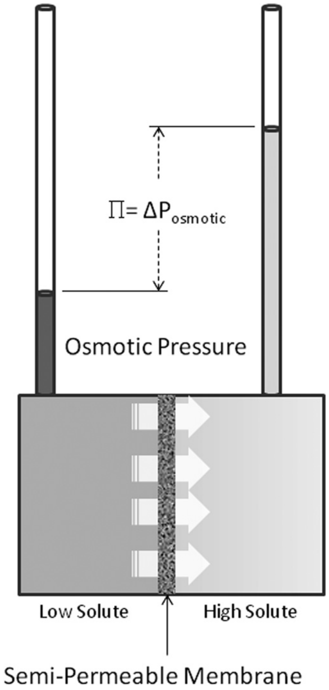


Figure 6.24. Osmotic Pressure Diagram

cartridges. Reverse osmosis can also be used to drive other solvents and moisture out of products that are being concentrated using similar methods, as shown in Table 6.8.

Pervaporation concentration is a similar process that is used for gas purification and extraction, and is based on reversing the Fickian diffusion exhibited through membranes in a manner similar to those used with fluids in reverse osmosis. The hydrostatic pressure applied to the feed gas overcomes the diffusion potential of the membrane and causes concentration of a purified gas on the *high concentration* side of the membrane, where it is extracted and either refrigerated or compressed.

Electrodialysis achieves an inverted version of osmosis in that it transports salt ions or other polar species through a membrane structure using an applied electric field in a manner similar to electrophoresis, and can be further utilized to concentrate or even create organic acids using selective membranes coupled with the appropriate electric fields.

Table 6.7. Table of van't Hoff Factors

Compound	Disassociates To	van't Hoff factor
Non-Electrolyte		1
Weak Electrolyte		1–2
NaCl	Na^+, Cl^-	2
$CaCl_2$	Ca^+, $2Cl^-$	3
$AlCl_3$	Al^+, $3Cl^-$	4
Na_2SO_4	$2Na^+$, $SO4^-$	3 (polyionic)

Table 6.8. Osmotic Pressures of Common Solutes

	Osmotic Pressure		Concentration
Solute	g/liter	moles/liter	PSI
NaCl*	35	6.0E-01	398.0
NaCl	1	1.7E-02	11.4
$MgSO_4$	1	8.3E-03	3.6
$MgCl_2$	1	1.1E-02	9.7
$CaCl_2$	1	9.0E-03	8.3
Sucrose	1	2.9E-03	1.1
Dextrose	1	5.6E-03	2.0

*Approximate Value for Seawater.

Separation and Concentration by Surface Activity

Foam and bubble separation uses an injected gas, usually compressed air, to create a froth of surface-active materials that adhere to the liquid-foam interface and are then carried out of the process along with entrained surface liquid [42]. This process can be helped by adding flocculating materials such as casein to help solids adhere to the rising bubbles and to be transported along with the foam. The foamate is then collapsed to give a resulting liquid that has a higher level of the surface-active material and any attached solids. Many types of industrial waste-water processing operations and protein concentration systems operate on this principle in order to concentrate solids and proteinaceous materials. An optimum velocity for gas-to-liquid mixes in foams can be constructed using Equation 6.9, though the reader is recommended to Stevenson (2007) [43] for a more thorough treatment of the derivation.

$$j_g^* = \frac{\rho g r_b^2}{\mu} mn \left(\frac{2}{n+1}\right)^2 \left(\frac{n-1}{n+1}\right)^{n-1} \tag{6.9}$$

j_g^*: maximum superficial velocity for a stable foam, m/s
ρ: interstitial liquid density, kg/m^3
g: acceleration of gravity, m/s^2
r_b: harmonic mean bubble radius, m
μ: interstitial liquid dynamic viscosity, Pa $\cdot$ s
j_d: superficial drainage velocity, m/s
m, n: surfactant type and concentration factors such that

$$\mathrm{m}\varepsilon^n = \frac{\mu j_d}{\rho g r_b^2} : \text{Stokes number}$$

Endnote

*Capillary condensation is a process where adsorption of a vapor-phase material into a porous medium continues until the pores become filled with condensed material, which may occur well below the saturation vapor pressure due to the large number of Van derWaals interactions in the minute spaces of the porous medium.

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Chapter 7

Food Preservation and Shelf Life

Introduction

The problem of preserving food and keeping its nutrients intact for long periods of time is an essential feature of cultures that have to cope with periods, whether seasonal or situational, where crops cannot be continuously produced or foraging cannot be continuously productive. Food preservation methods are as varied as the cultures, climates, and dietary habits that produce them, but most have common features. Indigenous cultures from the poles to the equator have relied on simple drying, smoking, salting, and pickling techniques for millennia, and many of these types of preservation methods have been reincorporated into the palates of various cultures. For other cultures, typically situated in warm climates, the nearly constant availability of fresh foods has shaped their dietary habits, and as those cultures have become more globally dispersed, the demand for high-quality fresh products has increased and created new challenges for fresh-food preservation.

As nations grew and sought global dominance, the saying that "armies (and navies) travel on their stomachs" became a limiting factor in the speed and effectiveness of military units, particularly where armies were large enough and scavenging insufficient enough to cause whole campaigns to fail. The limitations on traditional methods of food preservation were challenged by the requirements of global empires that could no longer depend on indigenous food supplies, particularly when retreating armies learned to destroy any useful materials or food as they traveled.

These needs began to be met by the development of ad hoc methods of bottled food preservation by Nicholas Appert in Napoleonic-era France, and the immediate adoption of the metal-can-based equivalent by their usual adversary, the understandably worried British Navy. With the subsequent understanding of the microbial processes involved in food spoilage by Louis Pasteur and others, food preservation not only allowed small groups of people to survive winters and to travel, but it became possible to merge the industrial revolution, changes in the productivity of the agrarian economy, and a burgeoning world trade into a system that is the ancestor of our current food preservation and distribution system. Much as the primitive preservation methods created distinct lifestyle changes for early people, these new processes allowed not only a continued food supply but the creation of previously unheard-of products.

Thermal processing was the first step, but was not well suited to large products; fitting an entire side of beef into a can would be a daunting task (or a very big can), but Henri Nestlé developed a canned infant formula in 1867 that was being distributed worldwide within five years, and the modern version continues to be sold today, as is James Kraft's thermally pasteurized cheese. Frozen foods, shown to be a viable method of preservation in the 1800s

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Food and Package Engineering, First Edition. Scott A. Morris.

as various methods of refrigeration were being experimented with, added another dimension to food distribution, allowing the distribution of frozen and chilled meats and vegetables on a grand scale. The development of vapor-compression refrigeration systems in the 1800s, despite opposition from well-placed natural-ice interests, furthered this process by allowing frozen food to travel great distances. In 1876, the French successfully shipped chilled meat from South America to France using ether-evaporation refrigeration and again in 1878, a shipment of frozen meat was shipped from Argentina to Le Havre using ammonia-based vapor compression refrigeration. By 1881, after several false starts, the dinner tables of Great Britain (and the economy of Australia) were enjoying frozen mutton that had been shipped halfway around the world with shipments exceeding 51,000 tons by 1900. This capacity for storage has been multiplied by the ubiquitous presence of (relatively) small domestic refrigerators in homes in developed countries, allowing chilled and frozen foods to be stored for long periods of time.

The ongoing search for improved preservation methods that are more efficient and cost effective have yielded some newer technologies such as irradiation and HTST/UHT processing, as well as newer combined technologies such as aseptic processing and packaging systems and *sous vide* distribution. As mentioned in the previous chapter, other methods using ultrasound, light, and electrical discharge may show some promise for use in specific processing applications, and will be highly dependent on the barrier properties of packaging to keep products in useable shape. In any event, the intent of all of these is to produce a product that retains as much quality as possible for as little cost as possible in order to survive the very competitive marketplace.

Further, the increased globalization of both people and the food supply have placed demands for fresh products of all types at an all-time high, paradoxically reversing the trend for preserved food and increasing demand on the transportation and logistics systems that can bring fresh flowers halfway around the world and fresh fruit around the calendar. This has resulted in the development of both very highly efficient transportation systems and several methods of extending shelf life, including controlled atmosphere (CA) storage and modified atmosphere packaging (MAP) that, when used in conjunction with (refrigeration-based) temperature controls, can keep produce, seafood, and meats in a very high-quality, near-fresh condition.

Deterioration of Food Products

To understand improved preservation processes, it is helpful to understand something of the nature of the processes that cause foods to spoil or deteriorate. Generally speaking, these can be broken down into several broad classes: microbial degradation, chemical degradation, and mechanical or rheological changes, the latter often brought on by effects of the distribution system.

Microbial degradation of food is typically prevented with preservatives, by reducing the temperature or moisture availability of the food to a point where the organisms cannot grow, or by enclosing them in a hermetically sealed package and inactivating the organisms to the point of commercial sterility as described in the previous chapter.

Chemical degradation is most often dealt with either by preventing the deleterious reactant (oxygen, for example) from contacting the product, formulating the product so that the reactions do not occur readily, or by adding a chemical preservative such as an antioxidant.

Mechanical and physical changes can be difficult to trace, often appearing as a mysterious change in viscosity or separation of ingredients in a product, as well as outright breakage, but when they occur, they may be dealt with by changes in the product formulation or by changes in the packaging or distribution system. This will be discussed more fully in Chapter 9.

Chemical Degradation Reactions in Foods

Since foods are complex chemical mixtures, the reactions and processes that can change their quality and safety are complex as well, and there is a huge and growing base of literature on the subject. This chapter (and this book) cannot consider every degradation mechanism in great detail, but several of the most common ones will be discussed.

What is more important from the food engineering and packaging perspective is the ability to remediate and control these reactions in a product in a manner similar to the *critical element analysis* discussed in Chapter 9. To do this, one must have a basic notion of several factors:

- What is the nature of the degradation reaction?
- What endogenous and exogenous factors accelerate or retard it?
- What is the final effect on the product?
- How can the reaction be controlled or utilized to advantage?

To understand the prevention or remediation of degradation reactions in food and biological materials, it is first necessary to understand the basic processes that cause degradation to occur. In general terms, the processes may be arbitrarily divided into chemical, biological, and environmental degradation, although these are not entirely clear-cut. Chemical degradation may include processes such as browning and oxidation reactions as well as many biochemical processes within the complex chemistry of the product. Biological processes may include things such as biotic degradation, but will also include fermentation, which is a preservation or even food-forming process for some products such as coffee, cocoa, yogurt, bread, and alcoholic beverages. Environmental changes may include thermal or photocatalytic reactions that are considered to be chemical changes in some instances, even though the remedial step is to keep the product from the extreme light or temperature exposure that will promote the reaction.

Sometimes, the results of these reactions can be hard to measure and it may be that the only practical solution when tracking degradation is to examine an easily assayed component that is a good indicator of the degradation reaction of interest. For example, the destruction of phosphatase that is used in the pasteurization reactions described in the subsequent chapter will give an idea of the thermal input and is easily measured.

Reaction Rates and Quality Degradation

For an engineer, the consideration of a particular chemical reaction will concentrate on a measureable reaction step, and the rate at which it occurs in response to a controllable stimulus. Reaction rates have been observed to approach several orders of curves, and variation of these will be correlated to changes in the inputs to the reaction. These are often referred to as reaction rate curves and may be the source of some error if the observed data is assumed to be applicable to conditions beyond those measured. An additional source of error is often found in data sets that are obviously non-linear but have been fitted to a linear or low-order curve because it is inconvenient to do otherwise, or because current experts have published results that only consider low-order effects. This may cause the results of calculation to be easier, and occasionally quite wrong.

Zero-Order Reactions

Zero-order reactions appear to act independently of exogenous factors or the concentration of reactants and obey a simple time relationship:

$$r = \frac{-\mathrm{d}A}{\mathrm{d}t} = c \tag{7.1}$$

r: reaction rate
c: constant
A: concentration of reactant
t: time

A_t, the concentration at time (t) can be found through integration to be

$$A_t = A_0 - kt$$

Where
A_0: initial concentration of reactant

$$k = r$$

First-Order Reactions

First-order reactions are simple, linear reactions based on a single reactant that follow the general equation:

$$r = k\left(\frac{-\mathrm{d}A}{\mathrm{d}t}\right) = k\,(A) \tag{7.2}$$

k: first order, rate dependent constant that can be integrated to produce

$$A_t = A_0\mathrm{e}^{-kt}$$

Although these are often easy to calculate, the risk of *over-smoothing* the results is considerable and higher-order results should be checked when possible.

Second- and Higher-Order Curves

These have a general form:

$$-\mathrm{d}A/\mathrm{d}t = kA^n \tag{7.3}$$

that gives a concentration A at time t of

$$1/(A^{n-1}) = \left[1/\left(A_0^{n-1}\right)\right] + (n-1)\,kt$$

$$\mathit{for}\ n > 1$$

Arrhenius Curves

Arrhenius curves are first-order, temperature-dependent correlations resulting from the integration of the first-order reaction that is often an accurate correlation of temperature-dependent processes, and correspond with many biological and physical processes. These follow the general form:

$$k_{\mathrm{T}} = A\mathrm{e}^{-E_{\mathrm{a}}/RT} \tag{7.4}$$

k_{T}: rate constant of reaction at temperature T, s^{-1}
A: experimentally determined prefactor.
E_{a}: activation energy, kJ/mol
R: ideal gas constant, $\dfrac{\mathrm{kJ}}{{}^{\circ}\mathrm{K} \cdot \mathrm{mol}}$
T: absolute temperature, °K

Activation energy – the energy threshold to be overcome in order to initiate a reaction and produce reactants – is often calculated via rearrangement of terms as:

$$E_{\mathrm{a}} = -RT \ln\left(\frac{k}{A}\right) \tag{7.5}$$

The temperature dependence of the prefactor (A), although often measurable, is frequently considered to be insignificant relative to the exponential components. Both first-order curves and Arrhenius curves are usually plotted on semi-log scales to better visualize the relationships of the reactant to time or temperature, and to understand the underlying chemical thermodynamics more completely.

Shelf Life Testing

Given the previously mentioned models and an understanding of the nature of the degradation of the product that may occur, a reasonable estimate of the shelf life of the product can be made. Unfortunately, there is too often no agreement about how the end of the products' shelf life may be defined. The first task is to quantitatively define what a "bad" product is, whether spoilage, expiration, broken, unsaleable, or some other criteria. Although some things, such as an insect infestation would be self-evident, sometimes a "bad" product is defined in a haphazard or offhand way, causing disagreement among suppliers, manufacturers, and retailers. It may also be useful to understand the distribution system in which the product is dispersed to the customer because a rapidly distributed product that is only on the shelf for a few days before being consumed will have very different considerations from ones that will sit for months.

A good starting point for deciding where the product's shelf life has expired is making the distinction between the product's being no longer saleable and being no longer useable. These factors are not necessarily coincident – a perfectly safe and wholesome product may be unsaleable because of surface oxidation and discoloration of the layer closest to the wall of a clear plastic container, as happened with initial trials of plastic ketchup bottles, or it may appear to be safe, but is actually spoiled, have off-flavors, or be legally unsalable because of the loss of a component so that it no longer meets its label claim. In any case, the specific criteria for acceptability must be quantitatively defined in terms of color loss, microbial count, or other factor that may be objectively measured.

The next step is to decide the specific (and measurable) changes that constitute failure in the product. This does not necessarily have to involve an elaborate and involved laboratory analysis, but the criteria for failure must be related to a reliable (and preferably standardized) measurement method. Additionally, shelf-life testing may involve subjecting the product to extremes of temperature, humidity, and transportation damage, as well as organoleptic evaluation and test marketing in order to determine what the worst possible case scenario is and how to remedy or avoid it.

Once the kinetics of the deterioration reaction are understood, it is possible to shorten the testing period for shelf-life evaluation by artificially increasing the factors that may cause the product to fail in order to shorten the testing period. This is most often done with temperature, although it might also be oxygen, partial pressure across a package membrane, or some other factor.

Q_{10} *Estimation*

One of the simplest considerations of quality loss is the Temperature Coefficient, or Q_{10} curve, in which quality change is considered as a function of a ten-degree temperature change. The concept of quality loss is an extension of standard formulations for microbial death at increased temperatures that has been extended to include the loss of a particular temperature-dependent quality factor [1]. This concept can be used for small-level determination of quality changes, and may be used to a certain extent to determine accelerated shelf-life results, but has many pitfalls if the results are extrapolated beyond measured data. Q_{10} is an approximation tool used for the assessment of how much a given quality parameter will change with an incremental (often 10°C) change in temperature calculations, and is based on the assumption of linearity of processes and the presumption that those processes are based on Arrhenius reaction kinetics.

From the previously described Arrhenius curve, one can see that a ratio can be established with a temperature change:

$$
\begin{aligned}
k &= A\mathrm{e}^{-E_\mathrm{a}/RT}\\
\text{For Q} &= \frac{k_2}{k_1},\\
\textit{and}\,\mathrm{Q}_{10} &= \frac{k_2}{k_1} \quad \text{where } k_2 - k_1 = 10
\end{aligned}
$$

$$
\frac{k_2}{k_1} = \left(\frac{\mathrm{e}^{-E_\mathrm{a}/RT_2}}{\mathrm{e}^{-E_\mathrm{a}/RT_1}}\right) \tag{7.6}
$$

$$
\begin{aligned}
\ln\left(\frac{k_2}{k_1}\right) &= \ln\left(\frac{\mathrm{e}^{-E_\mathrm{a}/RT_2}}{\mathrm{e}^{-E_\mathrm{a}/RT_1}}\right)\\
&= \ln\left(\mathrm{e}^{-E_\mathrm{a}/RT_2}\right) - \ln\left(\mathrm{e}^{-E_\mathrm{a}/RT_1}\right)\\
\ln\left(\frac{k_2}{k_1}\right) &= \frac{E_\mathrm{a}}{R}\left(\frac{1}{T_1} - \frac{1}{T_2}\right)
\end{aligned}
$$

Two important factors have to be noted; Q_{10} is dependent on the activation energy (E_a) value, and its intrinsic value will change with temperature – a ten-degree difference at 350°K will usually be substantially different than a ten-degree difference at 250°K for any value of E_a.

Once the Q_{10} value is found, the approximation of temperature-dependent shelf-life testing can be done as shown in Table 7.1. As shown in the table, with a Q_{10} value of 3, a shelf life of 26 weeks at 20°C (293°K) can theoretically be simulated in approximately 7 days at 50°C (323°K). Similarly, accelerated degradation can be reversed into an estimate of shelf-life parameters using similar tabulation or curves available, such as Figure 7.1.

Table 7.1. Effect of Q_{10} on Product with 26-Week Shelf Life at 20°C

Temperature °C	$Q_{10} = 2$	$Q_{10} = 2.5$	$Q_{10} = 3$	$Q_{10} = 4$	$Q_{10} = 5$
30	13.0	10.5	8.7	6.5	5.2
40	6.5	4.2	2.9	1.6	1.0
50	3.25	1.7	1.0	0.4	0.2

Although the Q_{10} curve appears to be a tantalizing means to shorten shelf-life testing, it must be treated with great care for these and many other reasons – certainly, a simple ice cube behaves very differently at −5°C than it does at +5°C! Similarly, phase changes or state transitions may occur in food components, secondary reactions may hamper or accelerate the product parameters that one is measuring, or some unanticipated secondary factor may be introduced, such as exceeding the glass transition temperature of a plastic packaging material and having a severe change in permeation [2]. It is possible to match estimated degradation rates against short-term data as an initial check, but results from accelerated shelf-life testing must be treated with great care and should always be verified against real-world data. In the hurry to get a product into production, it is a false economy to rush an unsafe or unsalable product to market, only to have to recall it or deal with the human and economic consequences of spoilage.

Amplification of Estimation Errors in Accelerated Shelf-Life Testing

One of the underlying problems with accelerated shelf-life testing is that the small exposure time that is used to extrapolate long-term effects also amplifies the effects of any error in measurement or procedure, or variability in samples. As shown in Figure 7.2, this can have a dramatic effect on the final results and cause severe misestimation of the product's shelf life.

Shelf-Life Testing Follow-up

The final step in any modeling exercise is "closing the loop" by validating the model. In the case of extending the shelf life of a product, the final results must be carefully monitored in order to assure that the product has maintained a proper quality and safety level. This may require field work to sample the *shelf duration* and stock rotation of products in the retail environment. This requirement is doubly important when accelerated shelf-life testing is used because it will

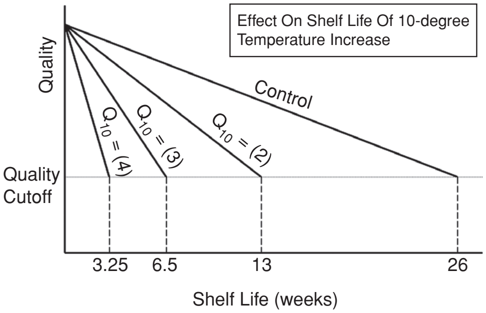


Figure 7.1. Graph of Quality Changes Due to 10°C Temperature Change at Different Q_{10} Values

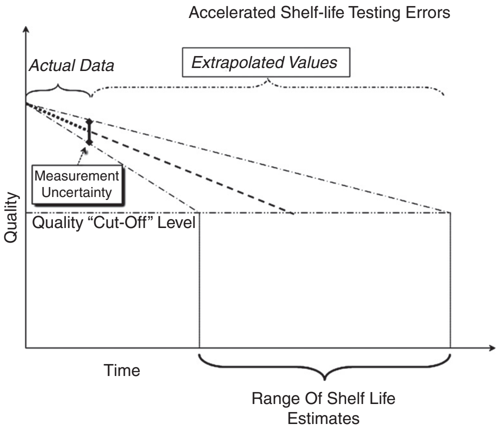


Figure 7.2. Graph of Shelf Life Estimate Error Amplification

give a strong indication of whether or not the shelf-life model is accurate. In any case, any data from real-world products, whether they have been sent through the distribution cycle or are stored under standardized conditions and then sampled, will be useful in improving the shelf-life testing process.

Examples of Specific Chemical Degradation Reactions

Browning of Foods

One of the more immediate reactions of foods to environmental exposure is browning, whether enzymatic or non-enzymatic. The difference is important, and both are strongly correlated with water content as well as temperature, water activity, and water mobility, which are discussed later in this chapter. Most browning reactions require a polyphenolic substrate such as a flavor constituent (cinnamic acid, for example), a coloring agent (such as anthocyanins), or other flavonoid-like compounds.

Enzymatic browning can cause both beneficial reactions such as those which create the distinctive properties of cocoa, tea, and coffee as well as raisins and other dried fruits. It can also cause harmful reactions such as those caused by browning and discoloration (pigmentation) in fruits, vegetables, and seafood. Most enzymatic reactions are caused by polyphenol oxidase or other similar enzymatic compounds that break down critical polyphenolic flavor, color, and occasionally texture compounds in foods. Enzymatic browning breaks these polyphenolic compounds down into melanins, creating the dark colors associated with the reaction.

Control or inhibition of enzymatic browning may involve lowering the pH of the product (such as the practice putting acidic juice on a piece of cut fruit), addition of a chemical preservative, elimination of oxygen availability to the product, or by blanching in order to inactivate the enzyme responsible for the reaction. Other control measures may include refrigeration to slow down degradation or freezing to below -18°C, although the exact mechanism of this is the subject of some debate. Rapid freezing both for direct production of frozen foods and the freeze-drying of foods is necessary to reduce browning in the final product. Because of the role of copper in polyphenolic oxidases, chelating agents can also control browning as well as

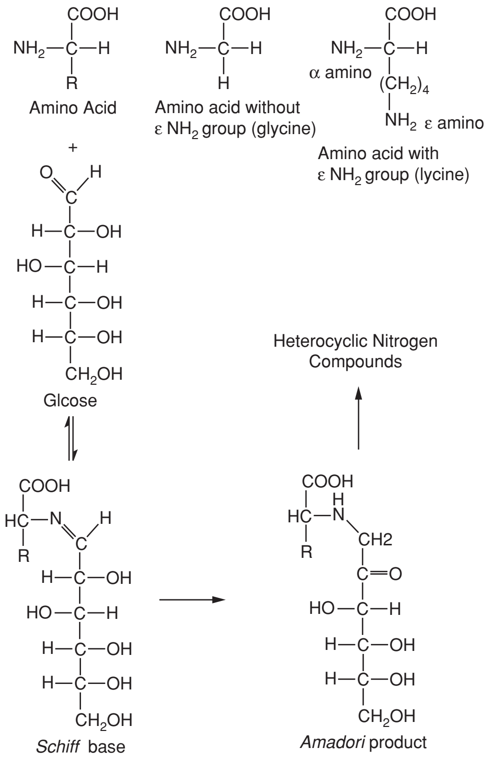


Figure 7.3. Basic Maillard Pathway
Source: U.S. Geological Survey, Scientific Investigations Report 2004–5121. "Evaluation of Conceptual Models of Natural Organic Matter (Humus) From a Consideration of the Chemical and Biochemical Processes of Humification"

modification of the product that enzyme is acting upon. More involved methods for the control of enzymatic browning, such as irradiation, pressure treatment, and other alternative processing methods as discussed in Chapter 6, have been evaluated for the reduction of enzymatic browning with varying degrees of success.

The most common forms of non-enzymatic browning are caramelization and the Maillard reaction (often called *Maillard browning*). Both reactions require thermal input and are often involved in the browning or coloring of cooked foods. Caramelization – a dehydration and pyrolysis reaction that results in oxidized sugars with low water availability – is used extensively in cooking to intentionally produce both flavor and color changes, the most easily recognized being the enediols and dicarbonyls of the caramel compounds. In most instances, caramelization is controlled by careful measuring of the amount of heat or sugar available during processing. The Maillard reaction (Figure 7.3), on the other hand, is a complex polymerization reaction between sugars, water, and protein's amino acids, which generates changes in the color and flavor of the product. It can affect the color, flavor, aroma, and nutritional content of the food, such as the browning of bread crusts, coffee, and cocoa, as well as undesirable changes such as flavor loss and the creation of toxic or mutagenic compounds and precursors.

Because the Maillard reaction is determined by the sugar and amino acid involved, these may be manipulated to control the reactions or to produce a wide variety of flavors and aromas, both natural and synthetic. Further control of Maillard browning is achieved by controlling the reactants, pH, and water availability (Maillard browning peaks in the $0.6 < A_w < 0.7$ range), as well as thermal energy available for the reactions by controlling temperature.

Other Discoloration Reactions

With the continued high demand for natural food colorants that do not have to undergo strict regulatory review, the stability of natural colors may be critical in maintaining consumer acceptance of a product. Oxidation and degradation of other natural color compounds such as carotenoids, anthocyanic compounds, and the like are usually more direct breakdowns of the complex pigmenting compounds and are directly affected by oxygen availability, temperature, light exposure, and pH, as well as many naturally occurring processes such as enzymatic attack or microbial growth. Stabilization of natural colors often involves reducing the availability of moisture or the addition of a preservative such as sulfur dioxide, which is commonly used to prevent discoloration of dried fruits.

Rancidity and Oxidation of Fats and Oils

Rancidity of lipids may occur by three general mechanisms: hydrolytic, microbial, and oxidation resulting from the action of water, microbial enzymes, and oxygen, respectively. Free radical lipid autoxidation – an oxidation of fats and oils that usually causes some type of quality loss – follows a well-documented reaction pathway [3]. In general, the reaction proceeds in a manner similar to the synthetic plastics polymerization reactions discussed in Chapter 4, with initiation providing active sites for a continued reaction that only terminates when the material has been depleted or the reaction is quenched by antioxidants or other compounds. Some oxidation reactions are used as a low-rate type of polymerization for thickening and binding items such as oil finishes and the pigment in vegetable oil artist's colors used in the past. The lipid oxidation reaction, shown in Figure 7.4, begins with the loss of a hydrogen atom because of heat, radiation,

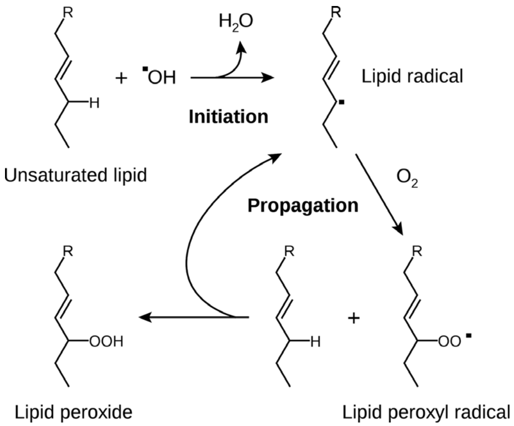


Figure 7.4. Lipid Peroxidation Pathway
Source: Tim Vickers, after Young IS, McEneny J (2001). "Lipoprotein oxidation and atherosclerosis". *Biochem Soc Trans* 29 (Pt 2): 358–62. PMID 11356183

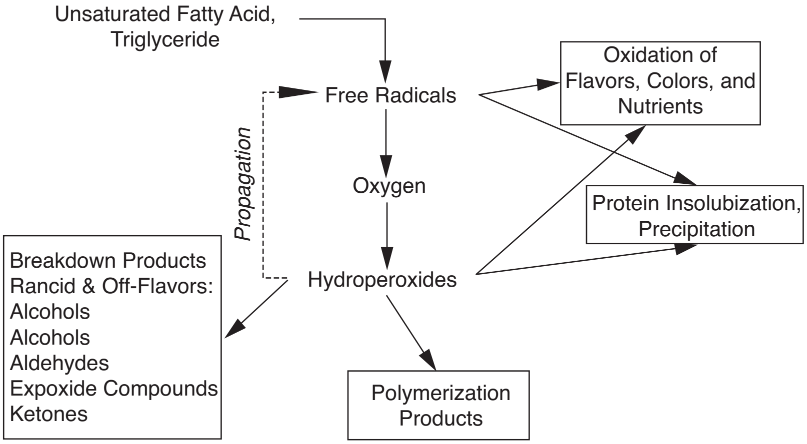


Figure 7.5. Lipid Oxidation By-products

enzymes (lipogenases), or metallic compounds. The lipid material then becomes a free radical, with a binding site available to bond to oxygen, forming a peroxy radical that then reacts with other lipid compounds to form hydroperoxides. The ongoing reaction terminates by combining radicals to form more stable reaction products.

Decomposition of these hydroperoxides can result in either polymerization products that can be toxic, or breakdown products that are often volatile and may affect product quality. Hydroperoxides can also react with proteins, membranes, and enzymes to affect cell function [4].

Photooxidation reactions require the photochemical production of a triplet sensitizer that interacts either with a substrate or with oxygen. In the latter case, a singlet oxygen is produced that is very reactive and is thought to be capable of initiation of the autoxidation, and will produce hydroperoxides and breakdown products in a manner similar to radical-initiated photooxidation [5].

Regardless of the pathway, lipid oxidation will produce a broad spectrum of aldehydes, esters, peroxides, and free radicals that may damage other food components such as vitamins and proteins, as shown in Figure 7.5.

Control of lipid oxidation involves control of oxygen, control of light, heat, and the addition of reaction-controlling additives such as antioxidants and finally water, which at high A_w values will quench the reaction, and at very low levels is correlated with low reaction rates.

Environmental Agents and Shelf Life Reduction

Gas Permeation and Exposure

As mentioned in the preceding discussion on oxidation, oxygen remains a powerful environmental agent that may degrade product quality over time. Oxygen is usually excluded from food materials, often by a combination of packaging, treatment during processing, and the *scavenging* effects of both the product oxidizing remaining oxygen during storage and intentionally included in-package devices and materials. As modified atmosphere packaging (MAP) processes become more prevalent, the ability of a package to retain and maintain a stable desired

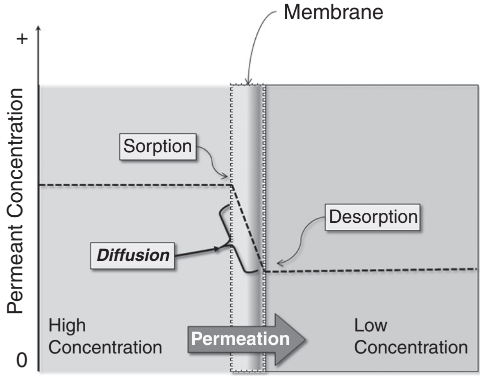


Figure 7.6. Permeation Model Based on Fickian Diffusion

microatmospheric mix, not only with regard to oxygen content but other gasses such as CO_2 and ethylene, will become more important as well.

Gas permeation is traditionally modeled using the basic Fickian diffusion model where permeation occurs along a concentration gradient and involves surface sorption-desorption phenomena as well as bulk diffusion within the polymer matrix that is driven by the concentration differential, as shown in Figure 7.6.

The Fickian diffusion model described in Chapter 2 assumes a steady-state, isothermal, and linear (permeant concentration and thickness independent) coefficients, and can be written as:

$$J = -D\frac{\delta c}{\delta x} \tag{7.7}$$

J: Diffusive Flux, $\frac{\text{mol}}{\text{m}^2/\text{s}}$

D: Diffusion Coefficient, m^2/s

$\frac{\delta c}{\delta x}$: differential concentration across the structure's thickness, $\frac{\delta\left(\frac{\text{mol}}{\text{m}^3}\right)}{\delta m}$

The solubility coefficient, the ratio between the partial pressures of the permeant (P) and the concentration at the surface of the solid phase (C), can be given as:

$$S = \frac{C_1}{P_1} = \frac{C_2}{P_2} \tag{7.8}$$

It is generally considered that there is a small discontinuity between the concentration of the bulk permeant and the surface concentration. The experimental determination of D and S is most commonly achieved by using an isostatic or quasi-isostatic permeation cell, as shown in Figure 7.7.

The measurement of gas concentration increase on the *static* side of the solid-phase membrane will give both a steady-state rate of concentration increase and a time lag that may be used to estimate values for D and S, as shown in Figure 7.8, which is often sufficient for simple, steady-state models and initial estimates of values.

Calculation of the P and S value estimates may be taken from the data compiled for the particular permeant-matrix combination and converted using the known thickness of the material

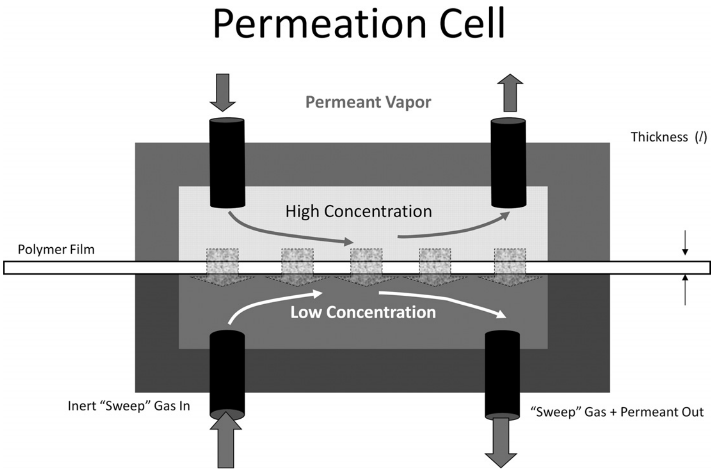


Figure 7.7. Cross-Sectional View of Gas Permeation Cell

(l) and the lag time to establish steady-state permeation rate through the film.

$$L = \frac{l^2}{6D} \tag{7.9}$$

$$D = \frac{l^2}{6L}$$

$$D = \frac{\bar{P}}{\bar{S}}$$

$$\bar{S} = \frac{\bar{P}}{D}$$

l: thickness, m
D: Diffusivity,
L: Lag Time, s
$\bar{P}$: Steady State Permeation Rate
$\bar{S}$: Solubility Coefficient

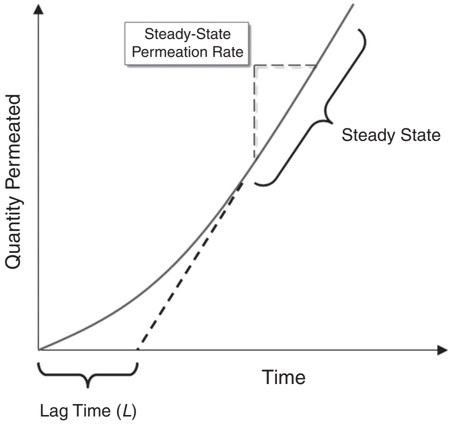


Figure 7.8. Permeation Rate and Lag Time Used to Determine Solubility and Diffusion Coefficients

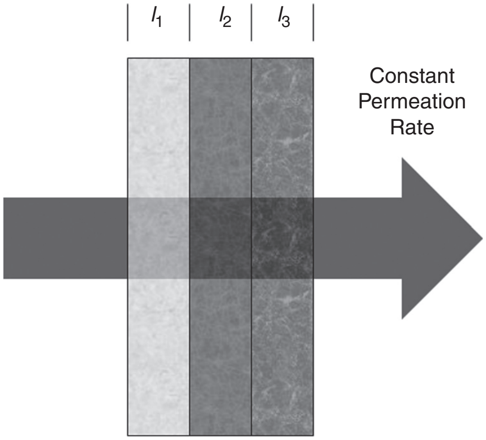


Figure 7.9. Multilayer Permeation

In more practical terms, gas and vapor transmission through packaging matrixes is usually expressed as a permeation rate, and is often expressed in odd and sometimes very mixed unit sets – there appears to be no standard beyond a basic (quantity)/(time) ratio.

$$\bar{P} = \frac{\Delta Q \cdot l}{\Delta t \cdot A \cdot p_\mathrm{p}} \tag{7.10}$$

$\bar{P}$: permeation rate
ΔQ: quantity of material permeated,
l: thickness of the material,
Δt: reference time period
A: membrane(film) area
p_p: partial pressure differential of permeant
Note that mixed units systems are common.

For laminates and co-extrusions such as shown in Figure 7.9, the mass-transfer parallels with heat transfer can be extended to give an overall permeability of a layered material as:

$$\frac{\Delta x_1 + \Delta x_2 + \Delta x_3 + \cdots + \Delta x_n}{\bar{P}_\mathrm{composite}} = \frac{\Delta x_1}{\bar{P}_1} + \frac{\Delta x_2}{\bar{P}_2} + \frac{\Delta x_3}{\bar{P}_3} + \cdots + \frac{\Delta x_n}{\bar{P}_n}$$

Or

$$\bar{P}_\mathrm{composite} = \frac{\Delta x_1 + \Delta x_2 + \Delta x_3 + \cdots + \Delta x_n}{\left(\frac{\Delta x_1}{\bar{P}_1} + \frac{\Delta x_2}{\bar{P}_2} + \frac{\Delta x_3}{\bar{P}_3} + \cdots + \frac{\Delta x_n}{\bar{P}_n}\right)} = \frac{\Delta x_\mathrm{overall}}{\left(\frac{\Delta x_1}{\bar{P}_1} + \frac{\Delta x_2}{\bar{P}_2} + \frac{\Delta x_3}{\bar{P}_3} + \cdots + \frac{\Delta x_n}{\bar{P}_n}\right)} \tag{7.11}$$

Some Fallacies of the Steady-State Model

The steady-state permeability and diffusion models work well with simple permeants and diffusion through fairly inert matrixes, but in real-world applications, many factors can crop up to cause large deviations from predicted values. The largest of these is confusion between permeation processes, which are controlled by diffusion mechanisms, and bulk flow occurring through a large opening or defect in a material and controlled by pressure differential. If bulk flow is occurring, it will overwhelm any sort of diffusion-mediated transfer. It is not unheard of for analytical laboratories to be asked for permeation rates of packages that are perforated or have large ports cut into them, which means that the values are entirely dependent on the mass flow rate of leaks rather than the permeability materials being tested. The analysis of microperforated films as described in Chapter 4 represents a borderline case where the actual mechanism may be pressure- or diffusion-regulated, and in practical terms an effective permeation rate must be known.

Another common phenomenon is interaction between the permeant (or a co-permeant) and the diffusion coefficient of the barrier matrix. Non-linear permeation can be said to occur when the permeability depends on permeant concentration, thickness of material, time-related changes in materials, or some other external factor. One of the most common examples of this phenomenon is plasticization of a polymer matrix in a food packaging system by a volatile constituent (usually a flavor compound) or by a fat or oil contained in the product.

Factors That Can Influence Permeation

Permeant Characteristics

Typically, larger and more complex molecules will have a slower diffusivity than smaller, simpler compounds. The extreme example of this is hydrogen, which can diffuse through metals and glass. The solubility of the permeant in the polymer matrix (which implies interaction with the molecular structure of the polymer), as well as the presence of co-permeants, can markedly affect the diffusion of the permeants and significantly change the permeation rates. Organic solvents, for example, have a very high permeation rate through many hydrocarbon-based polymers, whereas inorganic gasses such as nitrogen may have a much slower rate, even though their molecular size is smaller.

Polymer Functional Groups and Additives

More complex functional groups, such as hydroxyl groups on a carbon backbone, have been shown to produce a much lower oxygen permeation rate than simpler alkanes, with other groups producing intermediate values. Inert additives may or may not change the barrier characteristics depending on how well they are bonded to the polymer matrix. Simple, inert additives are thought to create microvoids that allow a higher permeation rate. Other additives such as plasticizers and modifiers will increase chain segmental mobility and allow chain movement, increasing the permeation rate.

Structure and Morphology

Simple, linear HDPE will have a much lower permeation rate than polypropylene or more variants with high degrees of branching. Similarly, complex and cross-linked materials will have a much lower permeation rate than shorter, simpler materials. This is presumed to be an effect of the free volume created in the less densely packed linear structures. Similarly, a low level of amorphous structure or a high degree of orientation will reduce permeation as well, because both of those states will allow a higher degree of close-order packing and therefore less free volume for permeant penetration.

Environmental Conditions

Temperature is the most obvious environmental factor that will affect the barrier characteristics of a polymer. Below the glass transition temperature (T_g), the inflexibility and lack of segmental rotation in the polymer chains will prevent the rapid diffusion of many permeants, but as the temperature increases and the polymer achieves a rubbery state, the permeation rate will jump dramatically. Humidity will also play an enormous role, particularly with hygroscopic polymers such as nylon and water soluble-barriers such as the vinyl alcohol (PVA) compounds. Longer-term effects can result from the degradation of the polymer by sunlight or oxidation, as well as the effects of mechanical abuse.

Water Vapor Permeation

Water vapor permeation shares many of the characteristics of the simple gas permeation models, but with the added complication that the partial pressure across the barrier will probably not remain constant. With the permeation of gasses, particularly oxygen, the assumption is made that the gas will be bound up in reaction products. For a simple Water Vapor Transmission Rate (WVTR) in plastic films, this assumption is maintained during testing by creating a constant partial pressure across the film membrane with desiccants, as shown in Figure 7.10, with results usually reported in g $H_2O/m^2/24h$, although this may vary widely and may mix unit systems.

Although this method will produce good data and can be used in the same way as the gas permeation method to determine diffusion and sorption data, real-world applications may be more complex. With moisture permeation, the assumption that a constant partial pressure exists is usually invalid because the partial pressure will change as the product becomes hydrated and its water activity changes. This change in water activity with increasing hydration is usually modeled using a moisture sorption/desorption isotherm (Figure 7.11), which must be experimentally determined.

Creating a moisture isotherm is usually achieved by storing product at a particular relative humidity and measuring its equilibrium uptake in comparison to a desiccated sample. The equipment for this may be quite complex, but adequate measurements may be made by using sealed containers that are humidified with saturated solutions of specific salts, as shown in Figure 7.12, an oven (preferably with vacuum) for desiccation, and an accurate scale to measure the weight difference between the hydrated and desiccated samples.

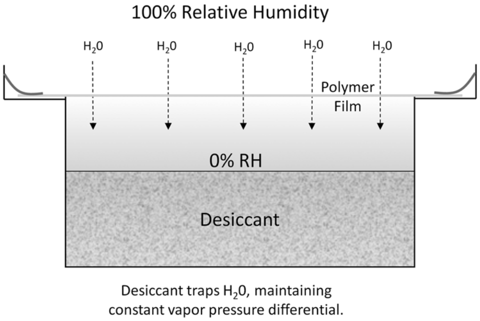


Figure 7.10. Moisture Permeation Testing Cup

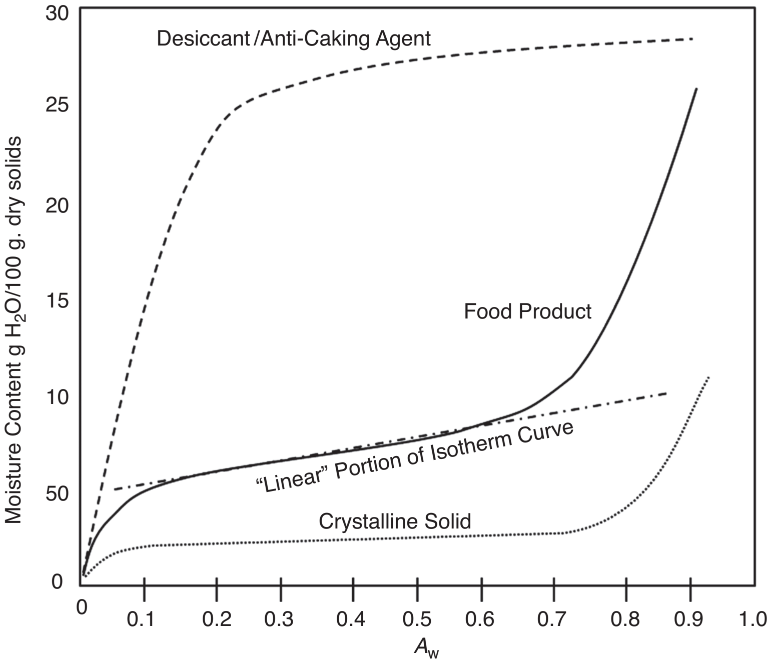


Figure 7.11. Moisture Isotherms

Because of differential binding of moisture during sorption or desorption, hysteresis usually exists between the sorption and desorption isotherm curves, as shown in Figure 7.13, and the results should be considered in relation to whether moisture gain or loss is likely to occur in the product.

Additionally, the surface area of the product must be considered. Grated cheese products have a huge, slightly hydrophilic surface that can create a rapid mold growth problem even if the larger block of the same cheese shows little immediate tendency for it. The difference is that the grated cheese product has an enormous surface area such that the binding of a small amount

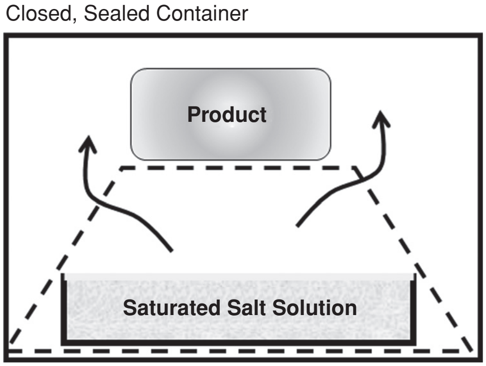


Figure 7.12. Humidification of Product Using Saturated Salt Solutions in Closed Container

Table 7.2. Relative Humidities of Various Salt Solutions

Temperature °C				
Salt	15.0	20.0	25.0	30.0
Phosphorus Pentoxide*	0	0	0	0
Sodium Hydroxide	9.6	8.9	8.2	7.6
Lithium Chloride	11.3	11.3	11.3	11.3
Magnesium Chloride	33.3	33.1	32.8	32.4
Potassium Carbonate	43.2	43.2	43.2	43.2
Magnesium Nitrate	55.9	54.4	52.9	51.4
Potassium Iodide	71.0	69.9	68.9	67.9
Sodium Chloride	75.6	75.5	75.3	75.1
Potassium Chloride	85.9	85.1	84.3	83.6
Potassium Nitrate	95.4	94.6	93.6	92.3
Distilled Water	1.0	1.0	1.0	1.0

*Not Recommended

Source: Greenspan. L. (1977), "Humidity Points of Binary Saturated Aqueous Solutions." *Journal of Research of the National Bureau of Standards* 81A(1): 89–96.
Available from NIST at http://nvl.nist.gov/nvl3.cfm?doc_id=89&s_id=117.

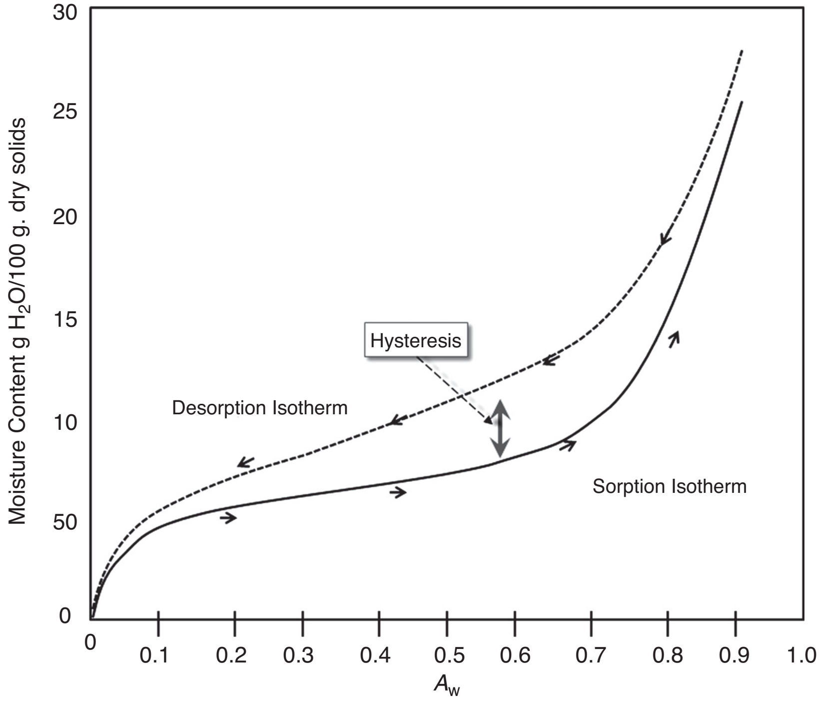


Figure 7.13. Sorption and Desorption Isotherms Showing Hysteresis

of moisture over the large area will create a much larger capacity for crossing the minimum moisture threshold and of supporting growth, particularly of molds.

Many studies have been done to fit a generalized equation to moisture-sorption isotherms, and there is a wealth of literature on these and their modifications. One of the most common and most broadly applicable is the Guggenheim-Anderson-DeBoeur (GAB) equation:

$$M = \frac{M_m C k a_w}{(1 - k a_w)(1 - k a_w + C k a_w)} \tag{7.12}$$

M: equilibrium Moisture Content, dry solids basis, g/g
M_m: monolayer Moisture Content, dry solids basis, g/g
a_w: water Activity, g/g

$$\mathrm{C} = \mathrm{C}'\mathrm{e}^{(H_1 - H_m)/RT}$$
$$k = k'\mathrm{e}^{(H_1 - Hq)/RT}$$

H_1: heat of condensation of water
$\mathrm{H_m}$: heat of monolayer sorption
$\mathrm{H_q}$: heat of multilayer sorption
C′, k′: experimentally determined coefficients

Moisture-Related Degradation Reactions

In addition to the lipid oxidation, enzymatic, and browning reactions that have been previously discussed, the growth of microorganisms in foods is intimately associated with the level of available moisture, with mold growth occurring at approximately $A_w > 0.6$ and bacterial growth beginning at approximately $A_w > 0.9$, with toxin production somewhat above that. Similarly, oxidation, browning, and other degradation forms will vary with water availability, as shown in Figure 7.14.

Predictive Models of Moisture Sorption

Because the moisture sorption model is assumed to be non-linear in that the partial pressure of moisture vapor changes with the ongoing humidity change in the package, creating a predictive model is much less direct than the simple calculations performed for simple gas permeation models. Although the GAB model and others provide an analytical approximation to use in other calculations, creating a practical model with experimental data is most readily accomplished with the aid of simple spreadsheets or even a good programmable calculator. In most cases, if the permeation rate of the polymer film is known, the partial pressure can be adjusted in an ongoing progression of values to achieve the equivalent of a stepwise integration along the sorption isotherm curve as it approaches equilibrium.

The flowchart in Figure 7.15 shows the general programming layout for a moisture sorption estimation equation.

Water Activity and Water Mobility

Water activity has been used to predict and explain a large number of phenomena and serves very well for a number of everyday reactions and processes. Additionally, it has the advantage of being easily (and cheaply) measured. Unfortunately, it is difficult to measure the water activity

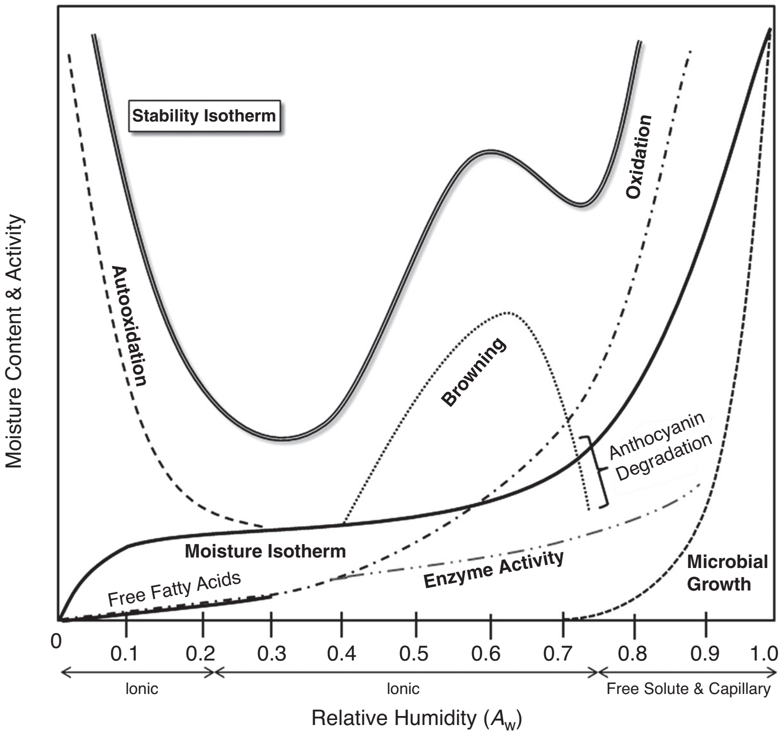


Figure 7.14. Relationship of Water Activity to Spoilage Mechanisms
Source: Labuza, T. P. and Nelson, K. A. "Water Activity and Food Polymer Science: Implications of State on Arrhenius and WLF Models in Predicting Shelf Life." *Journal of Food Engineering*, 22: 271–89. Used With Permission

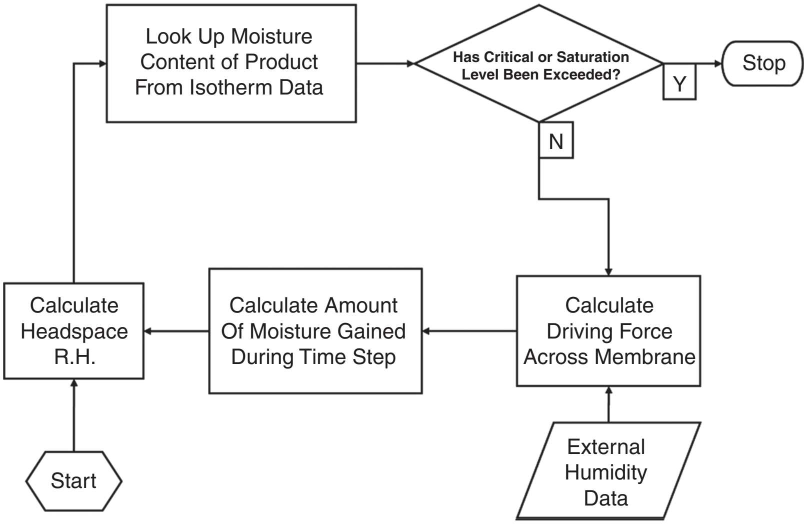


Figure 7.15. Flowchart for Shelf Life Estimation Program

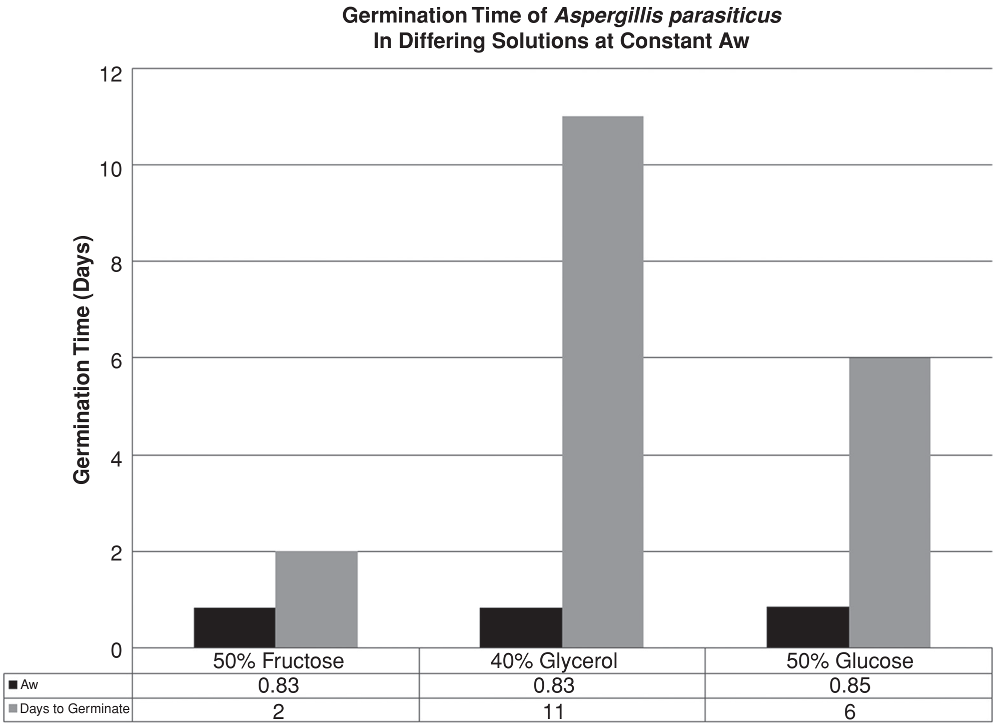


Figure 7.16. Germination Time Differing By Media Type Rather Than Aw

of frozen foods at very cold temperatures even though moisture migration and browning are occurring, and there are a number of unexplained phenomena, such as a study that produced wildly disparate germination data for *aspergillis parasiticus* held at the same water activity with growth media that differed only in their ability to bind water, as shown in Figure 7.16 [6].

A better explanation is the concept of *water mobility*, which gives the phase of water-containing compounds as an explanation of whether water is available for degradation or other processes. In an amorphous food product, water will act as a plasticizer and the product will exhibit many of the same characteristics as other polymers, showing glassy, rubbery, and melt states with increasing water mobility. As an example, see a generalized phase diagram for a standard-pressure solids-water system shown in Figure 7.17.

It can be shown that a small change in temperature at a particular weight fraction of water (shown as A-B) will cause a shift in phase from glassy to rubbery in both laboratory models of starch-water systems and frozen foods, with a marked increase in water mobility and an attendant increase in product degradation. Similarly, the transition from glassy directly to a melt state above the freezing point of water can be quite marked. This principle has been borne out in subsequent studies of frozen foods, which show that a repeated transition into the rubbery region, even though the food is still apparently frozen solid, will result in the acceleration of freezer burn and increased degradation of color and quality.

More complete diagrams are available showing that the state of water in foods may be a great deal more complex than was originally thought, and that both measuring it and determining the final outcomes may be a great deal more difficult than the simple use of A_w. The advantages

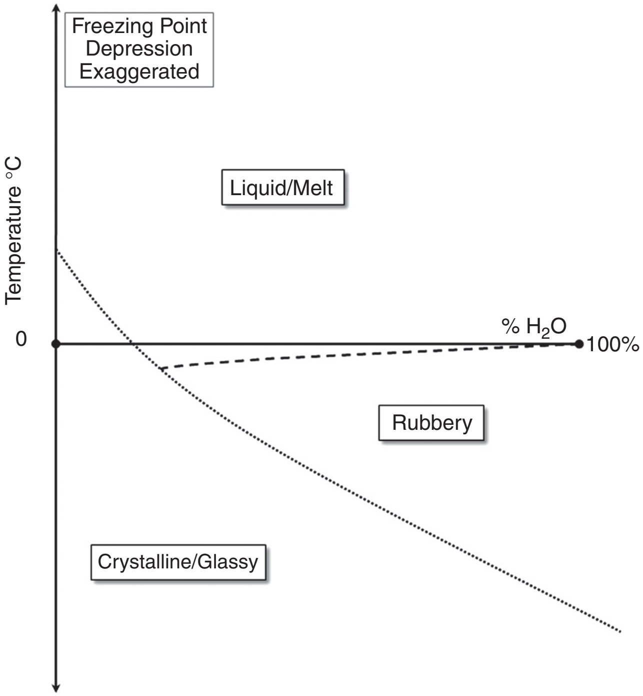


Figure 7.17. General Phase Diagram of Water in Foods

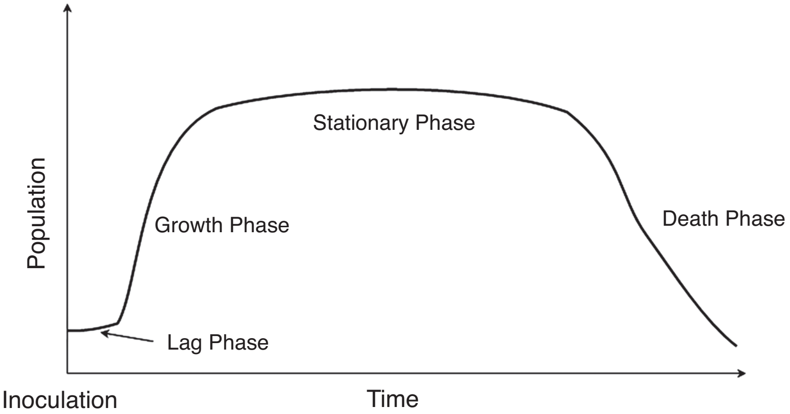
outweigh the difficulties, in that the predictive model has both a practical result and a better theoretical explanation.

What is clear is that the prediction of degradation mechanisms must take the state of water into account when anomalous behavior occurs, and that the changes in temperature and solvent/solute ratios that would not cause a great effect in A_w values may significantly alter the water availability for degradation. Indeed, the formation of intracellular glassy compounds is the mechanism by which many of the grains and plants (or their seeds, which we often eat) resist denaturation and survive dry periods, and more astonishingly how some seeds may be viable after millennia of dry storage while other species that cannot do this show no drought tolerance at all [7].

The great disadvantage in using the water state or water mobility concepts for practical applications is that the values may be difficult, time-consuming, or expensive to measure. Current measurement methods revolve around differential scanning calorimetry (DSC), nuclear magnetic resonance and magnetic resonance imaging (NMR, MRI), and Fourier transform infrared spectroscopy (FTIR). Development of fast, inexpensive scanners is ongoing, and there has been limited success with devices such as small portable MRI instruments to determine the state of water in frozen foods [8].

Microbial Product Changes

Microbial action both creates and destroys certain food products, and may help or hinder long-term food storage depending on the type of organism and whether or not it is considered part of the food product. In addition, microbial biopreservation technologies offer the promise of using



Lag Phase	Little Reproduction	Adjustment to growth media and initial reproduction.
Exponential (Growth) Phase	Reproduction >> Deaths	Few competitors, lots of nutrients.
Stationary Phase	Reproduction ≈ Deaths	Competition, waste products, and nutrient supply limits growth
Death Phase	Reproduction << Deaths	Nutrient depletion, waste saturation.

Figure 7.18. Microbial Growth Curve

cultures of microorganisms that are added to extend the shelf life or enhance the safety of food products.

Food microbiology, like food chemistry, is its own discipline and can only be generally discussed here. The types of microorganisms that are of most interest in food processing are bacteria, yeasts, and molds, and all exhibit the same general growth patterns shown in Figure 7.18.

Inoculation

Although this may bring syringes to mind, it simply refers to the initial introduction of the microbial species to its growth media (usually the food product).

Lag Phase

A period of low, metastable population level that occurs as microorganisms adjust to the new environment. The slow growth rate is often due to metabolic adjustments or population selection.

Logarithmic (Growth) Phase

A period of rapid (usually exponential) population growth as the microbial population expands into the nutrient supply and has little accumulated waste.

Plateau Phase

Microbial growth and deaths are approximately equal as nutrient availability decreases and waste accumulates.

Death Phase

Death rate exceeds new organism production, usually as a result of nutrient starvation or the accumulation of waste products.

Because all populations of microorganisms have different growth characteristics in the various growth media provided by most foods, it would be impossible to offer anything but the most general description of growth factors for several typical organisms.

Factors Used for Preservation by Affecting Microbial Growth

pH

Acidity will affect the type of microbial growth that can occur, and foods below a pH value of approximately 4.6 are considered high-acid foods where all food poisoning and most food spoilage organisms will not grow, which makes acidification, as with some types of pickling, some of the oldest and most effective preventatives of microbial growth, although acidified high-acid foods with a high water activity are still considered at risk and may require thorough thermal processing. In rare instances, processing with alkaline materials may be used to produce stable foods such as lutefisk from relatively pH-neutral (and therefore spoilage-prone) fish products. Additionally, naturally produced low pH can be generated by fermentation that will produce other antimicrobial products such as ethanol.

Water Availability and Osmotic Pressure

Although the concepts of water activity and mobility have been previously discussed, the methods of controlling them have not. Generally, drying, freezing, or using preservatives such as salt will immobilize water to the point where microbial growth is slowed or prevented. Osmotic pressure gradients that desiccate pathogens can be built up by preservation in high-sugar syrup with or without ethanol's combination of toxicity and osmotic differential to produce similar effects.

Oxygen Availability, Oxidation-Reduction Potential, and Microbial Growth

The availability of oxygen may determine what kind of organism may or may not grow in the product. Because the exclusion of oxygen has been a long-standing practice in many packaged foods to reduce degradation both from oxidation and from aerobic organisms, the possibility of anaerobic organisms such as *C. Botulinum* as well as microaerophiles such as *Camphylobacter jejuni* makes the proper processing of packaged foods a critical step. Relatively recent developments such as bagged salads that have matched moderate oxygen transmission rate package structures, gas-flushed modified atmosphere packaging (MAP), and respiring produce products create yet another challenge in oxygen level management.

Microorganisms are also sensitive to the oxidation-reduction potential (Eh) that their environment provides. The potential for electron exchange can be expressed in millivolts (mV), with high-oxidation states represented by a high positive potential and high-reducing state represented by a high negative potential. As one might expect, aerobic organisms require an oxidized (high positive potential) environment to grow well and anaerobes require reduced (negative potential) environments. The Eh value, defined as 1.0 Eh = 1.0 mV of reduction potential, can be estimated by use of the Nernst equation and is usually referenced to a platinum electrode standard. Generally, the Eh value of a material will vary with both pH and with the presence of secondary compounds such as hydrogen sulfide (H_2S) that has the potential to lower the Eh value to approximately −300 mV. The state of the food materials will affect the Eh value, with freshly slaughtered meats having a high Eh value that prevents the immediate growth of anaerobic organisms, but decreases over time, and many foods and particularly plant foods and juices have a high Eh value that favors aerobic spoilage.

Note that the complex electrochemistry of cans and canned foods, discussed in Chapter 4, is an integral part of the electrochemical balance. Food stability as well as the stability of the can structure are intimately interrelated and present a challenge to provide structures that are stable and do not degrade or adulterate the product.

Shelf Life Extension by Preservative Agents

Preservative agents have also been used since antiquity, although most of these such as salt, fermentation acids and alcohol, and sugar are not commonly considered preservatives in the same sense as newer synthetic chemicals. Most of these traditional pickling and preservation agents work by providing a hostile environment for microbial growth either by immobilizing water or by raising the pH or alcohol content of the product to the point where pathogen growth is inhibited. A brief description of some common antimicrobial preservatives is provided in Table 7.3, but it is important to remember that there are a huge number of materials that are approved for use as food preservatives, and the table is by no means comprehensive.

For many types of preservatives, it is important to determine whether the preservative agent will be lost in processing, and whether it will affect the packaging material either by direct action, as with an acid- or alcohol-containing product, or by indirect mechanisms such as the uptake of the preservative into the packaging material matrix.

Shelf Life Extension by Packaging

Although packaging can control the transmission of materials in and out of a product, the packaging microenvironment may be more complex and subtle than one might initially imagine.

Table 7.3. Food Antimicrobial Compounds

Compound	Use
Acetic Acid, Potassium-, Sodium-, and Calcium Acetate, and Sodium Diacetate	Pickling, antimold agents, sauces, antibacterial additives.
Benzoic Acid	Acid food preservation.
Propionic Acid, Sodium, Calcium Proprionate	Bakery preservation; occurs naturally in Swiss cheese.
Sulfur and Sulfur Dioxide	Reduces nonenzymatic browning, antioxidant, antimicrobial.
Sorbic Acid	Mold and yeast control.
Nitrites, Nitrates	Meat curing
Methy-, Propyl- and Heptyl-Parabens	Antimicrobial in baked goods, drinks, jams, syrups.
Ethylene, Propylene Oxide	Chemical sterilants. Used on dry foods (nuts, grain, and spices) and to sterilize packaging materials. Also used to sterilize bandages and surgical instruments and materials.

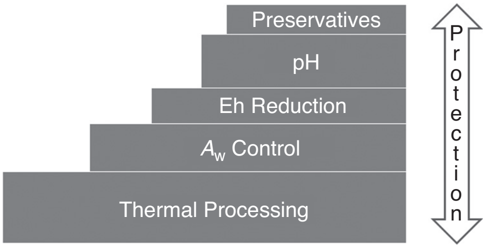


Figure 7.19. Staircase (Hurdle) Preservation Principles

Meat producers are carefully matching oxygen and gas transmission rates with modified atmosphere gas flushing to extend the shelf life of fresh cuts of meat. Fresh produce may be stored in a controlled-atmosphere macroenvironment before being shipped under carefully controlled conditions to market, and processed foods are often stored and shipped with carefully engineered packaging systems that have components that actively work to absorb gasses and moisture and to stabilize the product.

For fresh and processed foods, there are many additional post-packaging systems available for the extension of shelf life. Most of these depend on the establishment and maintenance of a microenvironment within the package that is optimal for the extension of shelf life of the product, and this, in turn, depends on careful management of many contributing factors for each particular type of product. For many types of fresh products, control of initial microbial load and then temperature control during storage and distribution is one of the most effective means of shelf-life extension, but further gains can be obtained by controlling the gas mixture within the package as well as other manipulations of the microenvironment.

Modified-atmosphere packaging (MAP) and active packaging are examples of tools used to ensure layered levels of impediment to microbial growth and reduction of processes such as oxidation, ripening, or staling, as shown in Figure 7.19 [9]. These are often termed *hurdles*, although a progressive staircase is a better metaphor, because microorganisms and degradation mechanisms must face progressive rather than successive layers of restraint.

Initial sterilization or microbial load reduction may be accomplished by many different means depending on the product type and the desired effect. The simplest of these is to ensure that processing conditions do not contribute to a relatively low initial load, but for most products, an initial antimicrobial wash or spray, or some other type of reduction may be useful. Continued maintenance of shelf life will then be dependent on the type and particular variety of product involved. For example, although the degradation mechanisms of pork and beef are quite similar, the optimum mix of gas treatment and package type may differ significantly, and even these will vary somewhat, depending on species.

Package-Product Interaction

Apart from the simple barrier function that most packages are presumed to provide, the package and product often interact with one another. Package-product interaction can be arbitrarily segmented into movement of materials either into or out of the package, as well as reaction with the packaging material itself. These interactions are the subject of both a great deal of development and engineering effort on the part of the food packaging industry, and the subject of some degree of concern among consumer advocates, toxicologists, and regulators. From a legal perspective, harmful materials being transferred into a product from a package structure or material will render it adulterated and therefore unfit for sale or use. From an engineering standpoint, materials transferred into a package material from the product such as the previously discussed materials that may affect the barrier properties, or an oily compound that acts as a plasticizer, can be a significant concern.

Extraction of Packaging Materials into Products

The extraction of materials into products, particularly food, drug, and cosmetic products, can have both toxicological and organoleptic consequences. Situations such as questions of health effects from the extraction of di(2-ethylhexyl)phthalate (DEHP) plasticizers into PVC blood bags and medical devices, vinyl chloride monomer (VCM) into containers for hot beverages, and bisphenol-A (BPA) compounds from plastic containers into food products have gotten a good deal of press exposure from time to time. More subtle effects such as the flavor or odor changes from printing inks used on packages or volatile compounds from paper formulations can also affect the salability of the product.

Extraction of compounds from packaging into the product can also have positive effects with items such as corrosion-preventative wraps for machinery and antioxidant-containing packages for cereals, butter, and margarine sticks. These intentional interactions are regarded in the United States as indirect food additives and must be declared on the label. In general, food packaging materials and food contact items along with ingredients and direct or indirect additives must either belong to a list of approved additives or the “Generally Recognized as Safe” GRAS list, European Commission-approved additives list or similar compilation. Since it would be tedious, if not silly, to test every traditional food material (water, for instance) as a hazardous additive, most regulatory systems exempt simple, naturally derived compounds from rigorous testing. Food additives that have been heavily modified or have a synthetic origin most often must undergo an approval process that will approve use at all levels, at limited exposures, or will prohibit their use altogether. In the United States, unapproved additives and food contact materials that release unapproved compounds must go through an approval process that is described in detail in Chapter 10.

Antimicrobial Packaging

The incorporation of antimicrobial agents into films has shown a good deal of promise, and there is a vast array of possible materials that might be used for this purpose [10], but the application suffers from the disadvantage of many components being non-diffusive and thus having no effect on product that may not be in touch with the film’s surface. This would be problematic for items such as cheeses and sliced meats, which will be likely to have irregular surfaces, but using a diffusive microbial may have enough effect on the localization to make the technology more widespread.

Endocrine Disruptors

Endocrine disruptors are, as the name suggests, substances that interfere with the normal endocrine functions in an organism. Discoveries that industrial effluents impaired the normal development of animal species have called into question the effects on human health and development by many compounds that are not directly toxic or carcinogenic. In general, endocrine disruptors operate by closely mimicking natural hormones and either obstructing the proper response to endocrine functions or by triggering them inappropriately. One of the larger current debates is the migration of compounds from plastic films and molded containers as well as from paper structures. It is not clear at this point whether there is certainty of the effect on humans, but there is enough concern about findings with animal models and cell lines that Canada has largely banned BPA plasticizers, particularly in polycarbonate structures such as baby bottles, because of concerns about neonatal and possible teratogenic effects. Additionally, the US FDA Centers for Devices and Radiologic Health issued a Public Health Notification regarding medical devices containing PVC plasticized with DEHP [11]. Other sources of BPA are in can linings, including those used for infant formulas, and some dental resins. Additional concerns stem from the presence of BPA in wastewater and groundwater runoff.

Extraction of Product Components into Packaging Materials and Structures

As with many package-product interactions, the extraction of components from a product can be either helpful or harmful, depending on the product and the compounds that are being transferred. Undesirable extractions will include the removal of volatile flavor and odor constituents, often referred to as scavenging or stripping, resulting in loss or change of flavor as well as the previously described changes such as increased permeation or loss of rigidity in the structure. Food products that have ingredients similar to compounds used in packaging materials can present problems as well. A good example has been the development of plastic containers for both food and lubricating oils. Initial moldings were found to absorb the oils (which are often used as plasticizers themselves) and weaken to the point where they would lose structural integrity, and it required the development of more stable resins before plastic oil containers were commercially feasible.

Desirable interactions have been the subject of a good deal of development work, ranging from absorbent pads to bind the “weep” from fresh-cut meats and vegetables to complex scavengers and absorbers intended to reduce the amount of oxygen, moisture, or other compound responsible for degradation of the product. When used in combination with gas flushing to create an initially favorable microclimate in the package, remarkable shelf life and quality improvements can be seen.

Successful controlled- or modified-atmosphere packaging for non-metabolizing products depends on several steps. It is important to control the initial concentration of the headspace gasses that will affect the product without bringing them to the point of anaerobic growth, as shown in Figure 7.20.

Usually this involves using a nitrogen or mixed gas flush or overpack and possibly processing of the product under a controlled atmosphere as well, and all of these factors must be carefully matched to the product characteristics as shown in Figure 7.21.

The permeation rates of the package then must be matched to the product and desired shelf life effect, usually resulting in a low oxygen permeation rate coupled with the ability to rid or bind metabolic by-products such as ethylene or CO_2.

Very often, the control of permeated or by-product gasses requires the addition of either an active packaging material or component, usually in the form of a small sachet of material containing an active ingredient, as shown in Table 7.4. The most common of these is an oxygen binder that consists mainly of finely powdered iron similar to that used in the fabrication of magnetic recording media, and reacts with oxygen and atmospheric water to bind small

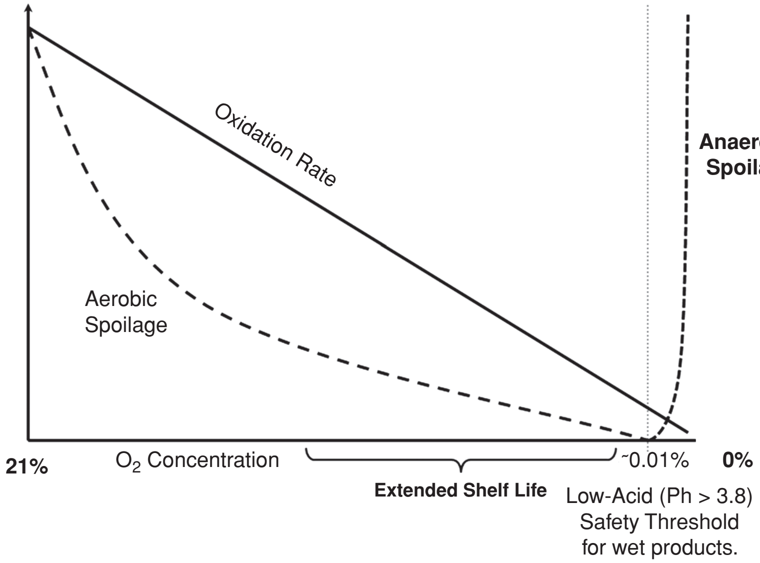


Figure 7.20. Degradation of Non-Metabolizing Products

amounts of oxygen into iron oxide. Moisture scavengers also can be added to prevent moisture from contacting the product.

Active Packaging

Active packaging is distinguished by its capacity to proactively affect some aspect of the package's operation beyond providing a simple, inert container or barrier material. Although the definition could be extended to the tin coating on steel cans and other traditional structural features, it is more commonly taken to mean proactive components that remove components

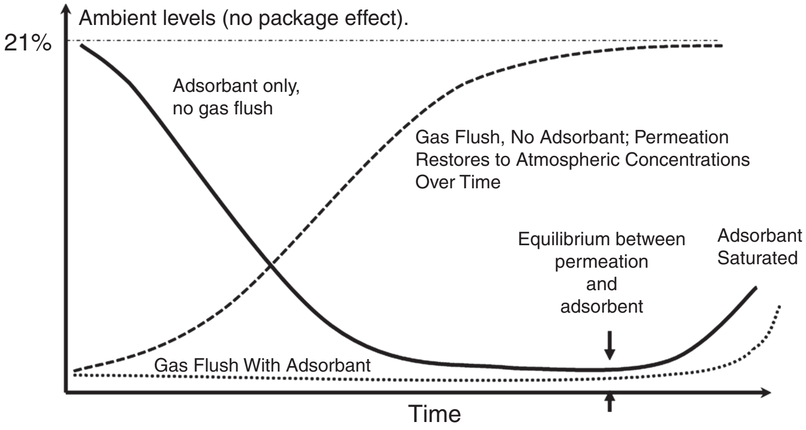


Figure 7.21. Oxygen Concentration in Package with Scavenger and Gas Flush

Table 7.4. Packaging Scavenger Compounds

Scavenger Target Compound	Type of Scavenger Used
H_2O	Adsorbing desiccant (silica gel, calcium chloride, clay)
O_2	Fe oxidation, antioxidants such as ascorbic acid
CO_2	Ca(OH)/NaOH blends, Na_2CO_3, LiOH
C_2H_4	Potassium permanganate ($KMnO_4$)

from the package headspace and react to changes in the product or the distribution environment either by indication or by proactively compensating for a deleterious effect. Active packaging is one of the ongoing areas where material science and other technologies such as nanomaterials, sorbents, and dispersants, as well as reactive substances, are being investigated as a means of improving performance or reducing the cost of packaging materials.

Absorbants and Dispersants

These are typically small sachets, patches, or layers of material that will bind up oxygen, moisture, ethylene, or other specific components that are either produced by the product itself or permeate in through the packaging material. Dispersants (often termed *reactors*) may release CO_2 to preserve fruit, ethanol to preserve baked goods, or release other flavor or odor constituents to maintain product quality, although these represent an indirect food additive that may need to be mentioned in the ingredients list or product label.

These applications must be balanced against the needs of the product, as well as the overall barrier properties of the package structure to prevent premature saturation or depletion of the active component. As previously mentioned, improper barrier selection may result in the premature expiration of the product's shelf life or an imbalance in the microclimate of the package that may result in package collapse or billowing. For films and structures that incorporate an oxygen-scavenging component, for example, a poor seal or constructing the rest of the structure of a low-barrier material will result in over-dependence on the absorption of oxygen by the scavenger and will be an inefficient use of materials.

Other active materials may be used beyond simple adsorbant and dispersive types, although these are often very specifically targeted toward singular problems.

Pitfalls in Using Active Packaging

One of the earliest lessons learned by packaging operations seeking to extend shelf life with the use of scavengers and other active components was that removing oxygen completely from a product, or increasing the rate of removal above the rate of permeation into the package, can drive the packaging into an anaerobic state, risking anything from fermentation to botulism. Additionally, when active packaging materials or additions are used, consideration must be given to the product's headspace circulating internal gasses freely so that the permeant does not travel through the product before it is absorbed. Products have been tested with absorbent materials and have been found to discolor or spoil everywhere except in the proximity of the absorbent, simply because the package was not capable of providing oxygen any other pathway to the product. The absorbent materials also have a finite capacity and may saturate and cause the product to abruptly degrade.

Processing of Product by Advanced Packaging Materials

One intriguing possibility that has evolved and which shows interesting possibilities is the advanced use of the package material or structure as part of the food processing operation. An example of this is the use of naringase on cellulose acetate film to reduce bitterness in grapefruit juice during storage to break down naringen, a glycosidic flavonone that causes bitterness [12]. Although the treatment could have been done during processing, doing so would have resulted in repeated clogging of equipment and an unacceptable increase in cost. In this application, the package itself became part of the processing system, and the concept represents an intriguing range of possibilities for specific treatments of products, such as the degradation of lactose in milk for lactose-intolerant customers using lactase-treated packaging. This may be where many of packaging materials research projects and particularly those that are nanotechnology-centered may find practical application.

Packaging and Shelf Life of Specific Food Types

While it would be impossible to contend with every single kind of food product, there are several larger categories that have some broad packaging requirements that should be included.

Meat and Poultry Products

Freshly cut meat products often produce water because of the reduced water-holding capacity of cut surfaces and degenerating cell structures. This "weep" is usually controlled by adding an absorbent material to the overwrapped package, or wrapping the meat in a moisture-proof bag at the point of sale. More important is meat coloration; consumers regard meat color as an indication of its freshness and desirability. Color "ideals" for different types of meats will vary from light pink in lamb to deep red in beef, and as will be shown, consumer preferences are generally slanted toward meats that have been allowed to "age" for short periods in the presence of oxygen. Meat color is based on many factors, but the controlling system is that of the heme structure in myoglobin (Figure 7.22) that is concentrated in the muscle fibers of meats, and is analogous to the same structure in the oxygen-carrying hemoglobin in blood.

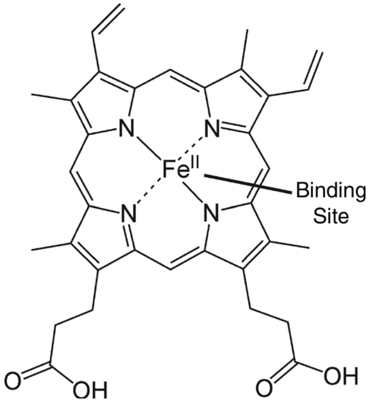


Figure 7.22. Heme Molecule with Binding Site
Source: Lennert B, Public Domain

Table 7.5. Myoglobin Coloration

Bonds	Compound	Color	Name
FE^{++} Ferrous	$:H_2O$	Purple	Reduced Myoglobin
	$:O_2$	Red	Oxymyoglobin
	:NO	Cured Pink	Nitric Oxide Myoglobin
	:CO	Red	Carboxymyoglobin
FE^{+++} Ferric (ionic bond)	−CN	Red	Cyanmetmyoglobin
	−OH	Brown	Metmyoglobin
	−SH	Green	Sulfmyoglobin
	$-H_2O_2$	Green	Choleoglobin

Myoglobin can assume many different types of coloration, depending on its chemical state, which in turn is usually caused by environmental conditions, preservative treatments, or microbial activity, as shown in Table 7.5.

The usual pathway for fresh meat is to begin with reduced myoglobin, oxygenate it to oxymyoglobin that is the state in which fresh meat is most appealing, before turning brown through conversion to metmyoglobin. This pathway may repeat itself as shown in Figure 7.23, but more commonly the meat is discarded or reprocessed in the metmyoglobin stage.

Bacteria may produce discoloration as well via the reactions shown in Table 7.6, which will depend on the species of bacteria as well as the conditions under which they grow. Two of these produce the characteristic green coloration of spoiled meat by producing choleoglobin and sulfmyoglobin.

Curing meats by adding nitrite compounds causes the meat to stabilize the color change cycle and will produce the characteristic pinkish colors of cured lunch meats. In curing, the myoglobin, oxymyoglobin, and metmyoglobin all stabilize to nitric oxide myoglobin, which is then converted to pink-colored nitrosylhemochromogen when heated.

Packaging of fresh meats thus presents a paradox – the extension of shelf life by restricting oxygen uptake while allowing the product to absorb enough oxygen to "bloom" and become attractive to consumers. Discoloration of meats during storage is a persistent concern, particularly as the industry moves toward more centralized production of consumer-packaged meat products, termed case-ready meats, that are prepared well in advance of store display and therefore more in danger of exceeding the time limit for optimal color. Solutions have been sought in modified-atmosphere packaging, particularly using carbon monoxide-based mixes

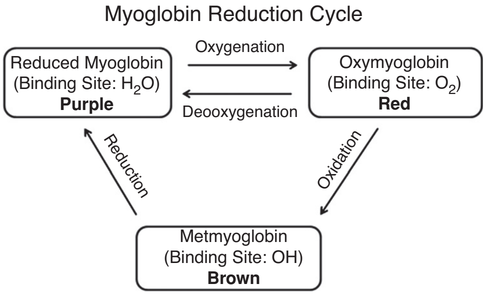


Figure 7.23. Myoglobin Cycle

Table 7.6. Bacterial Discoloration of Myoglobin

Pigment	Catalyst	New Pigment
Oxymyoglobin	Oxidation and Bacteria	Metmyoglobin
Metmyoglobin	Bacteria	Choleoglobin
Metmyoglobin	Bacteria	Sulfmyoglobin

that produces a stable pink color, and in carefully engineering the films used to optimize the best combination of barrier packaging. Degradation of cured meat products is usually the result of longer exposure to oxygen, light, or bacteria and will typically result in growth or graying on the exposed surface.

Often, this is due to light exposure, and particularly as a result of the high-energy blue spectra that exists in most fluorescent lighting systems in grocery stores. The light-related discoloration may be controlled by packaging and storage conditions, but has been hampered somewhat by marketing and legal requirements that often limit the packaging systems that may be used. Bacon is permitted to be packaged in a light-opaque overwrap so long as there is the ability to inspect the product through the outer packaging. Other “fresh” meats may have to have clear overpacks, allowing both inspection of the product and light degradation. Newer fully processed meat products such as cooked chicken and steak strips are packaged in a light-opaque container or a clear container with an overwrap. The degradation of meat and poultry products is a complex function of time, temperature, and environment, particularly oxygen availability and light exposure. With most meat products, the safe shelf life is determined by microbial growth, but in many cases, the product has changed and become undesirable to the consumer because of color changes long before any critical level of pathogen growth occurs.

Different cultures regard different colors of meat desirable, but in western countries, the primary preference is for a deep red color before cooking and various shades of red to brown after cooking. Unfortunately, because of the ongoing metabolism that occurs in the presence of the oxygen required to make meat “bloom” – to produce a “fresh” red color – oxidation occurs very quickly, causing discoloration and rancidity in the fats and limiting the shelf life. To extend the shelf life of meat products, they are usually chilled and vacuum-packed to reduce both the metabolic rate and the amount of oxygen available, which produces a deep purple color in the meat product, which consumers find unappealing.

Until recently, the result of this has been that carcasses, or sides or quarters of carcasses, were shipped in a vacuum-packed high-barrier bag from a central slaughterhouse, then further butchered at the retail store in order to provide enough shelf life to sell the meat before the color degraded. The open-air butchering and oxygen-permeable packaging provided a means for the meat to bloom red from its previous purple color at the cost of a fairly short shelf life. With a push toward centralized manufacturing from meat manufacturers and large retailers seeking to further cut costs, the butchering and packaging would be done in a centralized facility. This adds the complexity of trying to accommodate the conflicting goals of red coloration and long shelf life.

Several solutions have evolved to deal with this situation. One solution has been to provide a high-barrier overwrap of one or several display trays of meat that can be removed prior to display in order to allow the meat to bloom. This works reasonably well at the added cost and complexity of an overwrap. A complementary solution has been to add a gas mixture to the display package, typically a mix of carbon monoxide and carbon dioxide, to extend the coloration by converting myoglobin to carboxymyoglobin, extending the red coloration of the meat and reducing the visible growth of spoilage organisms. The great danger with this, as with many MAP solutions, is that spoilage does not occur but pathogen growth may continue, providing an apparently unspoiled but microbially dangerous product, so these methods must be implemented very carefully. A further extension of the MAP concept adds a scavenger to reduce oxygen levels in the product to reduce browning and rancidity, and can utilize antioxidants to further preserve taste and color.

Seafood

Seafood differs from many other meat products in that the initial microbial load and fat content is often intrinsically much higher, and the products are particularly sensitive to temperature changes and exposure to oxygen. Consumers prefer fish that is as freshly caught as possible, and will avoid fish that smell of the tri- and dimethylamines that are produced by the enzymatic degradation of the trimethylamine oxide in saltwater fish species. Additionally, odor production from autooxidation of fatty acids in fish, as well as the loss of flavor and color, is taken to be signs of reduced product quality [13]. Frozen seafood, although much more stable, suffers from quality loss due to temperature variation, light exposure, and oxygen availability, although this occurs much more slowly than with other products [14].

To extend the very short shelf life of seafood, many different tactics have been employed, but some of the first historical methods – rapidly shipping live seafood, or chilling and rapid shipment, or freezing – are still the most effective. This has created an enormous seafood rapid-shipment infrastructure with seemingly anomalous features such as the shipment of 30,000 pounds per week of lobster from very-landlocked Louisville, Kentucky, to various points in the United States because of the availability of access to a rapid air shipment terminal [15].

Packaging systems that have evolved to extend the shelf life of fresh and processed seafood require very strict control of both temperature and package microenvironment, but have the capacity to provide a very-high-quality product for an extended period of time. In the United States, the primary required means of controlling spoilage remains reduced temperature but secondary measures or multiple hurdles to microbial growth are required because of fears of temperature abuse and the resulting growth of potent pathogens such as C. Botulinum Type E [16]. The results of these types of packaging technologies vary widely among species and gas mixtures, with the best results being an approximately threefold extension of shelf life, typically using CO_2/N_2 mixtures, as shown in Figure 7.24 [17].

Larger-scale distribution systems include live, iced, and frozen distribution, as well as dedicated systems of controlled temperature and atmosphere shipping containers and racks, as well as high-barrier master packs containing retail packs that can reduce the temperature fluctuations, light exposure, and degradative microbial and chemical processes significantly.

Fresh Fruits and Vegetables

Fresh fruits and vegetables have the nearly unique qualification of being living (though usually senescent) organisms almost until the time that they are consumed. Because of this, it is important that a basic understanding of the maturation process as well as the storage and transportation conditions be understood.

Nearly all fruits and vegetables, once harvested, shift from a photosynthetic metabolism combined with respiration to solely respiration, requiring oxygen and moisture to maintain cell

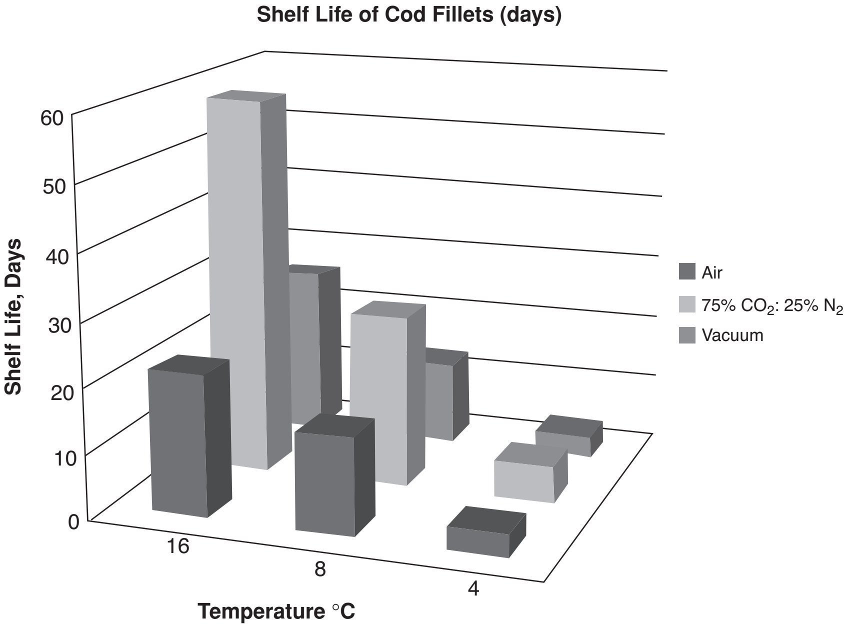


Figure 7.24. Shelf Life of Cod Fillets Stored in Different Gas Mixtures

turgidity and emitting carbon dioxide as a by-product that must be eliminated. Additionally, many fruits and vegetables emit ethylene gas as both a ripening trigger signal and a ripening by-product – a process that can also be triggered by damaging the fruit tissue or by artificially introducing an ethylene source to the fruit. To understand how these methods can control maturation and extend the post-harvest shelf life of fruits, vegetables, flours, and other plant organisms, it is necessary to understand the general importance of ethylene production within the crop. Ethylene biosynthesis both controls and is controlled by the presence of low levels of gaseous ethylene. First discovered in the 1920s by lemon growers who would use kerosene heaters (and their emissions) to store and ripen unripe lemons, the control and use of ethylene has become central to post-harvest handling of fresh crops. Exposing ethylene-sensitive fruit to an elevated level of ethylene gas triggers maturation and ripening. A common household version of this is placing unripe tomatoes (which are a fruit that ripen in the presence of ethylene) with bananas, which are high ethylene producers, in an oxygen-permeable container, typically a paper bag. The result is that the immature tomatoes will "artificially" ripen indoors after picking.

This same process allows control of aging and maturation through control of both the respiratory gasses and temperature in commercial large-scale controlled-atmosphere (CA) facilities. This effect can be obtained using refrigeration and ethylene-absorbent packaging materials or sachets for individual fruit packages to produce MAP that extend shelf life for whole fruits and vegetables, although the latter is currently not common in the United States. This must be done with caution because exposing produce to a gas mixture outside of their range of tolerance will create stresses that, in turn, will increase ethylene production and other detrimental processes.

Controlled-atmosphere (CA) storage involves the large-scale implementation of control over both temperature and atmospheric gas mixture during storage, and, if done properly, will slow the respiration and ethylene production rates. Purpose-built warehouses control oxygen

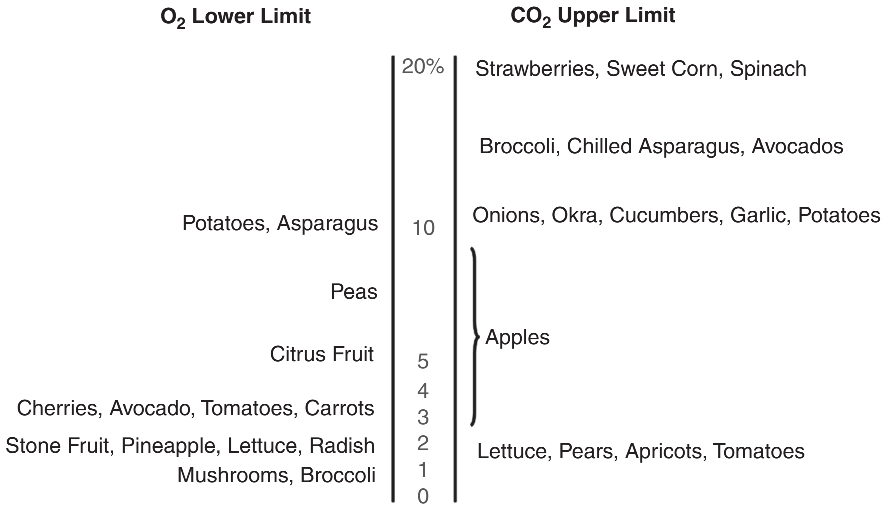


Figure 7.25. Produce Gas Tolerance

level and temperature and scavenge ethylene and CO_2 by the use of adsorbants that may be employed as pads or trays in the ventilation systems of the facilities. Potassium permanganate or activated carbon is commonly used to control ethylene, and lime is used to control CO_2. Similar technologies may be used on a smaller scale in packages or even incorporated into or coated onto packaging materials.

When the produce is to be shipped, it is briefly exposed to high levels of ethylene gas to "wake up" the fruit so it begins to mature during shipment, with final ripening occurring at the retail level or in the consumers' home. The delay of maturation makes distribution over long distances possible, because unripe fruit is usually physically stronger than ripe fruit, and vegetables often cannot withstand handling and shipping without severe damage or complete loss.

Since plant-based organisms vary widely in their respiration rates and requirements for preservation, the specific factors and results for extending shelf life will vary widely. The storage life of some types of fruit such as apples and tomatoes will be extended by many months; bananas may be extended for some weeks, and fresh-cut flowers only by a few days, as shown in Figure 7.25. In general, controlled-atmosphere storage to extend shelf life involves reducing oxygen concentration to reduce the rate of respiration, reducing temperature to similarly slow respiration and maturation, and removing ethylene to delay the onset of maturation. Cut fruits and vegetables have also benefited from a booming implementation of MAP systems that allow processing in central facilities and regional or national distribution for bagged salads and mixed fruit.

The extension of shelf live and the delay of the onset of maturity is a balancing act, as shown in Figure 7.26, because many plants' respiratory metabolism will fail at very low levels of oxygen, and the product will begin anaerobic fermentation. Similarly, the accumulation of CO_2 must be limited because extreme levels will poison the respiratory metabolism of the product.

To achieve this balance, the initial atmosphere of the package may have to be modified, and there must be a match between the metabolisms of the products and the permeation rates of the package. This may be further modified by temperature control of the product, but this is usually

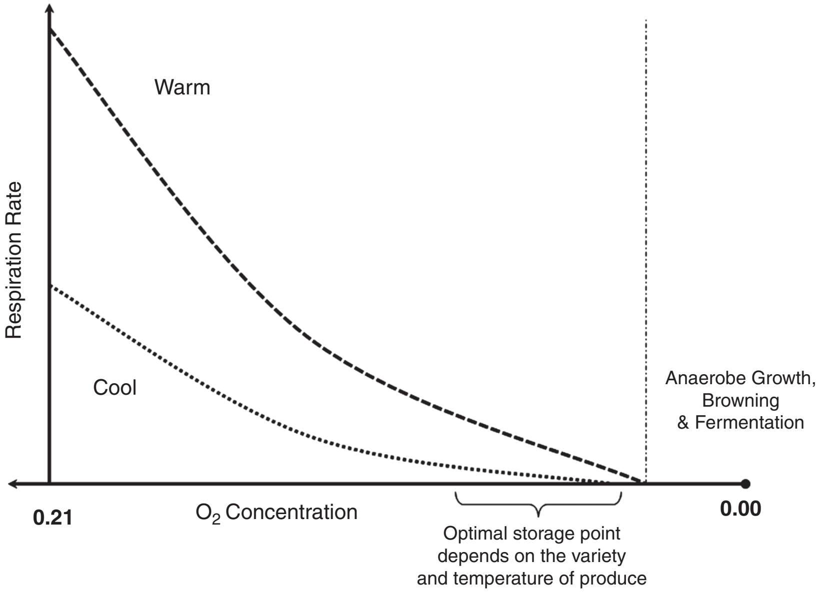


Figure 7.26. Degradation of Metabolizing (Vegetable) Products

achieved with temperature-controlled distribution rather than packaging. A more detailed list of environmental requirements is given in Appendix 7.1.

Control of Fruit Maturation using 1-methylcyclopropene (1-MCP)

Work is being done with a polyamine treatment, 1-methylcyclopropene (1-MCP), as an agent to slow maturation or to extend the mature phase of fruit's development and thus extend its shelf life by interfering with ethylene's biosynthetic pathway, which shares a common intermediate (S-adenosylmethionine). It effectively disrupts the ethylene sensitivity of an organism, putatively by interacting with ethylene receptors in the vegetable tissue and successfully competing for binding sites. This, in turn, delays maturation and has been shown to slow both phenolic and respiratory metabolic rates (and nearly every other process) in the organism [18]. Because its toxicity is extremely low and it disperses as a gas after treatment, current research shows little to no health affect from its use, and 1-MCP has been approved for the treatment of fruits, vegetables, and cut flowers in both indoor and outdoor uses [19]. Although this might be seen as a food additive and has been the subject of some controversy, its effects on the general CA and MAP treatments of flower, fruit, and vegetable handling, packaging, and distribution are likely to be profound.

Dairy Products

By definition, dairy products all involve a large liquid-milk component as their starting points. From there, the applications move outward to liquid products such as milk and cream products, thicker derivatives and cultured products such as sour cream, yogurt, and cottage cheese, and then on to solid and semi-solid products such as butter, cheese, and ice cream. With nearly

Table 7.7. Milk Process Type and Shelf Lives

Milk Process Type	Heat Treatment		Shelf Life
Pasteurized	72–75°C	15–40 sec.	~ 7–10 days when chilled
ESL	~125°C*	3 sec.	21+ days when chilled
UHT	135–150°C	4–20 sec.	6+ months at ambient
Sterilized	115–125°C	10–40 min.	9+ months at ambient

* i.e., regenerative heating to 75°-80°C, flash heat to 125°C, flash cooling to 70°–85°C.
Note: These reflect both European and American processing parameters and have broader values than shown in Table 6.2.

all of these products, the two most common degradation processes are oxidation and microbial action. To extend the shelf life of most of these products, treatments ranging from pasteurization to UHT sterilization are applied to lower the microbial count, with the exception of raw-milk cheeses that must be aged for at least 60 days.

Liquid milk products may be pasteurized then chilled and distributed through temperature-controlled systems including refrigerated dairy cases in retail outlets and consumers' refrigerators. These are usually packaged in coated paper or blow-molded containers that are often opaque to shield the product from light. Shelf-stable liquid milk has been available for some time and is sterilized via a UHT process as described in Chapter 6, and then aseptically packaged, but the caramelized sugars in this product have kept it from achieving a large market share in competition with "fresh" refrigerated milk, although it does well in areas that do not have access to reliable refrigeration. An intermediate version – extended shelf life (ESL) milk – may combine filtration, separation, a modified pasteurizer with several stepped temperatures, and sterile filling to provide an extended shelf life for refrigerated milk with no substantial change in taste. Values for many types of processes and their respective shelf lives are shown in Table 7.7. To prevent oxidation, this is usually combined with a thicker, opaque container, often made of HDPE or paper/foil/polymer laminate in order to reduce oxidation and prevent light from degrading the vitamin A content.

Butter, which is extremely prone to oxidative rancidity as well as mold-induced ketonic rancidity, is usually wrapped in an antioxidant-containing barrier package to prevent contamination and reduce the oxidative hardening and off-flavor at the surface during storage and distribution.

Cheese, which is moderately shelf-stable so long as surface moisture sorption and mold growth are avoided, can be pasteurized as previously mentioned or simply sold as sliced, grated, and block product in a protective covering. Because the moisture level in most hard cheeses is fairly low, mold growth on the surface is the largest immediate concern when no other major contamination (inadequate pasteurization or the inclusion of a contaminated additive) exists, and this is controlled by moisture barrier films. For shredded products, the large surface area adds the possibility of surface adsorption of moisture, causing problems throughout the product, so handling and pre-packaging preparation are also important. Some cheeses, particularly Swiss cheese, exhibit CO_2 outgassing as a function of the microbial action that is an integral part of the product, and a high-gas-transmission packaging material must be used to avoid unappealing inflated packages in retail displays.

Cultured products may be somewhat self-stabilizing but must be kept cold, and often products such as yogurt must actually contain an active culture to meet label claims linked to claimed health benefits. Most of these products are sold in high-barrier formed tubs and cups with a film seal to prevent contamination and indicate tampering.

Frozen products such as ice cream will not support microbial growth but will eventually develop “iciness” as the product coalesces into large, coarse crystals. Because ice cream is technically both an emulsion and a foam, this is primarily prevented by proper manufacturing processes and avoiding temperature abuse during distribution and storage, because components’ change may allow water to migrate and crystallize. High-barrier packaging can help this slightly by retarding moisture loss at the surface of the product, but the effect is limited.

Bakery Products

Most of the foods considered in this chapter are in a nearly unprocessed state, but bakeries represent a multibillion-ton food source for the United States alone. Breads, pastries, cakes, cookies, pies, and other types of baked goods, often filled with fruits, nuts, meats, cheese, and other dairy fillings, will complicate the matter with spoilage concerns of their own. Historically, these products have had a very short shelf life, requiring consumption soon after purchasing and therefore a large number of small-output bakeries to supply them. The drive to larger, centralized bakeries for many mass-distribution products has prompted several routes to extend shelf life, preserve quality, and maintain microbial safety of bakery products.

In general, staling is any non-microbial process that degrades the product quality and is thought to be a function of changes in the starch structure of baked goods, associated with moisture changes but more complex than simple moisture loss or drying of the product.

Microbial spoilage is most often thought of as a function of molds growing on bakery products because molds can grow at relatively low water-activity levels. Other types of microbial spoilage can occur, such as yeast spoilage causing blooming or fermentation of products and bacterial infestation, particularly in bakery products that have meat, dairy, or other components. The relatively neutral pH range (approximately 4.5–8.5) allows products to support a broad range of organisms.

Chemical spoilage apart from staling usually occurs via either oxidative rancidity of unsaturated fatty acids in the presence of oxygen or hydrolytic rancidity of triglycerides in its absence. In either case, the result is off-odor and off-flavor compounds that may interact with other ingredients in the product.

Shelf life extension and preservation is most often provided by a combination of preservatives in the product formulation and increasingly by modified-atmosphere packaging of the bakery product itself. In the case of baked goods that make an “all natural” or “no preservatives” label claim, the packaging becomes a critical part of maintaining product quality. Post-packaging treatment of the products to eliminate post-baking contamination has had some success with irradiation and high-intensity light exposure, but many of the processes such as infrared heating and high pressure treatment are too destructive to the product itself to be practical.

Modified-atmosphere packaging of baked products can extend the life of many types of baked goods by reducing mold growth (see Table 7.8) and can extend shelf life from days to weeks in many cases, but may not retard staling [20]. The gas mixture must be matched with a suitably selective permeable film, because excess levels of carbon dioxide can dissolve into the product and collapse both the package and the product. The presence of even small amounts of oxygen can lead to mold growth, and moisture permeation can lead to very rapid drying of the products. Additional protection may be achieved by oxygen-absorbent materials or components in the package. These will help maintain the low-oxygen atmosphere in the package and maintain and extend shelf life, and can be used with or without a mixed gas treatment, though a synergistic approach is the most effective [21].

Table 7.8. Gas Mixtures Used with Bakery Products

Product Type	CO_2	N_2
Breads, Buns, Cakes, Croissants	100	
Danish, Sweet Rolls, Tea Cakes	50	50
Pita Bread	73–99	1–24

Adapted from: Smith, J. P. et al. (2004), "Shelf Life and Bakery Products, A Review." *Critical Reviews in Food Science and Nutrition* 44(1): 19–55.

Potato Chips and Crisp Snacks

Crisp snacks, which are most often cooked in oils or have high oil content, have a twofold problem in terms of maintaining product quality, oxygen, and moisture. Moisture causes both loss of texture (sogginess) as well as being involved in oxidation processes of fats, whereas oxygen is the primary culprit of fat oxidation that may lead to off-flavors and staling. To prevent these problems, several simultaneous solutions are usually implemented: control of headspace gasses and the use a high-vapor-barrier, opaque film as the preferred packaging material. The exclusion of light, moisture, and oxygen will reduce oxidation of the fats significantly, but the modification of the "headspace" gas (which includes a good deal of interstitial volume in many products) can extend the shelf life of products significantly.

Because there are two simultaneous reactants working against the shelf life, the solution may be somewhat counterintuitive. Development of mathematical models must account for the interaction between the reactants, which in the case of fat oxidation involving oxygen and water availability can be very complex [22]. Studies have found that a modest water vapor concentration in the headspace may actually prolong shelf life with potato chips in high-barrier bags, although the textural changes implicit in this argue for careful control of headspace/interstitial gasses [23].

Beer and Wine Spoilage

Because beer and wine are already fermented, they provide both a modest degree of antimicrobial protection and a ripe growth media for competing organisms. The chief degradation mechanisms for beer that is produced using a good recipe and correct yeast cultures in a properly sanitized facility are usually the result of oxygen exposure, light degradation of isohumulone components in hops (resulting in a distinctive "skunking" off-odor), and temperature abuse. The usual protection methods beyond pasteurization, if used, include minimizing exposure to high temperatures, storage in light-blocking bottles, and reducing oxygen exposure. Some bottle caps for the brewing industry have been produced with an oxygen-scavenging seal because it is the only mode of oxygen ingress for a glass bottle with a metal crown cap.

Wine spoilage is compounded by several factors: long storage life occasionally exceeding a decade or more, the porous nature of traditional corks, and the intrinsic slow change of flavor characteristics over a wine's storage life. Light and temperature abuse as previously described for beer are common quality-degradation factors. Oxidation of anthocyanins and various phenolic compounds can change the flavor, aroma, and color of wine, and contamination by a variety of spoilage yeasts as well as sulfur compound formation and degradation can contribute to quality changes.

Natural cork materials also contribute both to the degradation and controversy of wine storage, with *cork taint* that results from the degradation of chlorine-bleached cork by filamentious fungi [24]. This produces a host of microbial breakdown products, most notably trichloroanisole (TCA) via the breakdown of trichlorophenol compounds, although other resulting by-products may be present [27, 28].

Appendixes

Appendix 7.1. Oxygen and Water Permeability of Plastic Films

Examples of Permeability of Polymer Films to Oxygen and Water Vapor		
(cc*mm) × 10^8/(cm^2*s*cm Hg partial pressure)		
Material	Oxygen Permeation	Water Vapor Permeation
Polyethylene, Low Density	55	9.0
Polyethylene, High Density	0.5	1.2
PVC – Plasticized	6	6.1
PVC – Unplasticized	1.2	N/A
Polystyrene	15–250	12
Oriented Polypropylene	21	5.1
PET	0.30	13
Nylon 6	0.38, varies with humidity	0.05
EVOH (Ethylene Vinyl Alcohol)	0.8–1.9, varies with humidity	100+
PVDC (Saran®)	0.05	0.3

Note: These are approximate values only, and should only be used as an illustration of relative values. Each supplier, product, product grade, and processing treatment will differ substantially from these values. Surface modifications such as metallization, coating, or printing will affect them as well.

Appendix 7.2. Ethylene Sensitivity of Various Produce Products.

ETHYLENE PRODUCTION/SENSITIVITY CHART				
	RECOMMENDED TEMPERATURE SETTING		ETHYLENE PRODUCTION RATE	SENSITIVITY TO ETHYLENE ACTION
COMMODITY	C	F		
FRESH FRUIT & VEG.				
Apple (non-chilled)	1.1	30	VH	H
Apple (chilled)	4.4	40	VH	H
Apricot	−0.5	31	H	H
Artichoke – Globe/Jerusalem	0.0	32	VL	L
Asian Pear	1.1	34	H	H
Asparagus	2.2	36	VL	M
Avocado – California	3.3	38	H	H
Tropical	10.0	50	H	H
Banana	14.4	58	M	H

(*Continued*)

Appendix 7.2. (*Continued*)

ETHYLENE PRODUCTION/SENSITIVITY CHART

COMMODITY	RECOMMENDED TEMPERATURE SETTING C	F	ETHYLENE PRODUCTION RATE	SENSITIVITY TO ETHYLENE ACTION
Beans – Lima	0.0	32	L	M
Snap/Green	7.2	45	L	M
Belgian Endive	2.2	36	VL	M
Berries – Blackberry	−0.5	31	L	L
Blueberry	−0.5	31	L	L
Cranberry	2.2	36	L	L
Currants	−0.5	31	L	L
Dewberry	−0.5	31	L	L
Elderberry	−0.5	31	L	L
Gooseberry	−0.5	31	L	L
Loganberry	−0.5	31	L	L
Raspberry	−0.5	31	L	L
Strawberry	−0.5	31	L	L
Breadfruit	13.3	56	M	M
Broccoli	0.0	32	VL	H
Brussels Sprouts	0.0	32	VL	H
Cabbage	0.0	32	VL	H
Cantaloupe	4.4	40	H	M
Cape Gooseberry	12.2	54	L	L
Carrots – topped	0.0	32	VL	L
Casaba Melon	10.0	50	L	L
Cauliflower	0.0	32	VL	H
Celery	0.0	32	VL	M
Chard	0.0	32	VL	H
Cherimoya	12.8	55	VH	H
Cherry – Sour	−0.5	31	VL	L
Sweet	−1.1	30	VL	L
Chicory	0.0	32	VL	LH
Chinese Gooseberry	0.0	32	L	H
Collards	0.0	32	VL	M
Crenshaw Melon	10.0	50	M	H
Cucumbers	10.0	50	L	H
Eggplant	10.0	50	L	L
Endive (Escarole)	0.0	32	VL	M
Feijoa	5.0	41	M	L
Figs	0.0	32	M	L
Garlic	0.0	32	VL	L
Ginger	13.3	56	VL	L
Grapefruit – AZ/CA/FL/TX	13.3	56	VL	L
Grapes	−1.1	30	VL	L
Greens	0.0	32	VL	H
Guava	10.0	50	L	M
Honeydew	10.0	50	M	H
Horseradish	0.0	32	VL	L
Jack Fruit	13.3	56	M	M

Appendix 7.2. (*Continued*)

ETHYLENE PRODUCTION/SENSITIVITY CHART				
	RECOMMENDED TEMPERATURE SETTING			
COMMODITY	C	F	ETHYLENE PRODUCTION RATE	SENSITIVITY TO ETHYLENE ACTION
Kale	0.0	32	VL	M
Kiwi Fruit	0.0	32	L	H
Kohirabi	0.0	32	VL	L
Leeks	0.0	32	VL	M
Lemon	12.2	54	VL	M
Lettuce – Butterhead	0.0	32	L	M
Head/Iceberg	0.0	32	VL	H
Lime	12.2	54	VL	M
Lychee	1.7	35	M	M
Mandarine	7.2	45	VL	M
Mango	13.3	56	M	H
Mangosteen	13.3	56	M	H
Mincola	3.3	38	L	L
Mushrooms	0.0	32	L	M
Nectarine	−0.5	31	H	H
Okra	10.0	50	L	H
Olive	7.2	45	L	M
Onions – Dry	0.0	32	VL	L
Green	0.0	32	VL	M
Orange – CA/AZ	7.2	45	VL	M
FL/TX	2.2	36	VL	M
Papaya	12.2	54	H	H
Paprika	10.0	50	L	L
Parsley	0.0	32	VL	H
Parsnip	0.0	32	VL	L
Passion Fruit	12.2	54	VH	H
Peach	−0.5	31	H	H
Pear – Anjou/Bartlett/Bose	−1.1	30	H	H
Prickley	5.0	41	N	L
Peas	0.0	32	VL	M
Pepper – Bell (Sweet)	10.0	50	L	L
Chili	10.0	50	L	L
Persian Melon	10.0	50	M	H
Persimmon – Fuyo	10.0	50	L	H
Hachiya	0.5	41	L	H
Pineapple	10.0	50	L	L
Guava	5.0	41	M	L
Plantain	14.4	58	L	H
Plum/Prune	−0.5	31	M	H
Pomegranate	5.0	41	L	L
Potato – Processing	10.0	50	VL	M
Seed	4.4	40	VL	M
Table	7.2	45	VL	M

(*Continued*)

Appendix 7.2. (*Continued*)

ETHYLENE PRODUCTION/SENSITIVITY CHART

COMMODITY	RECOMMENDED TEMPERATURE SETTING		ETHYLENE PRODUCTION RATE	SENSITIVITY TO ETHYLENE ACTION
	C	F		
Pumpkin	12.2	54	L	L
Quince	−0.5	31	L	H
Radishes	0.0	32	VL	L
Red Beet	2.8	37	VL	L
Rambutan	12.2	54	H	H
Rhubarb	0.0	32	VL	L
Rutabaga	0.0	32	VL	L
Sapota	12.2	54	VH	H
Spinach	0.0	32	VL	H
Squash – Hard Skin	12.0	54	L	L
Soft Skin	10.0	50	L	M
Summer	7.2	45	L	M
Zucchini	7.2	45	N	N
Star Fruit	8.9	48	L	L
Swede (Rutabaga)	0.0	32	VL	L
Sweet Corn	0.0	32	VL	L
Sweet Potato	13.3	56	VL	L
Tamarillo	0.0	32	L	M
Tangerine	7.2	45	VL	M
Taro Root	7.2	45	N	N
Tomato – Mature/Green	13.3	56	VL	H
Brkr/Lt. Pink	10.0	50	M	H
Tree – Tomato	3.9	39	H	M
Turnip – Roots	0.0	32	VL	L
Greens	0.0	32	VL	H
Watercress	0.0	32	VL	H
Watermelon	10.0	50	L	H
Yam	13.3	56	VL	L
Live Plants				
Cut Flowers – Roses	0.0	32	VL	H
Chrysanthemums	0.0	32	VL	H
Gladioli	2.2	36	VL	H
Carnations	0.0	32	VL	H
Potted Plants	−2.8-18.3	27/65	VL	H
Nursery Stock	−1.1/4.4	30/40	VL	H
Christmas Trees	0.0	32	N	N
Flower Bulbs – Bulbs/Corns/Rhizomes/Tubers	7.2/15	45/59	VL	H

N = NONE, L = LOW, H = HIGH, VL = VERY LOW, M = MEDIUM, VH = VERY HIGH.
Source: Dry Pak Industries Inc. Used With Permission.

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Chapter 8

Packaging Machinery, Filling, and Plant Operations

Machinery Types

There is an endless variety of packaging and food processing machinery that are available or that can be manufactured to the users' specification, and many of them are remarkably similar. One of the great problems in choosing machinery is distinguishing which, if any, offer any particular advantage over the other. Similarly, the degree of versatility must be considered; it is pointless to buy a do-everything machine when there is only a single task at hand, and similarly a machine with too little adaptability may be a bottleneck in a variable production process.

The assembly sequence of the particular product and package will dictate the type and position of the machines and personnel tasks, but the sequence of operations will follow the general pattern shown in Figure 8.1.

Intermittent and Continuous Machinery

Machinery can operate on an intermittent or continuous (*straight line*) basis depending on the needs of the production facility and the amount of capitalization available. Typically, intermittent machinery will take a single package or small number of packages, perform an operation on them all at once (often after stopping their motion), and then pass them along to the next process step. A continuous-operation machine accepts a stream of packages "on the fly" and performs the operation without stopping or slowing the motion of the overall flow of material. Whereas a four-station manual-feed filling machine might be suitable for a small winery, that machine would be pointless for a soft-drink bottler who requires several thousand fillings per minute to remain economically competitive. Conversely, while continuous machinery is more economical at high throughput rates, it might make little sense to have a high-capacity operation that is active only for several hours a week because of low demand, although for the smallest of markets this may happen because of the employment of used machinery and the lack of appropriately scaled equipment.

Machinery for Specialty Products

Whereas the specialized machinery for creating and filling aseptic and hot-fill products is discussed in Chapter 6, other similarly stringent requirements exist for many types of common products. Hair products may contain quantities of volatile peroxides and other aggressive chemicals that must be handled properly. Pharmaceutical products may have to be both produced and packaged under sterile conditions, some products contain fine powders that may contaminate

Food and Package Engineering, First Edition. Scott A. Morris.

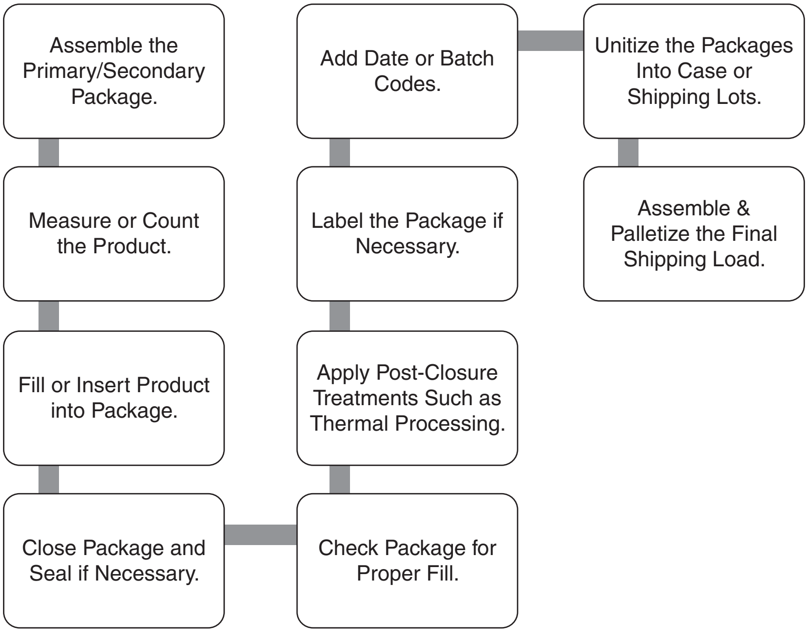


Figure 8.1. Package Assembly Sequence

other parts of the operation, and nearly all types of food processing equipment must be thoroughly cleaned regularly and then returned to service on a timely basis. Some of these machines must have glass-lined product-contact surfaces, or entire machines that are made of stainless steel to avoid corrosion or reaction with the product or cleaning solutions.

Other process considerations must be taken into effect; controlled-atmosphere packaging will require a gas supply system, as does sparging equipment for the previously mentioned wine filler, and for some products, the actual product manufacturing and handling system may be run under a gas layer to reduce the amount of oxygen present during formulation.

Package Erection and Assembly

Taking prefabricated packages from their collapsed or jumble-packed state to readiness on the production line requires machinery that is a specialization unto itself. Bottles must be unscrambled and oriented for proper filling, as must their closures. Flat cartons must be dispensed from magazines or otherwise loaded into machinery, then pushed open and the end flaps made ready for closing, bags may need to be grasped and opened, film may need to be preformed or heat sealed and trays thermoformed from stock. Each process will have its own unique list of operations.

Each of these operations is both specialized and necessarily meticulous – poorly formed packages will jam, misfill, or spring open farther down the production line. This is particularly problematic in food processing plants that often have live steam exhaust or a high humidity level during operation that can affect paper products and processes such as the handling of films and the setting of adhesives.

Fillers, Feeders, Metering, and Measuring

The essential job of fillers and feeders is to take product in a predetermined number or amount to fill the assembled package. There is a broad spectrum of different types of equipment to achieve this, many of which can handle difficult materials such as thick pastes and creams, or very fine objects.

The simplest of machines will fill and dump baskets, cups, or trays of material, are well suited to loose and granular products such as cereal and animal food, and can be used for single objects if the objects are properly oriented in feed chutes going to the packaging machine. These may be fitted with weighing sensors to allow a net-weight fill to be directly applied to the product, and may use a combination of smaller fill trays to approximate the net weight more accurately. It is also possible to use auger metering where the product is dispensed by either timing or counting the rotations of an auger that delivers product into the package.

Many types of powders, particulates, and granular products are subject to *bridging* or *arching* phenomena, where the powder or material will jam feed chutes if they are not properly designed for the product. Fine powders form cohesive arches using interparticulate bonding whereas larger particles will form interlocking arches where the mechanical locking of irregularly shaped particles provides the cohesiveness to form arches. Both of these phenomena rely on the same principles that traditional arch structures in bridges and buildings use – transferring radial compression into vertical and lateral force to maintain the arch structure. Additionally, *ratholing* may occur where product is only removed from the center portion of the hopper while leaving the material near the wall intact. Worse, the flow may alternate between ratholing and arching, creating erratic flow conditions, as shown in Figure 8.2. Proper design of the hoppers for the product as well as adaptive equipment such as agitators or *bridge breakers* may be necessary to keep the device operating properly.

The converse side of the bridging phenomena is that it can be used to stop product from flowing in certain types of measuring devices, such as screw-auger fillers. These are designed

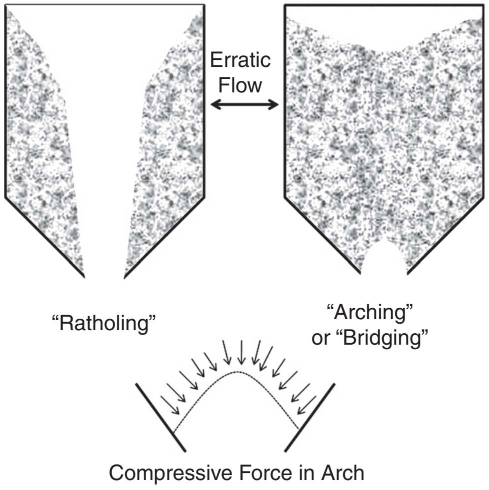


Figure 8.2. Particulate Bridging and Ratholing

with a small disk at the end of the auger that creates blockages when the auger is not rotating and rely on bridging to stop the flow between package fillings.

Direct counting machines can use trays, simple photocells, or complex vision-system pick-and-place manipulators to acquire the exact number of products required in a package. Similarly, it is possible to use the package or an inner tray as a measuring device, filling it with the proper number of product units, and then enclosing it in a larger secondary package. Liquid and semi-liquid materials are usually either filled with displacement or metering pumps or fed into a package by vacuum displacement, and often the product may be heated to reduce viscosity and to speed up the fill rate. Products that can change substantially when heated may have to be carefully handled with this type of system. For example, peanut butter, which is too viscous to handle efficiently at room temperature, is heated so that it may be pumped into packages, but protracted overheating will cause destabilization of the saturated fats added to prevent separation, leading to severe separation of the oil components and degradation of the product texture and quality.

Metering of liquid and semi-liquid materials can be achieved by timed flow, fixed-volume displacement pumps, piston systems, fill-level shutoffs, or drains in the filling head, and are roughly divided into constant-level fillers and constant-volume fillers. Constant-level fillers are most often used where the product can be seen through the container and a variable-fill level will make a package or shelf-full of product look as though some have been underfilled. This is most often used with glass containers because of their variable internal dimensions. This is the reason for many bottles' label-wrapped necks, which hides the fill line and allows a constant volume fill. Liquid fillers may have to include bottom-up filling capability, where a filling tube dispenses a thick liquid from the bottom of the container and withdraws as the fill level increases, or a pressurized seal to allow carbonated beverages to be filled under pressure.

Form-Fill-Seal Systems

Form-Fill-Seal (FFS) machinery is a preferred method for many food items, and as the name implies, it forms packages from roll stock around a central mandrel that incorporates a product fill tube and allows the forming, filling, and sealing of packages of nearly all types of products from hardware kits to liquid condiments. Many types of these may be multiple-head machines to produce small packets of sauces for fast-food restaurant use. With many types of food products, the product handling must be done accurately as the filled pouches are filled to avoid contaminating the seal surfaces. Additional types of machinery peculiar to the food industry will insert slices of meat products into folded or vacuum-formed film and seal it, or will even extrude a cylinder of cheese food product into a tube of plastic film and then flatten and seal the product to create the familiar wrapped processed cheese food slices.

Specialty machinery may be necessary for particularly sensitive materials such as fruit juices and meats that may discolor with the slightest acquisition of dissolved metal [1]. In the most extreme cases such as processing some types of juices and many types of pharmaceutical and cosmetic products, special surfaces must be constructed for contact with the product using materials such as borosilicate glass, Teflon, or other materials, as appropriate.

Robotic Operations

Robotic operations are most effective in jobs that are repetitive and predictable but require either handling heavy goods, as with palletizers that are discussed further on in this chapter, or

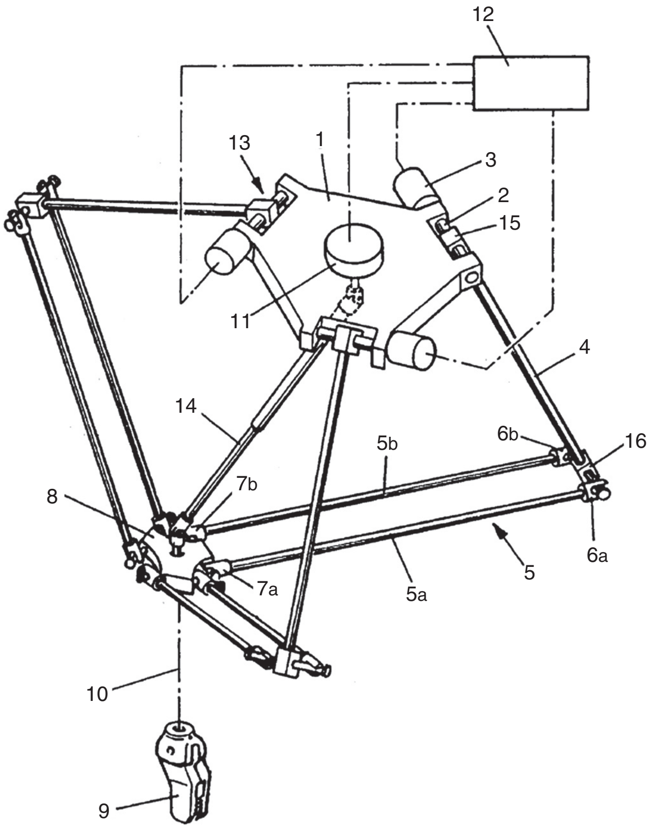


Figure 8.3. Delta Robot Detail
Source: U.S. Pat # 4,976,582

with fast, accurate pick-and-place operations that demand consistent, accurate results at speeds that human operators would have difficulty maintaining. The latter application is common in some types of food packaging operations, and one of the first and most complete integration of robotics in the food packaging industry was in the high-speed filling of boxes of assorted chocolates where dozens of different products had to be accurately placed in a moving container.

While many robotic installations mimic the human arm, or involve an articulated manipulator set on a rotating base, so-called *delta robots* (Figure 8.3) have been successfully integrated into many packaging operations. Originally developed by Raymond Clavel at École Polytechnique Fédérale de Lausanne, these can be built with high-speed actuators and lightweight carbon fiber elements to provide extremely accurate high-speed operation for the handling and placement of small, light objects. They have been implemented in many applications ranging from machine parts to bakeries and confectionary manufacturing.

Pre-closure Treatment and Closure Application

Closures and seals may be applied as discussed in Chapter 5, but increasingly a pre-closure treatment such as a headspace gas flush may be applied. This may require an extraordinarily complex system of nozzles and diffusers to avoid blowing the product out of the package or contaminating the seal. Vacuum application may be required, either alone or as a part of the gas-flush process as in a draw-redraw flushing where air is withdrawn, replaced with gas, and the process is repeated to ensure saturation of the flush gas. This procedure is common in products with high interstitial volume, such as bagged salads.

Accumulators and Conveyors

Accumulators are used as a means of aggregating the output of one stage of production in order to smooth the flow into the next step. Paradoxically, they are also used as dispersers, allowing a huge surge of input such as the unloading of a case of components, or the output of a batch of thermally processed product to be slowly metered out into other steps in the production process. Most often, these are simply a flat table or conveyor that allows the physical aggregation of material in a single plane, though it is possible to create multidimensional stacking or spiral accumulators. Because accumulators are used as buffers, they can be used to keep production synchronized among machinery operating at different speeds, to disperse high-output results into multiple slower machines (and vice versa), and frequently to correct poor line-integration practices. They also can be used as a *time delay* buffer, allowing machinery to be maintained or otherwise manipulated without bringing upstream production to a halt.

Conveyors carry material from one operation to the next and can be as simple as a smooth surface that lets material slide downhill or as complex as an air jet conveyor that floats containers along above its surface. Often, they provide powered rollers, discs, or belts that move product along. Conveyors also may act, in a limited sense, as accumulators, because they provide a wide area for product to aggregate between process steps, and large, spiral conveyors are often used in processing such as the cooling of product from ovens, chilling of products in freezers, or the *proofing* (final dough rising) of bread products in large bakeries because of their ability to provide more exposure time in less space.

Checkweighing, Inspection, and Measurement

Many packaging operations, particularly those involving food, require some kind of checkweighing or fill level inspection step to ensure that the package meets its label claim. The use of checkweighers demands a balance between the risk of under-filled packages (curve “C” in Figure 8.4) and therefore not meeting the label claim as required, and the cost of giving away extra product (curve “A” in Figure 8.4). Because of this, accuracy both in metering product and in measuring it after filling is at a premium. A tight grouping of fill weights or volumes as shown with curve “B” in Figure 8.4 as a result of both accurate metering and of inspection speaks well for the integration and adjustment of the filling line, as well as providing the most profitable setting for under-fill versus giveaway.

Although the weighing or measuring of the fill in a package may seem a simple matter, the implementation may be complex. Weighing a product on a moving conveyor belt may involve specialized machinery that samples the weight of packages at a precise time and place on a weighing belt, whereas fill levels, particularly in opaque containers, may require any number of steps including X-ray imaging. Checkweighers are also used for less intuitive applications such as checking consumer appliances to ensure that components have not been omitted from the final assembly.

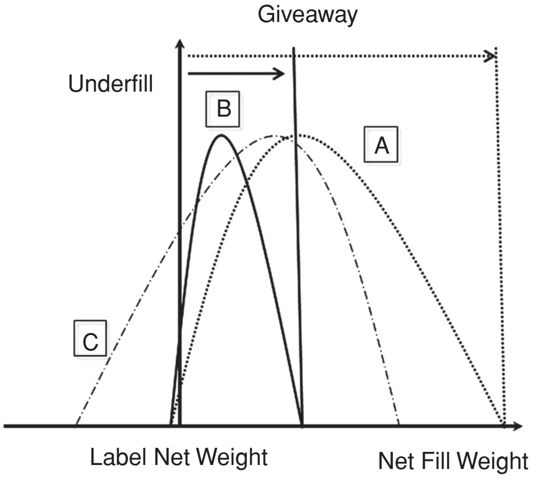


Figure 8.4. Fill Weight Distributions

Product Inspection

Inspection of the finished package is often a part of the manufacturing process. This can range from the occasional glance at the production line to sophisticated automatic inspection devices to ensure complete seals on shelf-stable foods and pharmaceuticals. It is tempting to think that human inspectors can be freed entirely from the tedious task of package inspection, but there are some caveats that must be considered when considering any type of inspection device, including checkweighers.

An inspection or measurement device (or person) must have several characteristics to provide reliable measurement or rejection of defective or out of tolerance products or components:

Sensitivity – the minimum magnitude of stimulus required to produce a specified output in a measuring device.
Resolution – the minimum amount of change in the measured quantity that can be detected by the measuring device.
Accuracy – the closeness to a "true" value, often a standard item or standardized measurement value.
Precision – the narrowness of distribution of measured points about a mean value.

A good inspection system should incorporate all of these characteristics, but cost and design considerations impose limits. The development of more complex inspection systems is hampered by the trade-offs inherent in creating devices or systems that will work well in high-speed production lines. Whereas some industries, such as glass production, have a sufficiently homogeneous product to have implemented automated visual inspection decades ago, this kind of automation has evaded much of the packaging and particularly the food packaging industry. For example, acoustic resonance testing on filled metal cans can provide a quick and reliable test of the can's integrity, but a stream of retort pouches coming from a filling line has both so much inherent variability in product and such subtlety in dangerous defects that manual inspection remains in place for all but the grossest seal defects, which are usually tested by low-resolution pressure differential machines.

The Base Rate Fallacy and Inspection System Failure

Inherent in any inspection system, whether automatic or manual, is the probability of *false positives*. Essentially this means that for a number of products being inspected, inspections will provide an indication of defect when there is none. In a population of manufactured goods that have a high quality level, this can result in a lot of product being needlessly rejected. The most common example of this is in medical diagnoses:

> *In a population where the known incidence of a particular disease is one case in 1,000 members of the general population, and the false positive rate for the medical diagnosis – the rate at which the diagnosis will tell you that you have the disease when you are healthy – is 1%, a positive test among 1,000 people will return 1 true positive test and 10 false positive tests – 11 positive tests in all. Thus, a patient getting a positive test would only have a 1 in 11 chance (about 9%) of actually having the disease.*

Although the previous example underscores the sensibility of "getting a second opinion" and has significantly changed many diagnostic procedures, it also highlights how quickly the number of false positives can grow in a large population with a low incidence rate and an apparently accurate test method [2,3]. It also indicates that the results can be quite counterintuitive and has lead patients who do not understand the concept to have unnecessary surgery based on a single diagnosis or even to commit suicide thinking they have a low-incidence fatal disease based on a single test with a relatively high rate of false positives.

In manufacturing environments, where the "population" may number hundreds or even thousands of units per minute, a very low actual defect rate coupled with even a modest rate of false positives can very quickly create an enormous absolute number of false positives, and a distrust of the detection system. For example, the production of canned goods at a rate of three hundred cans per minute, with an actual defect rate of one can in ten thousand, a test accuracy of 99.9% and a false positive rate of only .1% – all excellent figures – gives performance levels shown in Equation 8.1:

$$
\begin{aligned}
&\text{Defective Product:}\\
\text{Production Level:}\quad & 300/\text{minute} = 432{,}000/\text{day}\\
\text{Actual Defects:}\quad & (432{,}000/\text{day})\cdot(0.0001) = 43.2\ \text{defective cans/day}\\
\text{False Detections} &= 0.1\%\ (432{,}000/\text{day}) = 0.001\,(432{,}000/\text{day}) = 423\ \text{false detections/day}\\
\text{True Detections} &= 43.2\ \text{defective cans/day}\cdot 0.999 = 43.157\ \text{true detections/day}\\
\text{Total Detections} &= 466.157\ \text{detections per day}
\end{aligned}
$$

Thus, the probability of a detection being accurate is

$$
\begin{aligned}
&\frac{\text{True Detections}}{\text{Total Detections}} = \frac{43.157}{466.157} \cong 0.0926 \cong 9.26\%\\
&(\text{Missed Detections} = 43.2\ \text{defective cans/day}\ - 43.157\ \text{true detections/day}\\
&\qquad = 0.043\ \text{defective cans/day, or about one every 23 1/4 days}) \qquad (8.1)
\end{aligned}
$$

With such a low probability of accurate detection, due to the low incidence of real defects being swamped by false alarms, if the cost or annoyance of a single false-alarm event becomes significant, the overall cost of operating the detection system can make it unworkable. Much like a smoke detector that goes off with random household events, it will eventually be disconnected despite the inherent hazards involved. Anecdotal information from production engineers has indicated this to be the case for several of the automated detection systems that have been marketed and test-run in actual production systems. Therefore, for design and specification purposes, it may be necessary to develop a minimum acceptable false-positive level for a testing device or protocol.

For safety-related concerns such as seal integrity in food and medical packaging, the costs of failure detection can be significant if the implication of detection is that system parameters must be altered or the item must be exhaustively inspected based solely on the detection system's "flagging" the item. Of course, the costs of missing a defective item can be extraordinarily high in such cases when liability and safety concerns are factored into the situation. Multiple-level inspections or a more involved testing procedure may be necessary in this instance.

Case Packers

Although case packers are thought of as a distinct type of machinery, it is not unusual to have case packers that drive home at the end of their shift. Many operations still depend on manual labor for some level of case aggregation, filling, and packing. Although tedious, this can be assisted by accumulator tables where product can be lifted in case quantities or inverted cases turned over for the final grouping. Larger operations may automate many of the tasks, with machines lifting case quantities into shipping containers and sealing them. At this point, particularly for small consumer items and food, the handling of the filled case deserves some attention to the ergonomics of the material movement, discussed later in this chapter, because the filled case may be heavy enough to cause health or safety problems for the personnel involved.

Palletizers

Manual palletization may be used much as with case packing, but because of the risk of repetitive-motion injuries and the likelihood of dropped cases, there is often mechanical assistance used in the high-speed accumulation of pallet loads of finished goods. Palletization is one of the first areas where large-scale automation and robotics were integrated into packaging operations because of the combination of load weight, precision placement, and speed of operation. As heavy-lift robot arms become more capable, they may be preferred for ease of setup and flexibility of mixed product loads and interlocking stacking patterns.

If mechanical assistance is used in palletizing or handling, the case itself must be designed with the material handling system in mind. For example, vacuum-lifting structures in an automatic palletizer may put unexpected tensile stress on box flaps that will pull them open if the box-closing adhesive or tape is inadequate.

Machinery Acquisition

Machinery acquisition is a function of whether the line is expected to run continuously or intermittently, the production level and lead time available, the relative cost of other alternatives (including leasing, used equipment, and contract packaging), the payback period, and capital and installation costs. Because many machinery acquisitions are made to supplement existing lines, the equipment must be specified to interface properly with the existing operation. This may require retrofitting controls on the older machinery or the alteration of the physical characteristics of the components. One perplexing difficulty that may be encountered is the reluctance of a few machinery suppliers to adapt their machinery to the product design being considered, which argues strongly for involving machinery considerations throughout the package design process.

Machinery suppliers should be carefully investigated to ensure that parts and service are available, if necessary, and if delivery, setup, and installation schedules can be met because delivery times for custom machinery can be extensive. Additionally, operator training may be necessary and may have to be done as a jointly scheduled arrangement between suppliers and the production facility personnel.

As the global economy expands to include many types of industrial machinery that may have to be built to order or extensively modified, the current domains of equipment manufacturers will be subject to the inevitable sorts of changes and consolidations that other industry sector have seen. There is no reason to believe that the current broad range of small packaging machinery manufacturers in the United States can continue dividing domestic markets without substantial changes, some of which are already underway. Many small firms are being brought into consolidated operations either through purchase or by cooperative agreement. With that in mind, the range of suppliers is growing to include more flexible, lower-cost manufacturers from all over the world, and domestic manufacturers may become retailers of equipment sourced from many countries. As with many of these changes, the great concern is over the initial quality of machine fabrication as well as a continuing supply of service parts and upgrades.

Many machinery suppliers who are intent on remaining competitive in this increasingly diverse and competitive marketplace have turned to system integration as a value-added service to their machinery manufacturing operation, helping packaging lines with integration of new machinery into more optimal systems so that the customers can remain competitive as well.

Machinery Layout

When installing machinery, careful planning for current and future production requirements is essential. The best layouts have a great deal of time invested in planning and modeling before anything is installed or moved. It is critical to adapt the machinery layout to the space available, the equipment required, the materials movement demanded by the process, and the personnel that will be involved in the ongoing operation. Horror stories abound about structure and walls that have to be removed to get large equipment into a building, equipment specified for utilities that are not present in the building, inaccessible service panels, uncleanable process machinery, product that cannot effectively be moved out of the production facilities, and similar mishaps.

Unfortunately, many operations grow in piecemeal fashion, starting with manual, labor-intensive operations and expanding into greater levels of automation and complexity as the business grows. Even though it is usually not possible to start with a completely blank slate in terms of facilities and machinery, it may be possible to utilize expansion or redesign as an opportunity for improving control and integration systems. If at all possible, both the current and future manufacturing capabilities must be considered when specifying production layouts – will there be room to expand if production increases, or will temporary increases have to be contracted?

When laying out a production line, it is also important to consider the number and placement of operators, as well as the necessity of getting workers into machinery for cleaning, loading and unloading, repairs, and routine maintenance. Operator effectiveness and safety must be considered for economic effectiveness, regulatory, and ergonomic reasons.

Machinery Controls and Displays

Machinery controls have moved from simple indicator lights, analog gauges, switches, and mechanical counters to complex, touch-sensitive video displays that may interface with the rest of the production plant's network and may contain substantial computing capacity. Many of these can be networked so that the production status can be checked from any point in the network or from outside the manufacturing operations. If networked, the potential for remote operation either as standard operating procedure or for emergency purposes may be incorporated, but some attention should also be given to the integrity of the networks' security. Graphic display panels offer the advantages of language-independent icon-based operation, as well as changeable multilingual displays, adaptable displays with layers of operation detail, and graphic representation of data such as checkweigher values and production run charts.

Graphic and computer displays have advantages, yet it is worth looking into the design of controls for most efficient indication of particular operations – a simple red and green light can effectively and decisively communicate whether something is operating or not, with other simple status lights to indicate jams or a "hold" status. Similarly, a simple mechanical counter can be added to machinery at minimal cost as a backup device or confirmation of production levels.

Controls and display units must be mounted in accessible and visible locations, with adequate control systems to provide a fast line or machine shut-down capability in order to cope with a manufacturing or safety problem, and sufficient "lock out" capability to allow safe changeovers when necessary.

Plant Operations

Scheduling plant operations and logistics, particularly in a combined processing and packaging plant, is an entire business specialty unto itself. Much of the work has been supplemented by accurate computer analysis, but the efficient management of an operation still has to consider a large number of variables.

Production Run Schedules

For continuous-run products, the overall production level per time period must be determined for purposes of shift scheduling and materials ordering. For changeable, multiple product runs changeover time, supply of different materials and ingredients and shipping schedules must be accommodated.

Raw Material and Component Ordering, Acceptance, and Tracking

Ingredients, package components, and the like must be ordered, subjected to quality control procedures, and tracked so that they arrive where they are needed on a timely basis without shortages or excessive inventory.

Storage Levels of Materials and Components

Are a lot of small orders required or several large ones for any time period? Which is the most economical and practical alternative?

Is there sufficient storage if the products are being held for Just In Time requests from customers or other parts of the operation? If so, what is the optimal level of production?

Product Line Scheduling

Which products should be run at particular times in order to meet seasonal demand, spikes in product popularity, and opportunities for downtime?

Personnel Management

Which operators will be required to work during which shifts in order to meet production schedules?

Is it more economical to have a smaller number of shifts working harder or a three-shift operation running at reduced levels?

Facilities Management

Can the facility handle round-the-clock production or does it need to be stopped for cleaning, maintenance, or changeover for several hours each day or during a particular shift?

Is there sufficient transportation access to transfer materials in and product out of the facility?

Are the utilities (electricity, steam, fuel, wastewater, etc.) adequate to handle the projected production level?

Larger-Scale Concerns

If the production is scheduled over several facilities, how should it be arranged so that the market demand is met both in terms of delivery schedule and delivery of the required quantities to their markets in the most efficient mix?

If production is to be outsourced over several countries or even globally, how are the product levels to be most acceptably managed to provide for a continuity of product quality, supply, and brand identity?

Machinery Modification and Upgrades

Whereas much of the world's software upgrades are done automatically, the modification and upgrade of manufacturing machinery is much more complex and has both benefits and pitfalls. It may be beneficial to improve the operation of existing machinery with more capable control systems or a higher speed drive system, but the concept of diminishing returns (less and less reward for greater and greater investment) will begin to take over at some point, and it may be more effective to start with a new (or substantially reworked) production system, although justifying the capitalization of this is often a pitched battle.

Before any upgrade or modification is undertaken, it should be determined whether the final result can justify the engineering, software, downtime, and retraining costs involved. One should also consider unforeseen benefits, particularly with large installations that may require building or facility rework if they are to be replaced rather than refurbished. In some cases, the benefits are bureaucratic rather than physical, because machinery refitting or rebuilding may fit in a budget that otherwise does not have a capital expenditure allowance for new machinery – the equivalent of having a car's engine replaced when one cannot justify buying a whole new car.

There are also many older machinery installations with refitted controls, replacing older hydraulic, pneumatic, and mechanical controls with faster and more accurate electronic ones. In the best of cases, the combination of sturdy machinery infrastructure and fast, accurate controls can produce a good performance level, but the retrofitting must be carefully engineered and tested before installation, particularly on a high-throughput line that cannot afford much downtime.

Line Changeover and Flexible Manufacturing

Line change historically has connotations of production losses as an industry shuts down its production process and retools for a new model year. This has changed radically as demands for more productivity and flexibility have caused changeover methods to trickle down from large-scale manufacturing plants to smaller and more entrenched operations such as food manufacturing and packaging.

Taking lessons from Toyota's "Single Minute Exchange of Die" and "Single Touch Exchange of Die" methods, used to add rapid flexibility to manufacturing plants, as well as several other fast-change operations (such as stock-car racing pit crews), food manufacturers have begun to demonstrate extremely rapid changeover times. Tools and fasteners are optimized for changeover, racks of change parts and the necessary tools are modularized, and changeovers may be videotaped and reviewed by the teams doing the production line changes.

Generally, changeover time may be accelerated by several improvements:

- Finding and eliminating unnecessary tasks complexity that slows down changeovers.
- Externalizing the changeover tasks to off-line operations as much as possible. For example, gathering and staging the needed supplies and tooling in dedicated kits before the changeover occurs.
- Simplification by reducing the number of specialized tools needed, and labeling and color-coding tools, fixtures, and parts bins wherever possible to allow fast changeover and highlight any mis-installed components [4].

These improvements can reduce changeover times from hours to minutes and have added the capability of expanding production capacity without capital investment. This provides, as it did for Toyota, the capacity for rapid deployment of a variety of products by increasing the capacity for flexible manufacturing.

Flexible manufacturing (as distinguished from flexible packaging) is often seen as a goal for many linear and single-product production facilities of non-food items, and has been a facet of the food processing and packaging industry for many years. In the simplest of manufacturing environments – small crafts shops and food establishments – nearly all work is customized as is the packaging that is used depending on the order serviced. On a slightly larger scale, small food (and particularly dairy) production operations are required to make optimum use of common ingredients to make a variety of different products, often using many rearrangements of similar equipment profiles. In many instances, there will be common ingredients used (such as raw milk for dairies and vegetable oils and corn syrup for salad dressing lines, for example), but the pumps, vats, cooking operations, packaging, and labeling can vary from product to product. In contract packaging operations, these can be even more varied as both the nature and the name of the product changes.

Truly Flexible Manufacturing Systems (FMS), often termed *Mass Customization Manufacture* (MCM), where many different, made-to-order products travel down a single assembly line, has begun to occur for non-food items, but it requires that both manufacturing and packaging not only be adaptable but have the capacity to communicate the assembly and packaging requirements "on the fly." Fortunately, with visual coding of products and the potential use of RFID, Computer Integrated Manufacturing (CIM), and other data systems to carry the information needed, this is becoming a simpler operation. Unfortunately, the level of automation required is high enough that many packaging operations will shy away from the investment necessary to achieve it, preferring to run continuous batches, warehouse production runs, and then remix them into mixed-product point of sale displays.

The advantages of FMS systems are fast changeover, higher precision and quality, and lower costs due to labor savings. Disadvantages include a limitation on the breadth of scope of manufacturing possible (for example, a line that is machining pump assemblies may not be able to be adapted to the production of volume air blowers), and a substantial investment in equipment, software, and planning capability. Additionally, product designs may need to be reviewed to ensure their ability to integrate into the existing manufacturing system.

Paradoxically, Design for Mass Customization (DFMC) eventually represents a complete decoupling of the traditional product design and manufacturing systems in that the manufacturing system (in an ideal sense) is dynamically adaptable to the immediate market demands for many different products rather than strategic planning for perceived future demands. Additionally, truly flexible manufacturing systems may work against lean manufacturing systems in that the volatility of market demand for particular items may feed back into the system and require enlarged inventories of components to remain responsive. Thus, there is a conflict among the flexibility of the production run size, variability of the product, and delivery schedules [5]. This is most often addressed by the large-scale integration of modular elements in the production system, which allows the production facility to integrate different production modules, where each module may be made of one or several machines or processes, to create different "recipes" of production capacity, as shown in Figure 8.5. In a high-volume, low per-unit-profit industry such as packaging, and particularly food packaging, this may or may not be seen as a worthwhile investment, but as data, control, and computation costs plummet and visualization and task integration software becomes more usable, it may trickle down into the food packaging industry.

Coordinated Packaging Lines

A well-coordinated packaging operation traditionally required machinery that was built with common mechanical timing linkages, and may have required the simplification of the packaging design and other changes that can affect the competitive nature of the product after production. Changes in the controllers used in industrial equipment have allowed the implementation of data- and sensor-driven machine coordination based on industry standards that allow machinery from different manufacturers to communicate and operate efficiently.

New IEC-61131-3 standards for programmable logic controllers (PLC) represent a tremendous opportunity because they allow a uniform set of communication and operation protocols to be operated both internally and using software and XML protocols [6]. This allows machinery from different manufacturers to have a basis for passing information about operation and timing both to other machinery and to centralized control that can be used for both scheduling and optimizing production systems to operate as efficiently as possible. This also places demands on

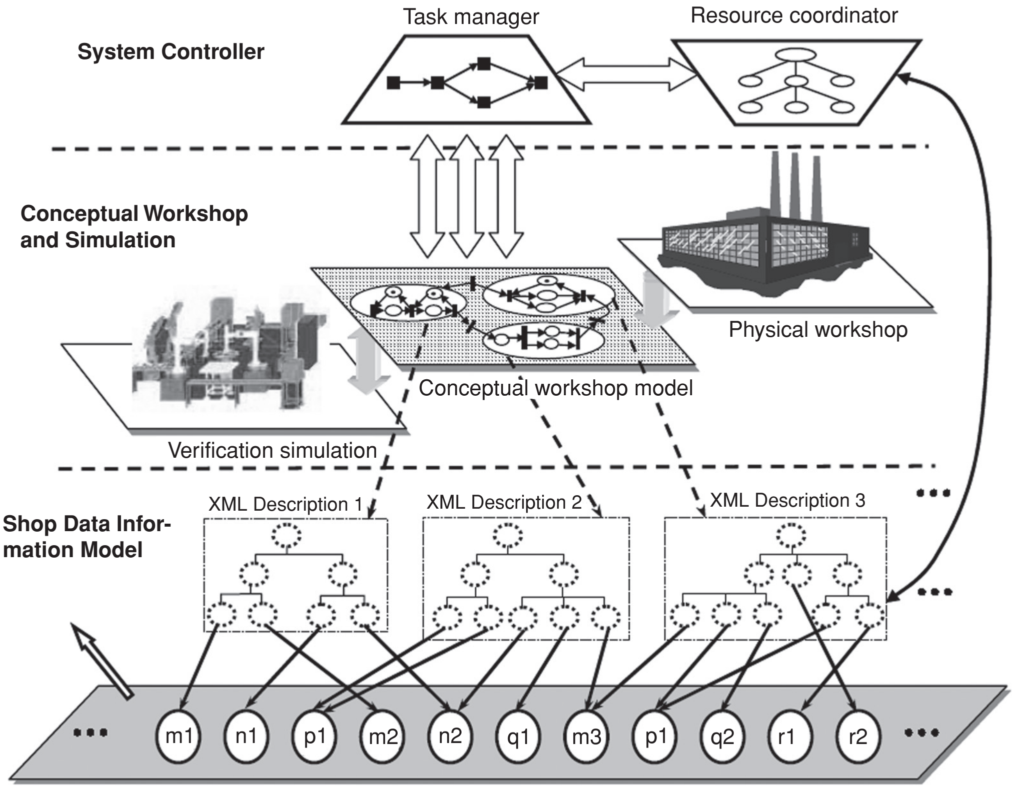


Figure 8.5. Flexible Manufacturing System Detail
Source: NIST

the machinery manufacturers to utilize the data transmissions efficiently and system integrators to use data to optimize systemic efficiencies.

Production Optimization

Optimization of production processes is an involved topic, and a complete discussion of the subject is well beyond the scope of this text, but it is possible to extend some of the basic concepts involved in order to provide a starting point for further reference. Generally speaking, the engineering concept of optimization is the manipulation of particular parameters in a system until a desired output (usually measured as a maximum or minimum value for a particular value) is achieved.

In its simplest form, the maximum speed of operation in any particular linear-sequential process is the speed of the slowest sub-process contained in it. This "weakest link" reasoning provides a good idea of the maximum speed for many flow-type processes that do not depend on timing, machine stoppages, or accumulation. Unfortunately, it is often applied to all types of more complex situations, often leading to inaccurate analytical results where the maximum speed of a process is actually well below that of the slowest sub-process it contains. The most extreme example of this would be a machine that requires an accurately timed product transfer running completely out of phase with the next machine in line, with the end result being two machines running furiously with no net production at all. There are many reasons for this occurrence, but the most common one is synchronization. A linear sequential process may have a device that is only capable of accepting items from a previous sub-process at particular times. If the previous sub-process is not timed correctly, the product will stall – be out of one process yet not accepted by the next. Other variables of timing include batch processes that disgorge items in large surges that have to feed into continuous processes that accept items in smaller quantities, and variable processes that may only accept items at a fixed range of rates.

These problems are often dealt with by adding accumulator capacity or by trial-and-error solutions, but with the declining cost of producing intercommunicating machine controls as well as networked central information systems, the effectiveness of optimization processes in high-speed manufacturing is only limited by the willingness to make initial investments in the analysis and production changes. The further benefits of production modeling and analysis is the ability to entertain "what if" scenarios, allowing trial changes to be modeled without disrupting ongoing operations, and minimizing changeover downtime.

The benefits of these analyses can be a remarkable increase in the operating throughput with little or no capital investment. In some scenarios, pre-construction modeling have saved huge amounts of capital expenditure on unessential building features and have pre-tested machinery and operations improvements in order to optimize their efficiency or to indicate that they may not be effective [7].

Basic Types of Production Optimization

Production optimization methods have grown from the observation that the basic principles of mass production tended to produce large quantities of both work in progress (WIP) and accumulated inventories of both components and finished goods, all of which may represent a great deal of capital that is not earning any sort of return. In an ideal sense, the best manufacturing operation would only have enough materials on hand at any point to finish the particular job at hand. The economics of purchasing and transportation dictate that the more economical alternative might be a very small supply of components on hand, purchased at an economic balance point of optimal ordering costs and brought in on a timely basis, which is discussed in the subsequent section on supply chain management.

Advanced Methods of Production Optimization

Complete production optimization is much more complex and must take into account the throughput capacities of machines, buffering, downtime, breakdown, and changeover factors, among others. Needless to say, this can be an extraordinarily complex task and one that many operations may avoid due to the lack of the personnel, time, or investment necessary to complete it. In many operations, particularly those that have grown from a small startup operation, this kind of analysis can have great benefits in the "tuning" of components that may have been added as the production facility's needs and capacities grew.

The usual procedure for optimizing production systems is a multistep process that requires a substantial amount of initial data, as well as the construction and validation of a mathematical model of the production system that will allow the incorporation of actual data to provide meaningful results. In the past, this often required a great deal of personnel time to accumulate, but with more automated controls and data collection, this has become somewhat easier, though this is balanced by the necessity of deciding which data are meaningful.

Model Types

The simplest of model types is a sketch made on anything from a whiteboard to a cocktail napkin. While these lack elegance, they are often the starting point for further and more accurate analyses. Beyond the iterative "sketch-and-toss" method, however, a quantitative result is necessary, and there are several commonly used methods.

For a simple production line, the types of operation are generally separated into several different types [8]:

Homogeneous: All of the operations have the same cycle time.

Non-homogenous: Cycle times may differ and may be affected by variations such as acceleration, deceleration, or distribution.

Synchronous: All of the production units operate at the same time.

Asynchronous: The production units all operate at different times.

Similarly, as the number of production lines increases in a facility, the concept of symmetric lines, all of which have the same characteristics and capacities, versus asymmetric lines which all differ, comes into play.

In order to create an analytical solution, the traditional method has been to create a series of simultaneous equations that describe the operational characteristic (cycle time, failure rate, etc.) that is of interest at each step in the process, and then solve the equations to create a generalized model that will provide an analytical approximation for the desired solution. Unfortunately, these methods required both a substantial background in linear algebra and a good working knowledge of computer programming to provide a solution.

Optimization Software Tools

More recently, tools to accelerate these solutions, both in the form of spreadsheets and numerical analysis software, have become not only available but convenient to use. Better still, several companies offer graphically-based software that simplifies the nature of the modeling and makes the process more intuitive. The availability of these tools does not eliminate the need for a working understanding of the mathematics involved, but it does reduce the arcane nature of the task and helps the industrial engineer solve production problems more efficiently. Graphically-based programs can also accelerate the rate of design changes and "what-if" thinking for production layout, as with the soy processing simulation shown in Figure 8.6.

Examples of advanced simulations using physics-engine-based software to produce real-time, quantitative simulation of both production processes and the response of control systems are shown in Figures 8.7 and 8.8, whereas examples of a software package that will provide design tools ranging from the product and secondary package through to truck and container load patterns are shown in Figures 8.9 and 8.10.

Real-Time Optimization

Given a sufficiently sophisticated and timely optimization model, the production optimization model can be incorporated into real-time control systems to continuously update and "tune" the

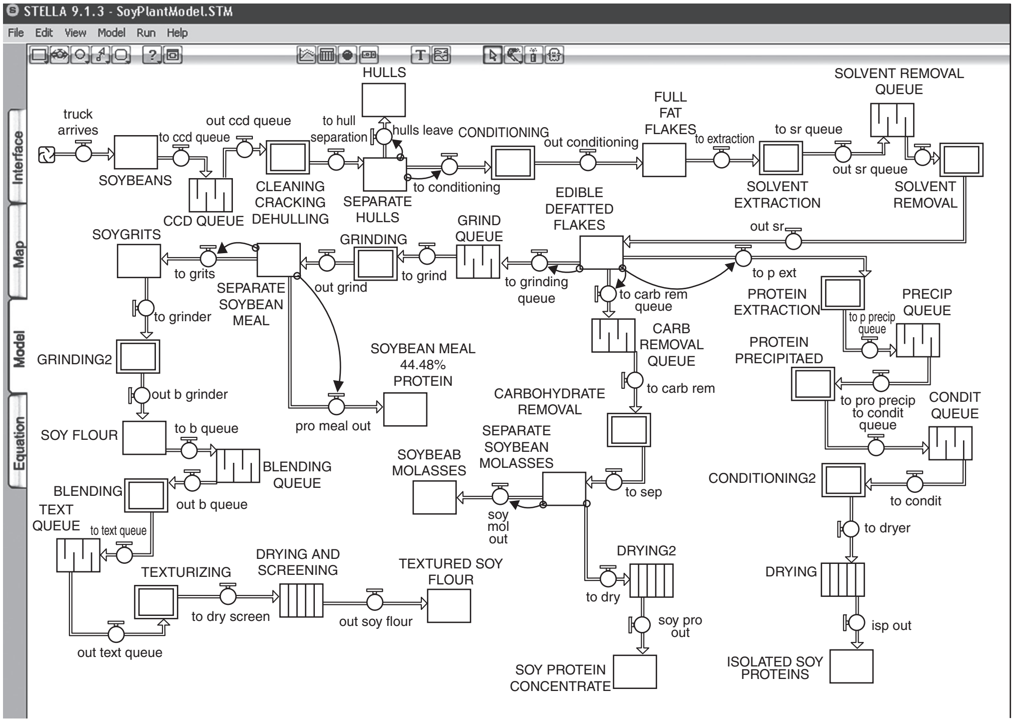


Figure 8.6. Soy Processing Plant Simulation
Source: C. Weeks and S. Morris, 2007.

manufacturing system to achieve a previously defined goal by anticipating and correcting the operating conditions in real time. Although this seems like a daunting process, nearly every new automobile currently manufactured has this type of system built into its drivetrain, responding to throttle and environmental inputs by continuously optimizing power, gear selection, fuel economy, and emissions to follow a pre-programmed model.

Integration of Manufacturing Processes

In a larger sense, the optimization of manufacturing processes should fit in with a larger-scale integration of Manufacturing Execution Systems (MES) information systems. This allows the manufacturing facility to exchange data with the larger manufacturing operation, and can provide a method to connect with the larger information cycle described in Chapter 1. Whereas the integration of orders and operations might be as simple as the efficient use of an order whiteboard, the advantage to a larger, more integrated manufacturing system can be to shorten and economize production cycles and production operations themselves, as well as integrating operations such as quality control, supply chain management, sales levels (and forecasts), and others into a more cohesive picture of the real-time operation of the organization.

While there is a separate industry built around large-scale software installations for these purposes, the smaller operation may benefit from taking the same principles forward on a smaller, more local scale, because the basic principle at work is timely cross-communication

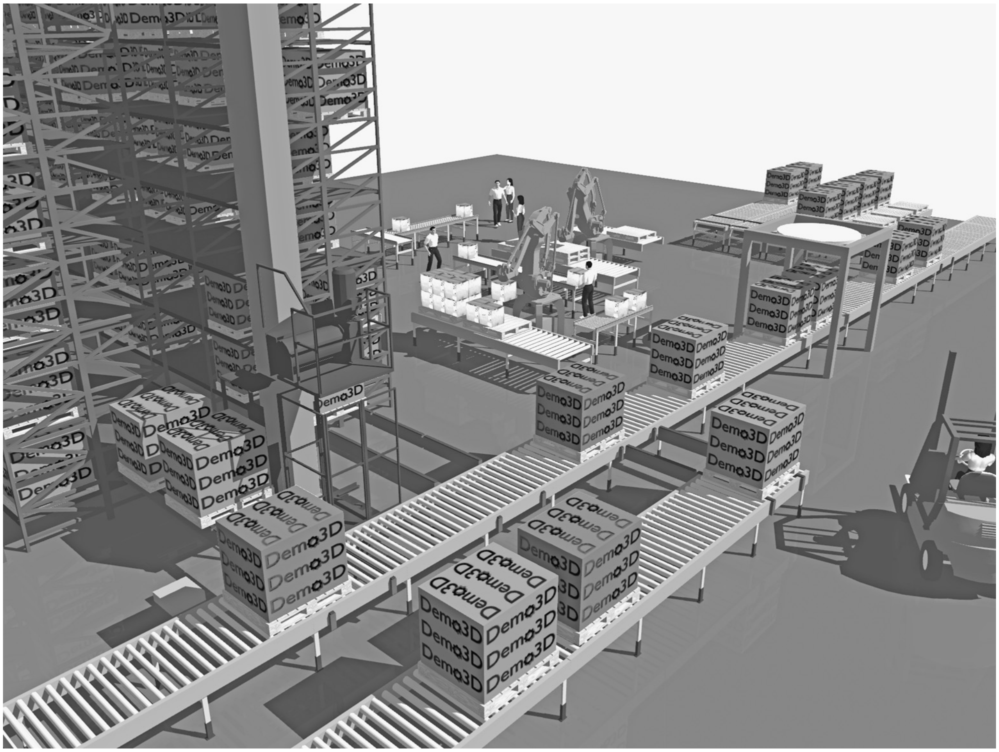


Figure 8.7. Real-Time Simulation of Operating Packaging Line
Source: Courtesy of Demo3D (www.Demo3D.Com), used with permission

of information about orders, work status, and completion information during production. Even fast-food franchises have adopted a reduced version of this to track food orders in real time and assure accurate delivery of the customer's order.

Supply Chain Management

Supply chain management concerns itself with the flow of materials, in-process goods, and finished goods from the point of origin to the point of consumption. It is a much larger field than can be addressed in this book, and is an entire industry unto itself, but a basic understanding of the goals and processes are necessary to understand the role of packaging and information flow into the supply chain. Further, supply chain concepts apply both to the packaged goods manufacturer who is seeking to reduce inventory costs while minimizing risk as well as to the products' retailers who are continually trying to minimize inventory without running out of it.

The rapid globalization and migration to the Internet of world commerce has placed supply chain management squarely in the spotlight as companies struggle to create and maintain flexible, resilient, and efficient manufacturing, distribution, delivery, and retail systems to match customer demand. Packaging extends this in somewhat unique ways in that the information carried in some coding systems is also used in automated recycling systems and carries the materials back to the point of origin or to a recycling facility.

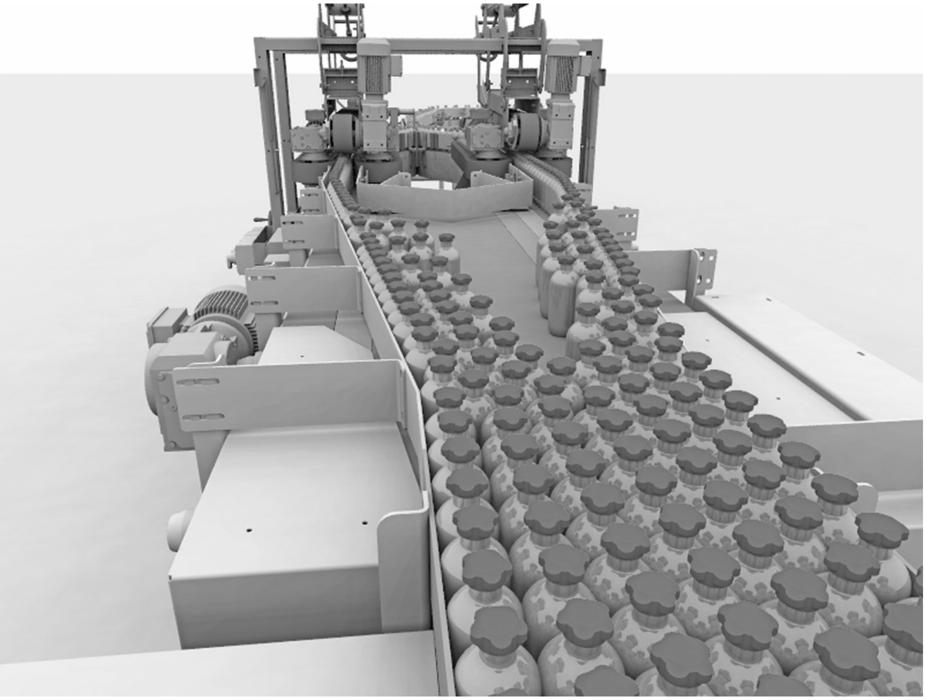
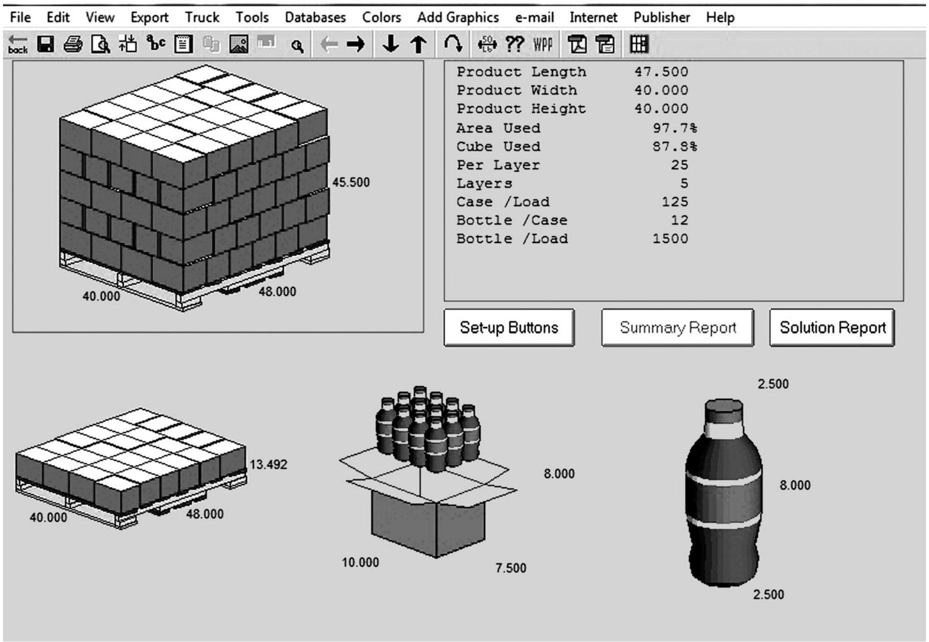
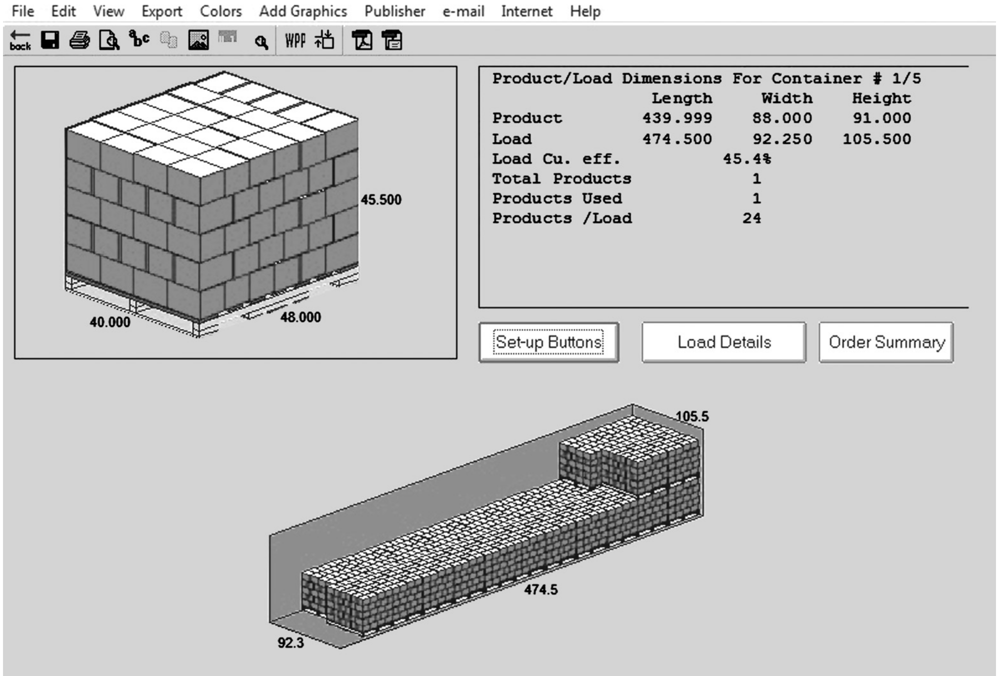


Figure 8.8. Real-Time Simulation of Bottle Handling and Control System
Source: Courtesy of Demo3D (www.Demo3D.Com) and Can Line Engineering, used with permission



```
Product Length     47.500
Product Width      40.000
Product Height     40.000
Area Used            97.7%
Cube Used            87.8%
Per Layer              25
Layers                  5
Case /Load            125
Bottle /Case           12
Bottle /Load         1500
```

Figure 8.9. Package, Shipper, and Palletload Design Using Software-Based Design
Source: Courtesy of Cape Systems Inc. Used with permission



```
Product/Load Dimensions For Container # 1/5
                 Length     Width    Height
Product         439.999    88.000    91.000
Load            474.500    92.250   105.500
Load Cu. eff.           45.4%
Total Products            1
Products Used             1
Products /Load           24
```

Figure 8.10. Vehicle Lading Using Software Analysis
Source: Courtesy of Cape Systems Inc. Used with permission

Supply chain management also concerns itself with strategic goals such as distribution site location, transportation sourcing, new product line integration, and economic optimization. The latter concern often manifests itself in the ongoing goal of reducing materials flow and waste to the absolute minimum possible. Considering that packaging is often seen as a cost item rather than the value-added system allowing products to be used, there is always an economic incentive to reduce the amount of packaging both in use and in inventory. There is a similar tendency to reduce resources for development efforts and new technologies, although emphasizing the added value provided by packaging may alter these perceptions.

Value Chain Analysis

Value chain analysis is a managerial tool used to track the value (rather than cost) added to products at each stage of their primary activities in conversion of materials into finished products throughout the supply chain (Figure 8.11). The value chain originates from the post-consumer environment and ends at the raw-material stage in a direction that is reverse of the supply chain. Addressing value in this direction allows each step of the conversion process to be evaluated based on the value of the conversion. Further, suppliers and support activities are aligned to deliver value that is meaningful at each step of the process. The final goal of value chain analysis is to provide analysis and optimization leading to a product whose value to the supply chain and to the customer exceeds the cost of the activities required to produce it.

Given that many products, and particularly food products, are inherently dependent on their packaging to add value to a somewhat generic product, and are certainly dependent on it to get

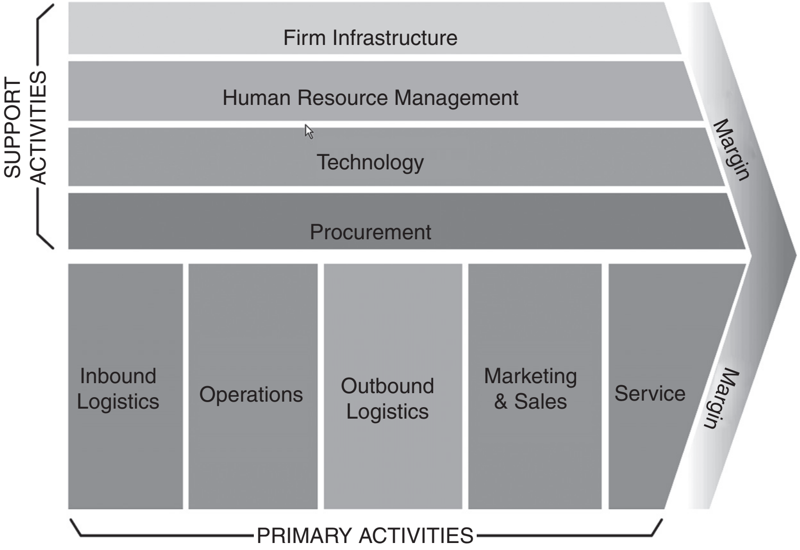


Figure 8.11. Value Chain Components
Source: Dinesh Pratap Singh. Used with permission

it to the customer in good shape, value chain analysis may be a means of increasing the focus on improved packaging technologies and systems that are meaningful to the final consumer and also customers within the value chain. Gains can be derived when value chain analysis and systems integration are employed to focus on specific goals such as increasing agility, shortening time to market, offsetting market fluctuations, and building customer confidence. Additionally, focusing on adding value with packaging may provide a competitive advantage both internally as support activities shift to maximize this, and externally as a specific product positioning is achieved to increase market share [9, 10].

Inventory Reduction Methods

Inventory reduction is one of the primary means of simple cost reduction in many manufacturing operations, and several basic methods for managing this will be discussed in this chapter. The simplest ways of reducing inventory costs are to manage materials inventories, work in progress, and finished product on hand to maximize economic returns. Although there are industries founded on managing and implementing these methods, several simple inventory management concepts will be discussed. All of these have the underlying idea of reducing the costs of production that also include costs of production space and equipment, capital costs, or opportunity costs. The last two of these terms are linked, in the sense that they represent the difference in the rate of return of using capital for the current purpose rather than applying it to another investment with similar risk.

A simple, conceptual example of this would be for someone to take their entire annual food budget and apply it in one of three different ways:

1. Buying a year’s worth of food at one time and storing it for use during the year.
2. Buying a week’s worth of food once a week.

3. Buying just enough food for the day or a particular meal in a single trip and have no inventory carried over.

While casual inspection of these three alternatives might highlight at least one that seems ludicrous, the "sensible" choice will vary from culture to culture and is almost always between one of them. For example, a year's worth of food may seem like a silly decision, but remote research stations may only resupply once or twice a year, and in some cultures, the only time available for shopping for those who work during the week may be on a Friday or Saturday. Conversely, daily shopping is not uncommon in many cultures, particularly those in which people depend on very fresh ingredients and may have a more traditional culture with regard to domestic tasks.

For purposes of this example, we can consider a few simple retail cost factors in each choice.

Ordering Costs

This is the cost associated with actually placing an order for goods or materials, and is independent of the order size. In the grocery shopping example, this would be the total cost of making up a list and then going to the store or ordering supplies online.

Storage Costs

These include the costs of the building to store materials, as well as refrigeration and other ancillary costs related to maintaining the stockpile of food.

Transportation Costs

These are transportation, handling, and inventorying costs and are assumed to depend on the order size, and therefore are large in total for the full-year purchase. It is also reasonable to assume that a large purchase will take advantage of the economy of scale and will result in a smaller per-unit cost, whereas a series of very small purchases transported individually over time will result in higher per-unit costs. In reality, this may be modified somewhat because a year's supply would require the use of a much larger vehicle than a usual automobile, whereas daily shopping can be carried by hand, but the general principle still holds true.

Out-of-Stock Costs

The technical definition of this is the cost of lost product sales when a particular item is not available for use in a manufacturing operation for retail sale. In the simpler example of buying groceries for personal use, this is the all too familiar scenario of running out of a particular item and having to run to a pricey all-night store to purchase it at the last minute. In both cases, these costs tend to be quite high on a per-unit basis.

Opportunity Costs

This is a term that accounts for costs for alternative uses of the capital in a particular investment or business strategy. This would be highest when tying capital up in a year's worth of grocery purchases and thereby making those funds unavailable for investment or emergency use.

Table 8.1. Grocery Purchase Example

Inventory Example – Total Annual Cost			
Cost Type	Yearly	Weekly	Daily
Storage	Highest	Moderate	Lowest
Ordering	Lowest	Moderate	Highest
Transportation	Fewest trips, Large Vehicle	Moderate	Most trips
Out of Stock	None	Moderate	High
Opportunity	High	Moderate	Low
TOTAL COSTS	High	Moderate	High

By inspection, one can construct a relatively simple qualitative chart of the total costs of each alternative (Table 8.1).

So, whereas most consumers achieve some sort of balance for their grocery shopping on an intuitive or traditional basis, it is possible to create analytically based systems that reduce the amount of capital tied up inventory to a practical minimum. Extensions of these concepts to the economic optimization of work in progress and finished goods are the goals of so-called *lean manufacturing* systems as well as modern distribution systems that seek to minimize the quantity of finished retail goods in storage and transit by large-scale transportation, logistics, and information integration.

Inventory Management Techniques

Inventory management techniques can be as simple as having a look in the freezer in the back room of a pizza parlor or as complex as a globally linked dynamic logistics management system. Some of the simpler examples given in this chapter will illustrate the basic concepts that are used, though extremely complex models can be adopted and are in current use in some operations, particularly in real-time distribution network restructuring and global sourcing of inventory.

Economic Order Quantity (EOQ)

This is a generations-old basic calculation for the generation of the optimal balance between the overall costs of ordering items for production as shown in Figure 8.12, and the costs of carrying an excess inventory (Equation 8.2) [11].

$$\text{EOQ} = \sqrt{\frac{2(\text{Periodic Useage of Units})(\text{Ordering Cost})}{(\text{Periodic Carrying Cost per unit})}} \tag{8.2}$$

Ordering Cost: Time to place and process order.
Carrying Cost: Cost associated with keeping inventory on hand

It does not incorporate any consideration of the costs of being out of stock (costs of lost production), nor does it account for rate of use or fluctuations in the rate of use of materials. This induces a risk of cost being accrued from an out-of-stock condition, which is not considered in the calculation but must be balanced against too much inventory, as shown in Figure 8.13.

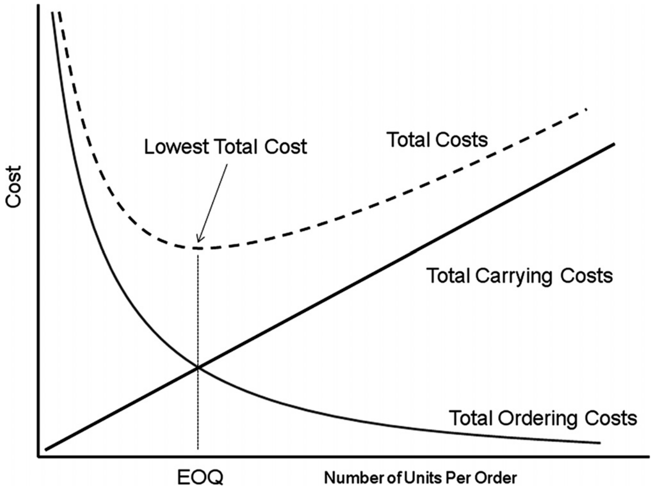


Figure 8.12. Economic Order Quantity

Note that actually getting accurate data for ordering costs and carrying costs can be quite difficult without a rigid method for analysis because it is subject to a great deal of estimation by the people involved. The ordering cost is also considered to be constant and the formula presumes that many things such as lead time, rate of demand, purchase price, and delivery and stocking happen in very predictable, constant ways.

Just In Time (JIT)

Just-in-time scheduling works on the principle that only the immediately necessary amount of material should be kept on hand, with the correct incremental replacement amounts delivered on a timely basis. This is a commonsense step that has been in place since the large-scale implementation of mass production, but was refined and publicized in large part by Taichi Ohno of Toyota in the 1950s and 1960s, who used it to provide flexible manufacturing capabilities

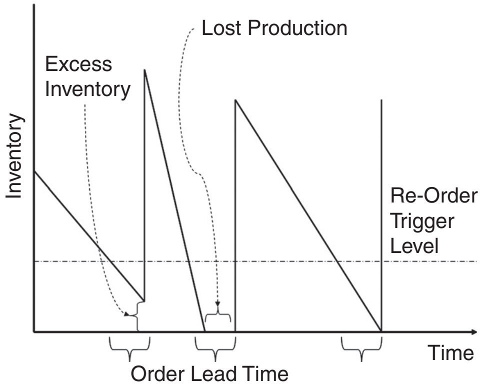


Figure 8.13. EOQ Ordering Showing Effect of Variable Lead Times and Useage Rates

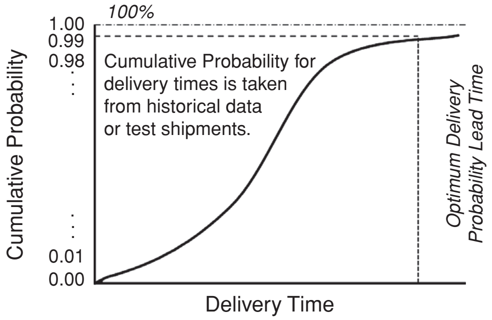


Figure 8.14. Delivery Time Cumulative Probability

with severely limited factory space. JIT methods incorporate statistical data about delivery times and can make approximate adjustments for the rate of material use. For JIT systems to work, the production facility must collect data about, and work with suppliers in order to accurately determine, what the cumulative probability of delivery times and conditions might be in order to minimize the risk of out-of-stock conditions as well as avoid accumulating excess inventories (Figures 8.14 and 8.15).

In a manufacturing operation, the absence of a single item of inventory can cause the manufacturing operation to stop entirely, and it may be economically advantageous to have it sent by any means, no matter how expensive. Supply chain disruptions can be enormously destructive, depressing stock prices, causing long-term financial problems and, in over-lean organizations, causing the failure of whole product lines [12].

Kanban Systems

Kanban (literally, "signboard") systems use internal indicators to trigger orders for new materials, often within a particular manufacturing process, and are an extension of the JIT system. The name is reputed to stem from the practice of putting a re-order tag or indicator near the bottom of a large bin of components, triggering a new order when the tag was uncovered. Current practical implementation usually has an order triggered when a bin of parts starts being used,

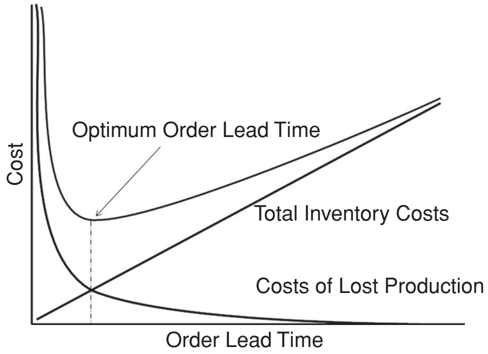


Figure 8.15. Order Lead Time Factors

with the rate of consumption tracked as a function of production. Overall, it is very simple and quite robust, and has rapidly replaced many Materials Requirement Planning (MRP) systems that were complex and cumbersome. More modern assembly processes use means of flagging parts, trays of components, and ingredient bins combined with barcode- or RFID-assisted re-ordering. The kanban system can be chained with many components and processes (and the initial manually handled paper tags can be replaced with networked data systems), making it ideal for large-scale manufacturing industries such as automobiles. The concept can be extended into JIT manufacturing and distribution that incorporates the basic concept of depletion-driven orders into other hybridized systems.

Kanban may be cascaded to trigger larger orders from a factory inventory or to trigger orders directly from a supplier. Optimum order sizes and rates of consumption as well as order lead times must be determined to keep inventory as low as possible. A net effect of the kanban system is to push inventory-carrying costs back onto suppliers, as well as to demand a tight supply delivery schedule, possibly causing orders to be in unusual quantities, all of which may carry economic consequences that should be considered. Simple kanban systems do not account for variations in part quality or type, nor do they consider delivery schedules. Additionally, kanban and similar systems represent a transition from “push” production that relies on an accurate estimation of market demand to a “pull” system, where production facilities respond to sales levels more directly and efficiently. As might be expected, many larger operations have moved away from literally putting cards into bins of parts and toward more sophisticated electronic methods that track part location and consumption, and which are integrated into larger supply chain management systems. Simple JIT and kanban systems attempt to compensate for variations in demand by back-chaining demand into the supply system, but often do not account for inventory delays and delivery times from external sources, nor do they do a very capable job of juggling several suppliers for a single item. Considering that this is easily included in other advanced inventory management models, the accumulation of external supplier data then becomes an important part of the overall economic picture. It becomes necessary to balance the costs of rapid or dependable delivery against the costs of being out of stock on a particular item – something that has been of great benefit to the rapid and overnight delivery industry. In the retail food distribution system, there are so many overlapping products that it often seems unlikely that the lack of a single item would close an entire store, so there is a wide range of alternatives depending on the product and its market niche, but having the product available for the consumer is a fundamental component for the success of a particular product line.

Thus, a more flexible and efficient management model relies on statistical information about delivery times and delays, as well as forward-looking predictive models about both supply disruption due to weather or other factors and demand to provide ordering and distribution that puts the product on the shelf just in time to be purchased without the accumulation of excess inventory or extensive outages of products, as shown in Figure 8.16.

The demand for fast, flexible, and efficient delivery in order to provide low inventory levels and high response to changing market conditions have pushed distribution logistics into complex modeling and simulation, and the plunging cost of data acquisition and transfer has allowed an ever-increasing degree of partnering and cross-integration both within and among companies.

Manufacturing Quality Assurance and Quality Control

Quality is an elusive concept when taken beyond a simple degree of satisfaction with a product. In most cases, there are two components of quality – quality of design and quality of

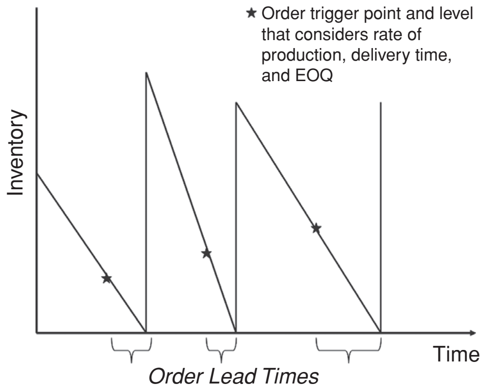


Figure 8.16. Demand and Delivery Time Optimized Ordering

conformance – that combine to produce *product quality*. Quality of design addresses how well the particular product design meets the needs of the situation for which it was designed and how well it can be manufactured under ideal circumstances. Quality of conformance follows this and addresses the issue of how well the product conforms to the specifications and tolerances demanded by the design.

Most day-to-day quality control (QC) work is aimed at addressing issues of conformance, while the more effective effort is in the creation of Design For Quality (DFQ) as well as Quality Assurance (QA). A good component design will have features that facilitate accurate and complete integration into the larger production system, and a workable quality assurance program can help ensure that quality and productivity will increase together with the reduction of rework and rejects.

The difference between quality assurance and quality control is often blurred, but a useful distinction is that the first is the set of processes and procedures that provide a manufacturing environment that promotes the production of a high-quality product, and the second is a set of processes and procedures that assures that the product is of acceptable quality when it is actually produced.

Before any work is done on either topic, the definition of what defines quality for a particular item is important. One of the more common problems in quality control and quality improvement is the lack of agreement on a clear, objective, and measurable definition of what a high-quality product or outcome is, how much variation is acceptable, and how these attributes are to be measured. Many disputes over quality arise from the difference in the perception of quality of a particular product between the producer and the consumer, and can be avoided by establishing, understanding, and communicating these criteria before production begins.

Typical quality-control attributes include dimensional tolerances, mechanical properties, color, specific composition, and more difficult-to-assess attributes such as taste and odor. Sampling plans are often taken from established ASTM/ISO and ANSI protocols, MIL-STD (military standard) testing systems, and others. The actual test methods used may be developed in-house, may be taken from a third-party standard such as a TAPPI test method, or be a combination of the two. It is important that an understanding is reached between the supplier and customer regarding test methods, sampling protocols, and other factors before delivery to avoid misunderstandings.

Sampling, Testing, and Remediation

Constructing a broad sampling plan is a difficult task, even for those with a deep love of statistics. Because of this, there are several quality-attribute sampling plans that have been used as the basis for product quality testing for some time. The MIL-STD 105 series (now superseded by the ANSI/ASQC Z1.4 sampling plan) and others provide a useful starting point for quality attribute testing. These can be obtained at minimal cost, and there are currently online calculators that incorporate the standards to simplify the task further [13].

Sampling can be broken down into sampling by attributes or by variable, single or multiple sampling plans, and rectifying versus non-rectifying sampling plans. The distinction between sampling by attributes or by variable is whether the inspection leads to a conforming/non-conforming (*Go/No-Go*) decision or an accounting of the number of non-conformities versus a continuous measurement of a particular variable. Single and multiple sampling plans are constructed to provide the most statistically useful acceptance decision at the least sampling cost. Often, because of the high cost of testing items versus a similarly high cost of inaccurately accepting or rejecting products, a multiple sampling plan will require an initial small sample test that can provide a clear accept/reject decision or may lead to additional testing before a final decision criteria is reached. Rectifying plans will also account for the disposition of items that have been found to be non-conforming. This may range from disposal costs for a small batch of ingredients to the costs of return and rework for a large order of sub-assemblies.

Increasingly, product testing and certification has been pushed back on the suppliers of ingredients and components. This has the advantage of reducing costs to the purchaser of these items, but puts quality control in the hands of those most likely to have an interest in misrepresenting the quality of the particular item. Because of this, quality audits and specific contractual obligations must be considered carefully, as should the remediation procedures such as defective item return, reworking, or disposal.

To implement a pre-calculated sampling plan, an acceptable quality level (AQL) must be established, and a lot size is usually determined. Lot sizes may be self-evident (a single container of components, shipment of product, or production shift) or may have to be designated in a continuous production operation. Additionally, a determination about which type of sampling to use must be made incorporating costs of testing and factors that are usually incorporated into the test protocol.

For example, for the normal, single-sampling plan shown in Figure 8.17, the lot size is between 3,200 and 10,000 units, and for a 1% AQL, the number of items to be sampled is 200, and the lot can be accepted if the number of defective items is five or less.

Quality Assurance and Quality Improvement

Quality assurance seeks to provide a system under which the quality of a finished product will continuously improve. This is particularly critical in food processing operations where the economics of the processing operation will dictate both speed and low cost, but quality failure can have catastrophic consequences.

History of Manufacturing Quality

As the world moved from small-scale crafts and manufacturing to large-scale mass production, the specialization of tasks and manufacturing of large quantities of interchangeable parts

Single Sampling Plan for Normal Inspection*

Lot size†	Sample size‡	Acceptable quality level§								
		0.15	0.25	0.40	0.65	1.0	1.5	2.5	4.0	6.5
Over 2	2	0	0	0	0	0	0	0	0	0
8	3	0	0	0	0	0	0	0	0	0
15	5	0	0	0	0	0	0	0	0	1
25	8	0	0	0	0	0	0	0	1	1
50	13	0	0	0	0	0	0	1	1	2
90	20	0	0	0	0	0	1	1	2	3
150	32	0	0	0	0	1	1	2	3	5
280	50	0	0	0	1	1	2	3	5	7
500	80	0	0	1	1	2	3	5	7	10
1,200	125	0	1	1	2	3	5	7	10	14
3,200	200	1	1	2	3	5	7	10	14	21
10,000	315	1	2	3	5	7	10	14	21	21
35,000	500	2	3	5	7	10	14	21	21	21
150,000	800	3	5	7	10	14	21	21	21	21
500,000	1,250	5	7	10	14	21	21	21	21	21

*Inspection by attributes (go or no-go) at level II (normal) for acceptance or rejection on the basis of a single sampling.

†Number of units in a batch or shipment.

‡Number of units to be inspected that are selected at random from each lot.

§Acceptable if the number of defective units in the sample are this amount or less, rejectable if above.

Figure 8.17. Example Using Mil-Std-105D

demanded that the operation be supervised to ensure good results. Unfortunately, the pressure to increase production volumes to meet a quota (and the rewards for doing so) often led to a "get the iron out the door" mentality, which resulted in a very high rate of rejected parts and defective assemblies caused by high part variability and poor workmanship. This required that the individual parts be inspected at some point in the manufacturing and assembly process, as well as further inspections to ensure that the complete assemblies functioned properly, and these methods often suffered from various lapses in attention or outright neglect because the reward system was often still tied to simple production levels.

The first response to this was to provide inspectors to "inspect in" quality as a separate oversight function in many manufacturing operations, providing a secondary and somewhat objective evaluation function in the manufacturing process. With the huge burst of industrial production required during World War II, the costs and delays of reworking defective goods and assemblies became critical, and various data-driven quality control methods began to be implemented, the most famous of which were outgrowths of Walter Shewhart's work at Bell Laboratories during the 1930s that brought careful use of statistics and economics into the picture [14]. This work became the foundation for what is currently termed *Statistical Quality Control* or SQC, which made inspections more efficient and provided statistical tools for the inspectors to use, and which became vitally important in the production of war materials.

During the reconstruction of Japan after World War II, Japanese industry became known time for producing shoddy imitations of goods from elsewhere. To assist in the redevelopment of Japanese industry, W. Edward Deming, who was prominent in statistical methods of quality control, and Joseph Juran, who strongly advocated collaborative quality management principles, began working with Japanese industries using ideas of quality control and quality management that had been rejected in the entrenched markets of the United States. These proved to be vital mathematical tools for quality control, and these revolutionary managerial methods were instrumental in bringing Japan to the forefront of efficient manufacturing of high-quality products by the 1970s, while the United States lagged behind. Competition drove many companies to reexamine their approach to quality control and most of them to depart from inspection-based quality assurance systems to company-wide, collaborative quality assurance models.

Diagnostic Tools for Quality Management

While an entire culture of quality management tools, software, and philosophy have developed over the last half-century or so, there are several tools that are simple to use and can prove useful in the determination of causes of quality problems at the production level.

To determine the cause of a quality problem, a thorough understanding of the process is necessary, as well as a grasp of the cause-and-effect relationships that verifiable data provide. Additionally, the difficult distinction between important and urgent problems (Juran's "The vital few and the useful many") must be made, and cause-and-effect relationships that contribute to these problems must be determined.

Process Flow and Contributory Factors

Useful tools in the visualization of process flow include flow charts that give a picture of movement of materials, energy, and labor through the production system's processes and activities, as shown in Figure 8.18. These may become quite complex but will provide a useful mental picture to help isolate not only problem areas in production design, but potential critical control points for use in safety management such as the HACCP programs discussed in Chapter 10.

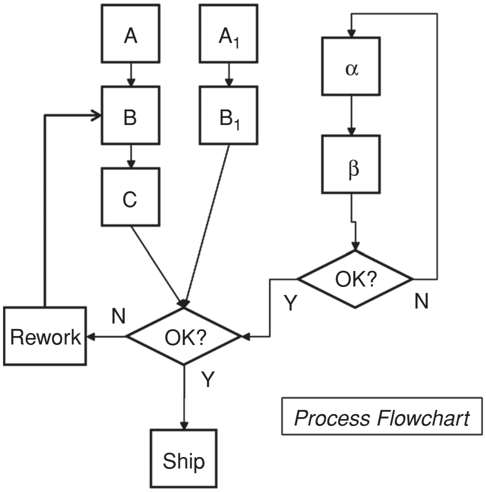


Figure 8.18. Production Flowchart

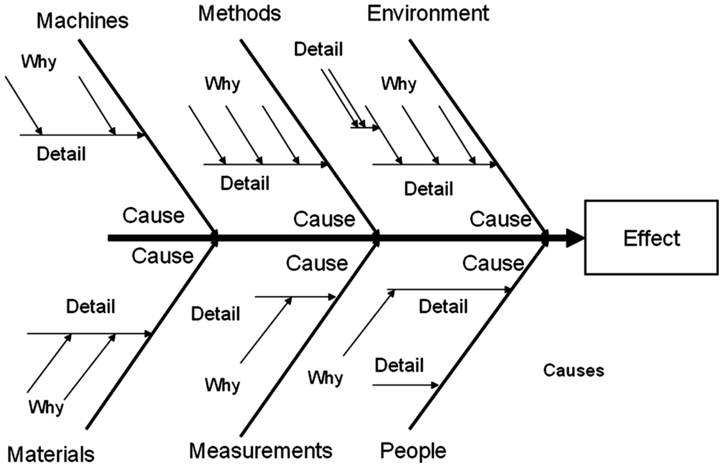


Figure 8.19. Fishbone ("Ishekawa") Diagram

Ishikawa ("Fishbone") Diagrams

While at the University of Tokyo, Kaoru Ishikawa (who also developed the concept of quality circles, among many other contributions) developed a distinctive type of cause-and-effect diagram that shows contributory factors in a process and, when dissected into sufficiently fine detail, can highlight unnoticed factors that contribute to quality problems. The "fishbone diagram" term comes from the distinctive fish-skeleton shape of the chart shown in Figure 8.19, each "rib" of which is a broad category of factors, listed in Table 8.2, which are dependent on the particular type of industry. Secondary and subsequent causes branch from the main "ribs" to give a useful picture of causes that might be usefully addressed.

Determining Importance, Magnitude, and Correlation

Pareto charts, histograms, run and correlation charts, and other statistical methods are used to determine not only which problems are important, but which causative factors can be shown to

Table 8.2. Ishekawa ("Fishbone") Diagram Cause Chart

Ishekawa Diagram Main Cause Chart	Type of Application		
	Manufacturing	Administration	Service
Causal Factor	Machine Method Materials Maintenance Personnel Environment	Price Promotion People Processes Location/Facility Policies Procedure Product	Surroundings Suppliers Systems Skills

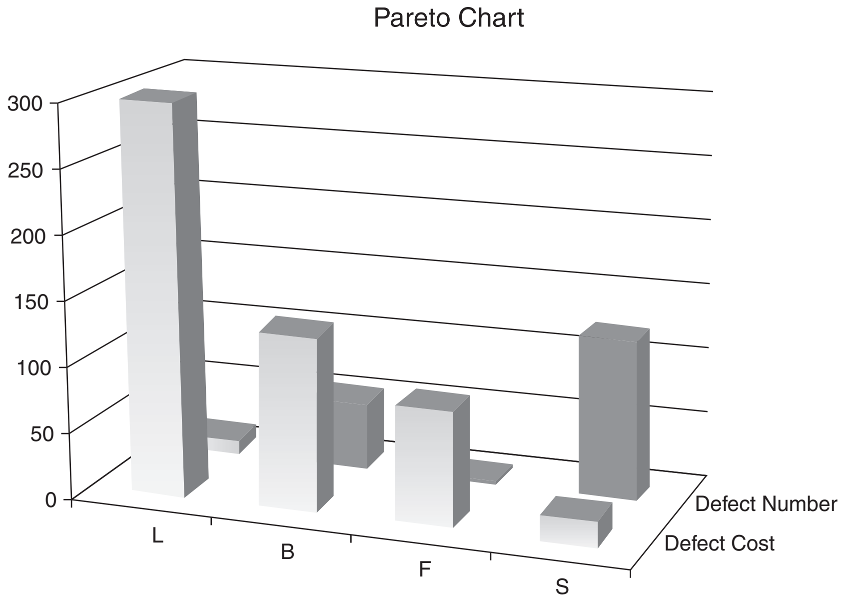


Figure 8.20. Pareto Chart of Occurrences versus Total Cost

have an effect in the creation of the problem and therefore point to the most urgent component to achieving a solution.

Importance and Magnitude: Pareto Charts

Pareto charts are initially used to chart the type and frequency of problems, and often are best used when the results of the problem (such as cost, product returns, or customer complaints) are used rather than the simple number of occurrences, as shown in Figure 8.20. A simple tally of a small number of problems will not stand out, but if they create a great deal of negative impact or expense, they will often create an obvious prioritization.

Frequency Histograms and Correlation

Correlation of cause and effect may be measured using any number of statistical tools; indeed, this is the bulk of the field of statistics, but several simple, useful visual tools are histograms (Figure 8.21), which will give an idea of the distribution of actual data measurements and process capability, and are often expanded to include time, work shift, or material supplier.

Correlation charts will give a visual representation of the likelihood of causal linkages between different manufacturing inputs. Figure 8.22 represents a closely correlated data set (high $\rho_{a,b}$ value) between variables A and B, and therefore an increased likelihood of a causal link, while Figure 8.23 shows a very low correlation because the data is broadly distributed in a nearly random fashion between the two variables.

Many of these tools are easily accessed with spreadsheets or even simple handheld calculators. Additionally, users who shy away from deep statistical analysis will gain a great deal of insight from the visual representation of data.

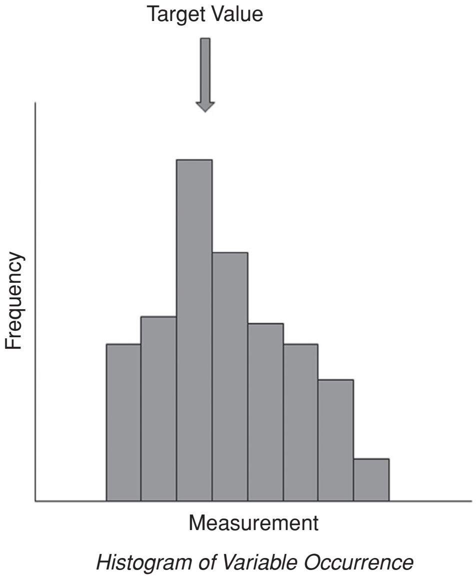


Figure 8.21. Histogram of Intervals of Measured Values during Production

Run Charts, Control Charts, and Time-Based Data

Information taken from ongoing production operations will often highlight time-dependent problems that may, in turn, showcase unusual causes that might not come to light otherwise. These *run charts* (Figure 8.24) highlight slow trends that may not be obvious from simple fixed-time examination of data, and the cumulative statistical data will also provide a basis for evaluation of ongoing control chart measurements during production.

Control Charts (Figure 8.25) represent a means of plotting an ongoing series of measurements taken from the production operation. These measurements, along with their standard distribution

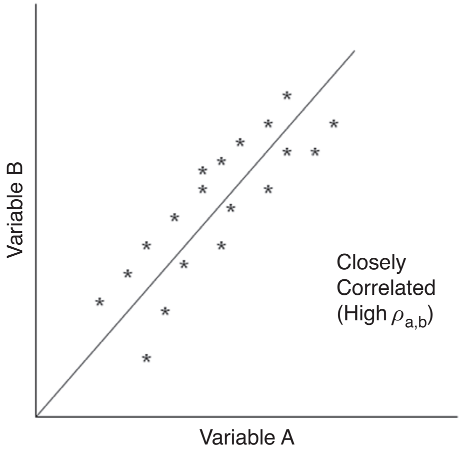


Figure 8.22. Good Correlation between Variable A and Variable B

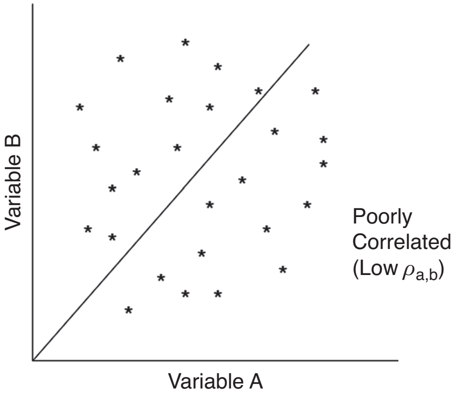


Figure 8.23. Poor Correlation between Variable A and Variable B

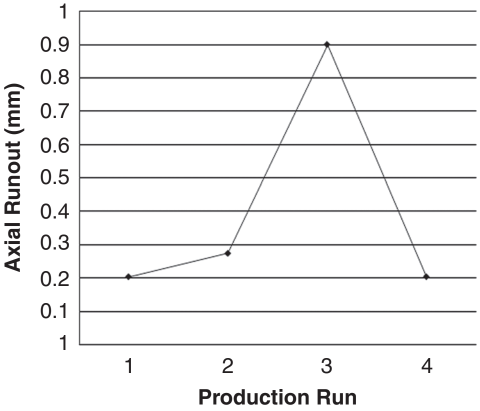


Figure 8.24. Run Chart of Measured Attribute (Axial Runout)

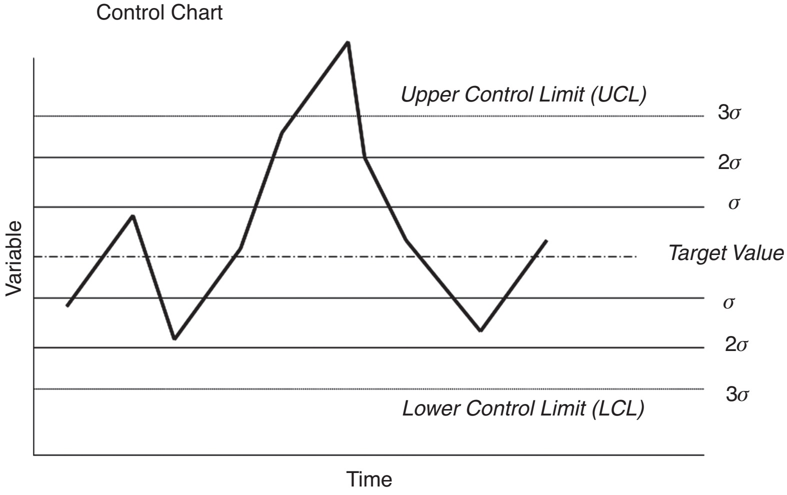


Figure 8.25. Control Chart Showing Measurements

Table 8.3. WECO Process Control Rules

WECO Rules state that a process is out of control if:

- A single point falls beyond ±3σ*
- Two out of three successive points fall beyond ±2σ
- Four out of five successive points fall beyond ±1σ
- Eight successive points fall within the same side of ±1σ
- A process variable is trending if 6 points in a row trend consistently up or down or 14 points in a row trend alternately up and down, indicating an oscillating trend.

**Where σ is one standard deviation taken from historical data.*

values, may be tabulated manually or taken automatically and displayed on an ongoing screen. The results can both show the stability of the operation and demonstrate the effect of changing speed to increase (or decrease) throughput.

Traditional *WECO* ("Western Electric Company") rules given in Table 8.3 are often used as a starting point for analysis of the results of run charts, although they may increase the number of false alarms [15].

Hypothesis Testing as a Problem-Solving Tool

Hypothesis testing is a useful tool for determining the cause of a problem that may be obscured by a large amount of information or mixed opinions about the source of the trouble. The steps of hypothesis testing as shown in Figure 8.26 consist of the following [16]:

1. A clear decision must be made about the problem or effect to be addressed.
2. List the hypothetical factors that are apparently applicable to the problem or effect.

		Hypotheses		
Significant Evidence		α *Most Likely*	β *Invalid Hypothesis*	γ *Least Likely*
	1	Consistent	Inconsistent	Consistent
	2	Inconsistent	Inconsistent	Consistent
	3	Consistent	Inconsistent	Inconsistent
	4	Consistent	Inconsistent	Inconsistent
Not Useful Evidence	5	Inconsistent	Inconsistent	Inconsistent

Figure 8.26. Hypothesis Testing Grid
Source: Morgan D. Jones, "Thinkers Toolkit." www.thinkerstoolkit.com, used with permission of the author

3. Construct a matrix with hypotheses as headers to the columns and available evidence as labels for the rows.
4. List the significant evidence that impacts the problem in the row headers.
   a. Include factors that are missing that should be present.
5. Working row-wise across the matrix, test the evidence for consistency with each hypothesis, one item of evidence at a time, labeling each square as being either consistent or inconsistent with the evidence at hand.
6. Refine the matrix.
   a. Are there other hypotheses that might need to be considered that were not put forth previously?
   b. Is there other significant evidence that might be needed?
7. Eliminate unnecessary evidence.
   a. Delete evidence that is consistent with all of the hypotheses because it has no diagnostic value.
   b. Similarly delete all hypotheses that are inconsistent with all of the evidence because they do not have relevance to the problem or effect.
8. Rank the remaining hypotheses by the weakness of inconsistency of the evidence.
   a. The hypothesis with the largest number of consistent hypothesis-evidence (or smallest number of inconsistent) pairs is the most likely hypothesis, in this case hypothesis α.
   b. It may be that there is no clear ranking, which may highlight the need for more data or different evidence regarding the problem.
9. Perform a “reality check” to be sure that the analysis is yielding real-world results.

While this may seem an ornate method of analysis, it is used in the investigation of aircraft accidents and crime scenes (and figures heavily in the base plots of a great deal of crime fiction). It has the advantage of being able to sift through a situation where a large number of conflicting opinions exist, and where hard decisions must be made with incomplete data.

ISO 9000 Series Standards, ISO 22000, and Six-Sigma Processes

The ongoing continuation of the *culture of quality* has brought forth several enduring process types that are incorporated widely in many types of operations. As with many well-publicized trends in management and corporate culture, the results have varied from astonishing improvements in product quality systems to bewildering paper exercises that wind up costing a great deal and returning little effect.

ISO 9000 series quality management standards began in 1987 as several distinct categories of standards, the ISO9001, 9002, and 9003 (and the European equivalent, EN 29000 series) standards, which covered several overlapping sets of activities, were created from the British BS 5750 quality system that was developed for the munitions industry during World War II [17]. These three distinct ISO standards were created for complete design through installation and service operations, manufacturing-only operations, and final inspection and test operations respectively. The confusion that this array of standards caused has been reduced somewhat after all of the standards were rewritten into the ISO 9001:2000 document, which was further revised in 2008. Additionally, ISO 22000 is an implementation of the ISO 9001 concept specifically adapted for food safety management systems.

The elements that make up ISO 9000 certification include:

- An effective quality system.
- Valid measurements and properly calibrated test equipment.

- Appropriate statistical techniques.
- A method for identifying and tracking products, including adequate record-keeping.
- An adequate process for handling, storing, packaging, and delivering products.
- Adequate processes for inspecting and testing as well as for dealing with non-conforming items.
- An internal audit system, including concrete evidence of compliance.
- Adequate training and experience among employees.

Although there is a wealth of information about the ISO 9000 systems, the essence of it is that the culture of quality must not only be created, but must be documented and improved on an ongoing basis. All processes, whether managerial, design, production, or service-oriented, are subject to examination and documentation as are processes for dealing with non-conforming goods and services. ISO 9000 certification is not done by the ISO organization but by private agencies, many of which work on a sliding scale based on company size.

Six Sigma

Six Sigma quality management practices are a formalization of the work of basic quality management advocated by Juran and others, and has been the subject of a significant amount of criticism for creating a huge infrastructures and bureaucracies that inhibit creativity and speed of implementation. In its initial form, Six Sigma was a tool developed by the Motorola Corporation in 1981 to improve the quality of its electronics parts and assemblies to create a defect rate of less than 3.4 defects per million opportunities (DPMO) where "opportunities" may represent physical products, consumer contacts, or procedural operations [18]. Motorola credits the process for more than $17 billion in savings, but the process has been subject to some criticism, not the least by Joseph Juran who considered it a ". . . basic version of quality improvement" [19]. Whether the quality improvement effort fits neatly into one of the pre-existing frameworks or is invented for an ad hoc process, the basic steps should go back to Shewhart's cycle of "Plan, Do, Check, Act" – a continuous cycle of measurement, evaluation, implementation, and reassessment that leads to a continuous improvement of the products and processes in any particular operation and does not require an overburden of bureaucracy or jargon.

Ergonomics

While some segments of the packaging and food production industry, such as high-volume beer production systems, have come to epitomize automated manufacturing systems, food production and packaging is still quite often a labor-intensive process that requires an understanding of the effects of the manufacturing environment on the employees.

Ergonomics – properly the study of human motion that is usually applied to the design of objects and devices – has also been used to define the area of industrial design that accommodates the human worker. Many of the common changes that people may be familiar with, such as monitor stands and ergonomic keyboards, have been developed as a result of studies done by the National Institute of Occupational Health and Safety (NIOSH). As data processing became a more commonplace mode of work, and particularly in the 1970s and 1980s, when a large amount of data entry was still being done by hand, there was a rise in the number of workplace injuries and chronic conditions – most often, eyestrain and carpal tunnel syndrome – related to simple factors such as the placement of monitor height and keyboard design.

Taken further, industries such as the meat processing industry that relies on a great deal of hand-work in unfavorable conditions (carcass processing in refrigerated facilities) have benefitted from changes in workflow brought on by NIOSH studies. Several other case studies will be considered here to illustrate both the approach that was undertaken to diagnose and make changes, and how those changes were presented in a financially favorable light.

Methods of Ergonomic Analysis

Most often, ergonomic analysis and changes are thought to be an involved process that requires a great deal of mechanical analysis, when often a bit of commonsense – or a few conversations with people doing the actual work – will suffice. Simple calculators are available to understand the potential for repetitive-motion injury as a function of simple parameters that can readily be measured, and to recommend Recommended Weight Limits (RWL) for particular operation, as shown in Figures 8.27 and 8.28 using the NIOSH Lifting Equation shown in Table 8.4 [20, 21].

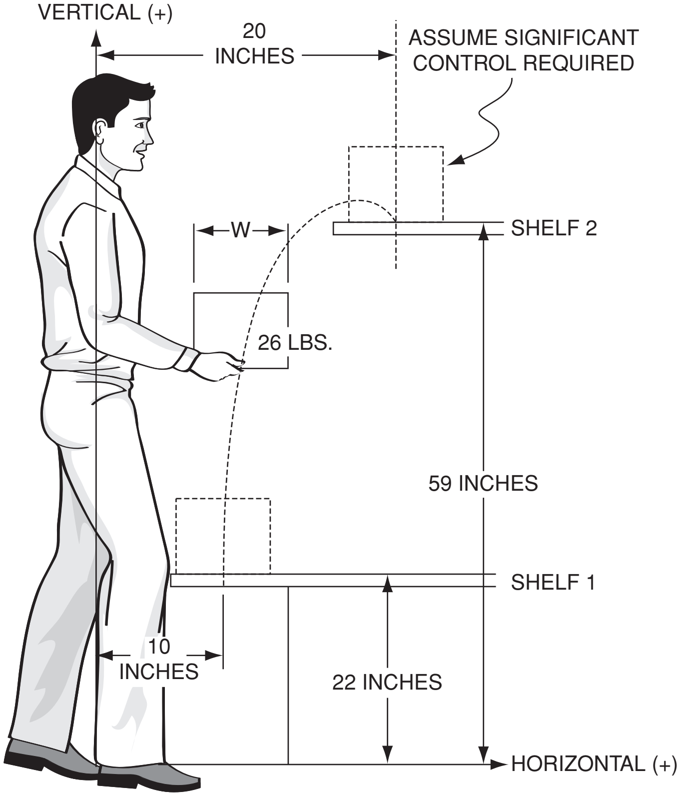
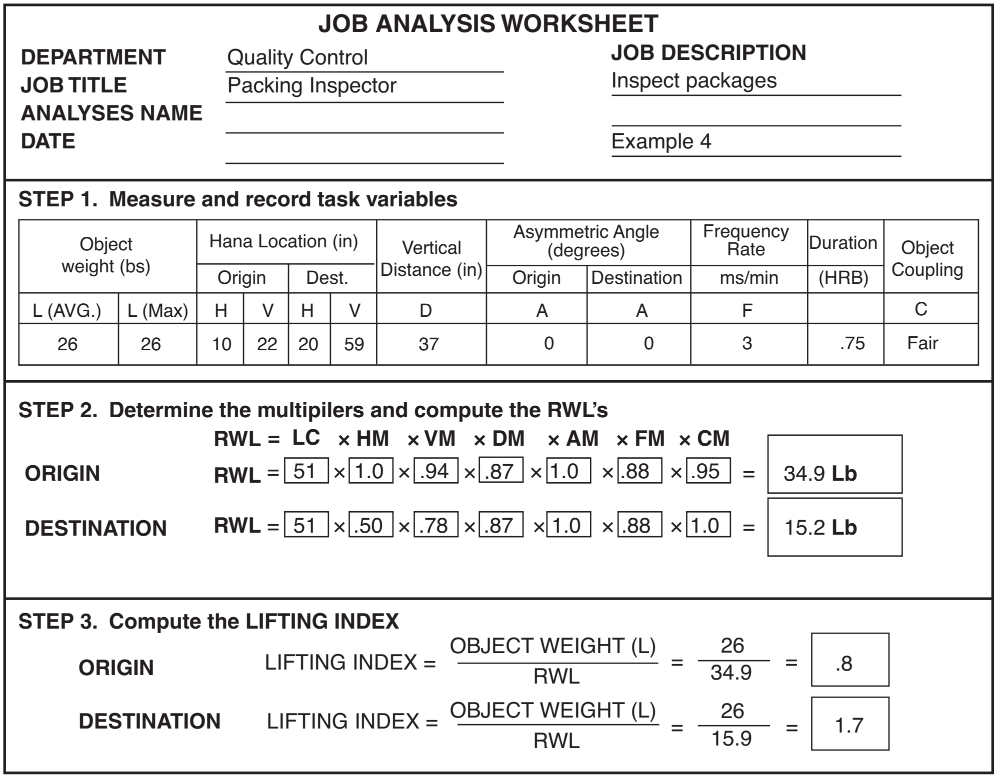


Figure 8.27. NIOSH Lifting Calculation for Package Instpection
Source: Centers for Disease Control and Prevention, National Institutes for Occupational Safety and Health



JOB ANALYSIS WORKSHEET

DEPARTMENT Quality Control
JOB TITLE Packing Inspector
ANALYSES NAME
DATE

JOB DESCRIPTION
Inspect packages

Example 4

STEP 1. Measure and record task variables

Object weight (bs)		Hana Location (in)				Vertical Distance (in)	Asymmetric Angle (degrees)		Frequency Rate	Duration	Object Coupling
		Origin		Dest.			Origin	Destination	ms/min	(HRB)	
L (AVG.)	L (Max)	H	V	H	V	D	A	A	F		C
26	26	10	22	20	59	37	0	0	3	.75	Fair

STEP 2. Determine the multipilers and compute the RWL's

RWL = LC × HM × VM × DM × AM × FM × CM

ORIGIN **RWL** = 51 × 1.0 × .94 × .87 × 1.0 × .88 × .95 = 34.9 **Lb**

DESTINATION **RWL** = 51 × .50 × .78 × .87 × 1.0 × .88 × 1.0 = 15.2 **Lb**

STEP 3. Compute the LIFTING INDEX

ORIGIN LIFTING INDEX = $\frac{\text{OBJECT WEIGHT (L)}}{\text{RWL}} = \frac{26}{34.9} =$ .8

DESTINATION LIFTING INDEX = $\frac{\text{OBJECT WEIGHT (L)}}{\text{RWL}} = \frac{26}{15.9} =$ 1.7

Figure 8.28. NIOSH Lifting Calculation Worksheet
Source: Centers for Disease Control and Prevention, National Institutes for Occupational Safety and Health

For more involved processes, more observation and analysis may be necessary to remediate the problem, but the cost reduction and potential process improvement are often a large multiple of the initial investment. As previously discussed, the analysis of problems occurring in complete production systems can be a multistep process, requiring an understanding of all contributors to the processes' operation. Once the problems have been highlighted, one can concentrate on the most urgent hazards in order of severity. Fairly often, the changes involved may be the sort that requires small changes or modifications that seem all too obvious once discovered, and it may be more effective to spend development time to reduce noise levels and provide proper lighting

Table 8.4. NIOSH Lifting Equation Calculation

RWL = LC x HM x VM x DM x AM x FM x CM

LC: Load Constant = 51 lb (23 kg)
HM: Horizontal Multiplier
VM: Vertical Multiplier
DM: Distance Multiplier
AM: Asymmetric Multiplier
FM: Frequency Multiplier
CM: Coupling Multiplier

than to require workers to wear hearing protection and to deal with operator errors, cleaning, and maintenance problems that are exacerbated by the lack of lighting and the difficulty of accessing equipment.

Because a great deal of the packaging industry relies to some extent on hand labor, if only to move materials into and out of processing operation, or to access machine changes or clear jams, and the food industry often relies on manual labor to assemble dinners or fill large containers, ergonomics is both an item of concern and a potential benefit for production facilities. For food processing operations that may be substantially altered from product to product, ergonomic improvements can be somewhat more difficult, but it is often possible to couple ergonomic standards to particular sub-operations that then can be reassembled as needed, paying attention to the intermediate links (table heights, for instance) that occur between them.

Example: Frozen-Food Distributor

A frozen-food distributor was incurring large injury rates from WMSD and other injuries in its facilities; through analysis of its operations, it discovered that many workers were suffering back injuries resulting from the repeated lifting of heavy institutional packages of frozen foods. Additionally, there was a high rate of back and shoulder injury associated with moving materials on pallet jacks (manual forklifts that lift a palletload of product just off the floor and can be moved manually), and other injuries associated with slipping in the cold environment.

After analyzing all shifts in the operation, both for types of injury occurrence and location and operation that produced them, several important items were discovered and inexpensively remedied:

- Institutional package sizes were reduced. This allowed workers to load smaller increments per lift, increasing loading time slightly but substantially reducing back strain during the process.
- Non-skid shoes were provided for the employees. This simple change reduced the number of slip-and-fall accidents remarkably at little cost.
- Pallet jacks with brakes replaced the existing ones that had to be stopped by brute force. The brake assemblies are a relatively inexpensive option and are usually operated by raising the pallet jack handle to the upright position. This change allowed pallets of material in motion to be stopped without additional force being applied by the operator.

Some of the secondary effects of ergonomic improvements are less likely to be immediately reflected in production quotas or quality valuations. Short-term health claims may be shown to be much less prevalent, but the longer-term effect on employee turnover or marginal customer satisfaction will be much more difficult to correlate with changes made in workflow layout.

Generally, the process flow for ergonomic evaluation in production facilities can be assisted by workplace claims, but a thorough evaluation should be made of the workflow and the ergonomics of particular tasks, as well as soliciting the cooperation of the people who actually do the work because they will know the task most intimately.

Remedies for most workplace ergonomic changes include simple steps that can often be fabricated in-house, or can be purchased. These include steps such as:

Movement Assistance

When moving materials from one place to another, the inertia or weight of the items can cause repetitive-motion injuries during handling. Mass movement assistance can range from something as simple as a low-friction tabletop to more complex lifting and movement fixtures or automated moving devices.

In many cases, such as the reduced package sizes mentioned in the example, the movement can be assisted by minor changes in items such as the way materials are delivered into the system. The best examples of this come from industries such as the automobile assembly where engine/transmission units are fitted with attachments that allow them to be moved into car bodies with the use of lifting and movement fixtures. This method can be used by specifying the form factor of the materials to be delivered into the packaging line, whether fitted with a lifting tab, provided with a slip sheet that allows easier feeding into a magazine, or other changes.

Positional Fixtures and Work Height Adjustment

If the task requires that workers reach into machinery, or need to extend significantly into the work task, simple supports such as elbow rests may allow a great deal of task improvement with little investment. Obviously, these should not circumvent safety fixtures. Employee seating or standing workstations should similarly be constructed to allow ease of movement and optimal access to the workpieces.

Very often, when materials or workpieces have to be moved from one station to another, the workers must lift them and place them at a different height. Adjustable height tables and work fixtures can assist in proper positioning. Similarly, the height of many workplaces is simply determined by the construction of the machinery or devices that must be used, with an adjustable chair added to accommodate individual worker dimensions. Adjustable tables, jigs, and fixtures can reduce worker fatigue and increase the accuracy of work.

Proper Lighting

Inspection tasks in particular require a good lighting source for most operations. Very often, inspection stations simply assume that a good bright light source will be sufficient for accurate vision of particular defect types, when in fact it may take a specific type of light (diffuse, specular, or even coherent) for ease of visualization of the defects that might be present.

Even non-inspection tasks can require lighting adjustments – newer spot-lighting systems using bright, low-power LED systems can assist in providing an unobtrusive visual aid to material flow or product assembly.

Environmental Adjustment

Working frozen-food facilities, around ovens, and high-temperature processing operations all require protective gear, but small changes in some environmental protection can have a profound effect on production. For example, improving insulating gloves' dexterity may reduce the number of dropped products in a frozen-food handling operation.

Task Rotation

Particularly strenuous (or tedious) tasks can be rotated within a workday so that no single worker will be exposed to high levels of a particular workplace. This typically has the added benefit of reducing boredom with a particular task and may be used to cross-train employees.

Table 8.5. Estimation of Costs and Sales Equivalent of Workplace Injuries

Estimation of Occupational Injuries and Related Costs as Sales (5% margin)					
Injury Type	National Average Direct Cost[1]* (US$)	OSHA Multiplier	Indirect Costs[2] (US$)	Total Cost Per Incident (US$)	Additional Sales Needed to Cover Incident[3] (US$)
Carpal Tunnel	24,000	1.1	26,400	50,400	**1,008,000**
Tendonitis	15,000	1.1	16,500	31,500	**6,300,000**
All Sprains/Strains	23,000	1.1	25,300	48,300	**966,000**

[1] Workers Compensation = medical treatment and wage indemnification.

[2] Indirect Costs = Administrative costs, lost time, overtime to cover missing employee, and related expenses.

[3] Additional Sales Needed to Cover Incident = Total Cost Per Incident/5% Profit Margin.

*Approximate

Sales Multiplier Method

The advantage of considering the worker in this instance has been shown to have several effects, the most profound of which is to generate the equivalent of a large jump in sales volume. When the economic effects of the internal savings resulting from ergonomic accommodations are translated through sales margins, the result can be the equivalent of an enormous increase in sales (or the cash-flow equivalent thereof). This type of reasoning has been used to successfully argue for changes that have other desired effects as well such as reduced downtime, reduced worker turnover, increased product quality, and fewer health claims [22].

As shown in Table 8.5, the effective equivalent of savings because of ergonomic changes has a huge multiplier effect, particularly given the extended health care costs of some of the injuries and disabilities involved. This can be a powerful argument to use with many types of process improvements, considering that ergonomic improvements, like many internal changes, are often seen purely as a cost item. The equivalent of increased sales has a deep resonance with management's concern for the bottom line and can make a powerful case for improvements.

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Chapter 9

Transportation, Distribution, and Product Damage

In a society that depends on the continuous availability of consumer goods from around the world, transportation and distribution are a critical part of the manufacturing and packaging scenario, and the ability of a packaging system to protect products during transit and distribution is a fundamental part of package engineering. To better understand the factors that come into play with distribution, it is useful to consider the nature of the distribution system, its modes and vehicles, and the demands that distribution can place on packaged products.

The transportation of goods to market can take every form imaginable, from being carried atop a person's head to being carried into space in a launch vehicle. For the purposes of this text, we will consider the most common mass-distribution modes, although it should be remembered that the final steps in a transportation chain might be the most damaging. Food products that have been carefully refrigerated all the way to the store may be left in a passenger car's trunk in the sun for hours before being unloaded at home; appliances that have been carefully packaged and shipped may be carried by pack animal; and certainly anything traveling with children will take a beating.

Transportation and distribution systems establish themselves as a complex function of infrastructure, distance, and diversity, and often do not do so in the most energy- or time-efficient way. There may be a great difference between the distribution systems used to deliver supplies to remote areas of the Scandinavian coast, Beijing, and Omaha, although they all may use very similar vehicles. Because of the efficiencies of cargo vehicles and their infrastructure, nearly all mass distribution of merchandise is predominantly dependent on a combination of the four basic modes of transportation: truck, rail, ship, and aircraft (pipelines will not be considered). Each of these modes and their infrastructure will be described in general terms, along with some of the intermodal facilities commonly used to handle materials. The dynamic environment that each creates will be discussed subsequently in this chapter.

Energy Efficiency

With fuel supplies increasing in price and subject to both natural and man-made instabilities, the fuel efficiency of transportation, although not always accurately reflected in tariff rates and costs, becomes a large factor when deciding transportation type. Table 9.1 illustrates some of the relative efficiencies of different modes of mechanized transportation.

Food and Package Engineering, First Edition. Scott A. Morris.

Table 9.1. Fuel Consumption Comparison of Different Freight Modes

Vehicle Type	Ton-Mile Per Gallon	Kg-Km per Liter
747-400F Cargo Aircraft [1]	24.8	9,380
"Semi-Trailer" Cargo Truck [2]	155	58,640
Space Shuttle "Atlantis" [3]	187.5 + 46.88 ton-mile/lb Solid Fuel	70,930 + 92.51 tonne-km/kg Solid Fuel*
Railroad (US) [2]	413	156,230
Barge (Inland Towing) [2]	576	223,085
Oceangoing Container Ship "Emma Maersk" [4]	933	352,960

*A "tonne" (metric ton) is 1,000 kg (2,205 lb), whereas a US "ton" is 2,000 lb (907 kg).

Truck Transportation

Truck transportation is probably the most ubiquitous mode of motorized conveyance for bulk items. Although it is much less energy-efficient than rail or ship freight, it has the advantage of being able to operate over many types of undeveloped road systems and to deliver relatively small quantities of various items on a timely basis to individual locations without freight terminals. Trucks are typically constructed as some variety of a "Semi", a semi-attached articulated coupling trailer pulled by a motorized cab. In developing countries, this may be scaled back to smaller, single-chassis trucks, many of which can operate on unimproved roads and even open desert. The implementation of intermodal transport containers has provided the capacity for trucks to be the flexible beginning and final delivery component in a freight system that can also use rail and water transport.

Rail Transportation

Rail transport is the most energy-efficient means of land transportation, and makes non-stop trips across continents as a matter of routine operation. Because access to rail systems is not usually as extensive as access to roads, rail systems are often used for large shipments, unitized shipments, and for shipments of vehicles, commodities, and fuels, although due to the limited rail corridors in many regions, scheduling and conflicts with scheduled passenger service can present a problem. With the implementation of multimodal containers, rail transport has shifted from traditional freight yards to intermodal facilities where containers are offloaded from rail cars to semi-tractor transport for local delivery without direct handling of the products.

Water Transport

Oceangoing vessels are used for energy-efficient coastal and intercontinental shipment of containerized freight, bulk commodities, and fuels and vehicles. Although service is slow, as many freight vessels operate at optimal hull speeds rather than full rated speed, per-ton freight costs are very low. Access to ports and terminals may be a limiting factor for many water-based shipping operations – seaports are somewhat scarce in Ulan Bator and Laramie, Wyoming – but many distribution routes incorporate water-based shipping in at least part of their distribution plan, and nearly all trans-oceanic shipping is done by water.

Barges, which have played a role in the efficient transportation of goods throughout history and particularly at the beginning of the Industrial Revolution, are used in inland and protected waterways, although oceangoing barges may be used for coastal work and specialty products. Container barges, which are handled with standard tug-towing equipment, can be used in shallow-draft waterways, although their capacity is a good deal less than that of a dedicated container ship. These most often operate on rivers and canals, although many countries with well-developed road systems may use trucks for speed of delivery and leave barge and river transport for bulk materials and fuels.

Air Shipment

Air shipment is the fastest, most complex, most costly, and least energy-efficient means of conveyance, but it offers the advantage of very fast movement of goods. It is particularly advantageous for very perishable items such as seafood and fresh flowers and for time-critical ones such as military equipment, famine relief, and financial documents. Additionally, air shipment offers the possibility of delivery in areas inaccessible by other means such as remote, mountainous, polar, or – if one includes launch vehicles – even extraterrestrial regions.

Air shipment is not the most effective means of conveying everyday, low-value items where other means are available because of the high costs involved, but express delivery operations rely on air fleets ranging from small "feeder" propeller aircraft to very large international cargo aircraft based on the Boeing 747, Airbus 380, or even the sole Antonov AN-225. Specialized manufacturers, especially those in the aerospace industry, may also rely on specially designed aircraft to transport equipment and sub-assemblies from other operations for final assembly at their main facilities.

Mixed Transportation Modes

One of the critical problems in cargo handling and distribution occurs when goods require multimodal transportation. Moving goods from the factory to the consumer may require several changes between truck, rail, and water transport. The solution to this is the use of intermodal transport containers of various types described in the distribution packaging section. These are typically interoperable between rail, truck, and ship platforms with a minimum of handling and represent a substantial leap in efficiency and security over the traditional handling of individual cargo items.

With the rapid increase in global shipments, the limiting factors on shipments are becoming increasingly those related to transfer infrastructure, with ports, rail facilities, and roads continuously being pushed to expand their capacity. Intermodal facilities, particularly those combining rail, truck, and ship loading, are often critical bottlenecks, with the attendant congestion and pollution causing secondary problems that limit economic activity. Because of this, industries may locate sites (or relocate old ones) based on transportation availability as much as any other single factor, considering that getting raw materials in and finished goods out is critical to large-scale operation.

Distribution and Warehousing

In the food distribution industry, the extremely changeable and flexible nature of the retail food market, coupled with demands for lower costs and high response, has produced an extremely efficient and data-driven industry that has all but eliminated warehouses and backroom inventory in favor of just-in-time delivery and high-speed computer-driven ordering systems. This system uses information garnered from Point of Sale (POS) information and other data-driven systems to tailor ordering and distribution into a nearly continuous stream of goods from raw materials through manufacturing and distribution to the final consumer. In order to understand the motivation for the types of changes and infrastructure necessary to create this type of system, an understanding of the basics of inventory and supply chain management is useful.

Distribution and Inventory Economics

In very simple terms, management of inventory and ordering structures demands that a balance be struck between the costs of ordering materials, the costs of keeping inventory on hand (so-called *carrying costs*), and the lost sales associated with *not* having a particular item on hand as discussed in Chapter 8. As anyone who has done much grocery shopping will acknowledge, stores seem to prefer to err on the side of being occasionally out of stock on a particular item rather than keep excess inventory on hand. The reality is that stores must manage their supply chain very carefully because customers can take their entire purchase elsewhere if too many favorite items are out of stock, and must maintain supply of fast-selling items as well as those that may sit on the shelf for a longer period.

This process has been automated, and in some systems can incorporate information about delivery times and availability to allow orders to be sent at the correct time, such that the new inventory will be put out for sale at the same time that the last of the old inventory is being sold. These types of logistics and materials management practices stem from work done in the manufacturing industry that sought to wean manufacturing away from older make-and-warehouse practices and into just-in-time manufacturing and supply chain management that were discussed in Chapter 8.

The Information Cycle

Because the ordering and distribution system is information-driven, the information cycle, first introduced in Chapter 1, can be a useful map of how orders are generated and handled. For this, a grocery-retail model is used, but the general principles apply to any sort of manufacturing, retail, or general distribution system.

When inventory is removed, usually through sale to a customer, the item is either checked out manually (a practice that is becoming thankfully rare) or scanned out of inventory using a bar-code reader or RFID system. This information is transmitted to an inventory computer, which then subtracts that amount from the inventory on hand. When inventory on the shelf gets sufficiently low, an order is triggered to suppliers. This process is staged backward at several levels, as suppliers and then manufacturers in turn manage their own inventory and shipments. The final result of this system is that direct consumer demand drives both manufacturing and distribution on a nearly continuous basis, providing inventory “on the fly” and reducing the amount of inventory accumulating at any given point in the system to an absolute minimum. Warehouses have been replaced by *cross-docking* operations, where inventories of a single product from a manufacturer arrive by the truckload at one loading dock, are unloaded, sorted, and then redistributed into *break bulk* – mixed product truckloads – at other loading docks across the facility (thus, the term), which then leave immediately to restock retail operations. In effect, the inventory seldom stops moving from the moment it leaves the producer until it reaches the retail shelf. The exception for this continuous-flow model is for seasonal items such as fruit and vegetables, as well as holiday items that may be processed at a particular time and held for later redistribution.

Food retail businesses typically operate at a very low profit margin – often 1–2% – but have an enormous turnover of inventory. Grocery stores average 19 complete inventory turnovers in the course of a year, and often a great deal more for individual perishable items [5]. The economic implications of more efficient distribution and transportation are that large retail operations are able to reduce inventory costs by being able to sell inventory extremely quickly. Because many distributors and manufacturers offer a discount for those customers who pay for their orders before a specified period of time (for example, a "2% 10 net 30" discount reduces the final bill by 2% if it is paid within 10 days of receipt, and is due in full after 30 days), the inventory is often sold before the retail operation is required to pay for it. This provides the interesting paradox of a retail operation that sells inventory at or below its billed cost and still makes a profit because of the billing discount. This would not be possible in a slow or inefficient distribution system, and places small operations at an extreme price disadvantage. Additionally, the advent of global discount chains has changed the manufacturing-retail relationship, as manufacturers may be required to produce items such as clothing and electronics at a price point for that particular retailer and its distribution system. Beyond this, several of the largest retailers have begun to arrange for "depot" operations, where the manufacturers themselves own the inventory until it is sold, effectively transferring any inventory-carrying cost entirely away from the retailer and back to the manufacturer or wholesaler.

Data from Distribution Systems

Because data is increasingly inexpensive to gather using automatic scanning operations, information about secondary phenomena in the distribution system can be gleaned if there is a large enough statistical base to work from, and knowledgeable people and computing resources are available to extract meaningful information from the data. Information about particularly hazardous transportation routes can be taken from shipping records and return information, and delays in delivery can be correlated to both the carriers contracted for delivery as well as geographic and meteorological data (perhaps giving specific information about how much longer delivery times will be in remote winter locations).

Advanced algorithms have begun to be implemented into the manufacturing and transportation industries that manage materials sources, manufacturing locations, and delivery systems and even utility sources in order to reduce costs and risk to a minimum. These may be based on "brute force" analysis of the manufacturing system, or on advanced concepts such as genetic algorithms, neural networks, holonic systems, and swarm intelligence that have been pioneered for other fields, such as software development [6, 7].

Integration of distribution and sales information and correlation with credit card information, customer "Rewards Cards," product registration cards, and user surveys allow retail operations to pinpoint information about particular customers' buying habits, locations, and timing. When coupled with optimal cost data, delivery information, and alternatives and advertising promotions, a comprehensive and fairly adaptable system of retail management has emerged that allows fast and responsive distribution of goods. Deeper data mining into customers' habits for both commercial and governmental ends have been a subject of debate and litigation as data storage and computational costs have dropped to the point where whole populations may be scanned for particular attributes or behaviors [8].

The Role of Packaging in Logistics and Inventory Management

The old image of distribution packaging has always been stacks of boxes and barrels sitting in a dusty warehouse, when in fact most inventories do not remain in one place any longer than is absolutely necessary once they leave the manufacturer. In this scenario, packaging becomes, in the most literal sense, the spokesman for the product in automated inventory and distribution systems. The package now carries machine-readable data that serves as both inventory control and distribution routing information, principally through bar coding, although there is great pressure to make the transition to RFID information systems that do not require access to the individual product in a bulk shipment. The shipping container or bulk package may also contain shipping or routing information in addition to standard information about contents and production data.

Logistics systems may use this information to properly route and handle products that require special consideration such as flammable and perishable goods. It is also possible to attach devices that will measure and record temperature fluctuations, shock and vibration, and other environmental inputs to assist in the effective and safe distribution of goods.

Data Tagging and Data Acquisition Methods

Bar code formats are simple, standardized optical patterns that may be stripes, checkered patterns, or even roundels that allow an optical scanner to interpret the pattern to decode the tags' data. These are usually incorporated into the label design on consumer packages and may be imprinted on distribution container tags, although at larger scales of distribution, they may be applied via inkjet printer or adhesive tag to the outside of the shipping container. The specifics of bar code and RFID data systems are more fully described in Chapter 4, but this chapter will be more concerned with the larger-scale applications of the data contained in the bar codes and their effect on distribution systems and manufacturing flow. Similarly, passive RFID tags are machine-readable components that are energized by the electromagnetic field of a reader device and return digital data via a radio link. Unlike optical systems, the data capacity of RFID systems is not constrained by size and optical resolution, although cost barriers are the current limitation. RFID systems for specialized use, typically self-powered "active" RFID systems, can support enormous quantities of data and may be linked to powered onboard systems for temperature, shock and vibration, or other data.

Data is collected from most optical code systems via a monochromatic laser scanner, similar to those used in supermarkets. Railroad cars historically used a large, multicolored coding system for traffic management, although this was only marginally successful due to dirt and maintenance problems, and has been replaced with RF-based AEI (Automatic Equipment Identification) systems. RFID data is transferred from the package or device via a reader that incorporates a transmitting antenna to power the RFID device and a receiver to receive and translate the returned signal. Restrictions on allowable power for readers, combined with the tendency of many packaged goods to damp out radio signals buried in the interior of a shipment of lossy materials, have proven to be a frustrating limitation for many RFID systems and, when combined with relatively high tag costs, have slowed the large-scale implementation of RFID inventorying and distribution systems for small consumer items, although larger-scale assembly operations such as automobile plants use them to assist in adaptive assembly automation and painting-line sequencing.

Hybrid systems that reference tag data to larger files stored in devices or online databases for customer use are often used as a means for overcoming data storage limits, and have opened the possibility of other applications such as “intelligent” home appliances, although these may create accessibility or security issues for more remote or sensitive applications.

Limitations on Data

Although the previously described linked systems have no realistic limit to the amount of data linked to a particular package, discrete systems will have several limitations. Bar code systems have limitations on the surface area available for data encoding. Although some very data-dense printing methods and coding schemes have been developed, practical limits on printing accuracy and scanner resolution limit data tags to several kilobytes of on-board information. Similarly, memory capacity of current RFID tags used on consumer goods and luggage is less than 1 kb of data, although larger active units for military and equipment use may have extensive data storage capacity.

Distribution Packaging

Distribution packaging is distinct from consumer packaging in that in most instances, distribution packaging is used for the large-scale shipment of materials or components to be used in the manufacture of other products. These are typically shipped in multiple quantities and are seldom labeled for use by the consumer. Some notable exceptions to this are the bulk distribution of materials such as gasoline, landscaping materials, or even water in remote areas. “Large-scale” may be a relative term as well, considering the distribution packaging for high-value items such as pharmaceuticals or electronics, which are physically small and go against the notion of a huge bulk shipping container filled with product. Most often, the distribution of goods such as food ingredients and machine parts from suppliers to manufacturers involves the most economically advantageous quantity to be shipped, whether it is a tanker truck full of molten chocolate or a single case of high-value pharmaceutical ingredients. This, in turn, depends on the production needs of the customer.

Distribution packaging for food items depends on the food material itself, the order quantity, and its intended use. Food items for use in small restaurants or delicatessens are packaged in substantially different systems than bulk ingredients intended for use in large food-manufacturing operations. Bulk transport of food ingredients in the most economically efficient manner may involve large tanker vehicles or intermediate bulk containers. If these are to be used, the distribution system must be able to load, transport, receive, and use the product properly. Sanitation, temperature control, and specialized loading and unloading systems may be required to make the best use of large-scale shipping, but the savings in manpower and handling efficiency can be enormous. The dairy industry is the most pervasive example of this, with temperature- and time-controlled shipment and clean transfer and handling facilities from the dairy to the consumer.

Containerized Transport

In 1956 the container ship *Ideal-X*, a reinforced military surplus oil tanker, sailed from Newark, New Jersey to Houston, Texas, with ordinary semi-truck trailers chained to the deck. In Houston, the loaded trailers were re-attached to truck cabs and driven to their final destinations without any other handling. This elimination of the manual labor of cargo loading and unloading reduced the cargo loading cost from US$5.83 per ton to less than US$0.16 a ton, and began the revolution away from cargo nets and toward shipping container standardization 9. The result of this is the current use of Intermodal Shipping Containers, which, although no longer made of surplus truck trailers, can be swapped from rail to air to truck transport with simple mechanized handling equipment. Intermodal shipping containers are large steel containers that can be loaded and sealed, then shipped by oceangoing vessel, truck, or train (and, in rare cases, by air) without opening the container and handling the contents. Intermodal shipping containers are typically specified in *twenty-foot equivalent units* (TEU), derived from the original US military shipping container that was ten feet long. TEU are used to express the relative number of variously sized containers being conveyed, based on the equivalent length of a 20-feet-long container. A 40-feet-long container, therefore, is equivalent to two TEU, and large-scale shipping operations are usually measured in numbers of TEU that are shipped, with world container ports expected to handle in excess of a half-billion total TEU in 2009. This has resulted in lower shipping costs as well as a substantial reduction in theft and damage during the shipping operation, and has caused the redesign of the world's cargo shipping fleet into container ships, including huge "post-Panamax" carriers that can carry 11,000 TEU in shipping containers lashed to the decks and stowed in the hold areas but are too wide or long (greater than 294 meters in length, 32 meters in width, and 12 meters in tropical freshwater [TFW] draft) to transit the Panama Canal's older locks, and thus designated to travel the distance around the Cape Horn. A third, wider set of locks is scheduled to go into service in 2014, creating a "new Panamax" size limit of 366 meters LOA, 49 meters in beam, and 15.2 meters in tropical freshwater (TFW) draft to partially alleviate the problem [10, 11]. When back on land, one or several containers may be loaded onto flatbed rail cars, and over-the-road trucks with specialized trailers can carry cargo containers directly from the port to the final customer without ever having to directly handle the cargo. Thus, the increasingly integrated container shipping system allows intercontinental shipping using trucks, rail, and oceangoing vessel to efficiently move products from nearby location to customers everywhere.

Unitized Air Shipment

Aircraft shipping often uses smaller cargo containers called *Unit Load Devices* (ULD) that can be either an air-freight pallet or a container configured to the specific aircraft's fuselage design and freight deck. They are necessarily lightweight in design and do not offer the same degree of protection to the cargo as an intermodal container because they are always carried inside the aircraft, but carry individual freight manifests and tracking information [12]. These offer the same speed of loading and unloading that make the intermodal containers advantageous and further accelerate the pace of rapid air-freight operations. ULDs are loaded into the aircraft fuselage and rolled back along the cargo deck for air transport. They are usually not intended for intermodal use but can be shipped by truck flatbed into sorting facilities and are most often used by express parcel services.

Fluid Tanks

Fluid tanks other than the common tank-trailer are available for large-scale, secure shipment of fluid materials ranging from chemicals to wine. Two methods predominate for this type of distribution shipping: tank containers and flexi-tanks. The former is a discrete tank that is unitized to fit within a space frame that fits intermodal standards, and can be handled by the same equipment. These can be constructed to handle sterile and aseptically processed, hazardous, or pressurized materials, and can be constructed to safely handle a variety of fluid densities. Flexitanks are standard intermodal shipping containers that have been fitted with a flexible liner bag allowing the full volume to be filled with liquid. This method has the advantage of a lower initial construction cost, but great care must be taken, particularly with high-density liquids, that the hydrostatic pressure of the fluid does not distort the sidewalls of the container and that fluid surge does not allow the container to become unstable.

Intermediate Bulk Containers (IBC)

These are large containers that can be used to store and ship ingredients, and can be constructed in many variations to suit the product and the nature of the distribution system. Most often these are sized to the approximate footprint of a standard shipping pallet, although larger ones for specialized loads such as live fish fingerlings may be the width of the transport vehicle. These containers nearly always require mechanical handling assistance, most often a fork lift, overhead hoist, or similar device. Rare exceptions exist that have been built for aircraft assemblies and may be fitted with casters to allow manual movement.

Rigid-wall IBC systems may be constructed of plywood, welded steel wire, molded plastic or corrugated paper, or Coroplast$^{\text{TM}}$, and can be lined to provide a sealed environment to any degree necessary. The latter is important because it allows the container to be used for bulk liquid or semi-liquid ingredient shipping from production facilities in one location to another, including trans-oceanic shipment without contamination. Less stringent conditions permit the shipment of nearly any type of material such as grains, flours, and plastic resins. IBC systems may be designed as returnable, semi-returnable, or one-trip containers, depending on the nature of the product, the distribution system, and the requirements of the customer. Returnable systems may be emptied, with the liners – if present – removed and folded flat for return shipment. Semi-returnable systems may have a recyclable sidewall made of corrugated and a returnable bottom pallet. One-trip containers are made to be recycled or disposed of after a single trip, and may be more lightly designed. Any of these containers can be ordered with specialty fitments to allow product unloading, pumpout, drainage, or other functions as necessary.

Flexible Intermediate Bulk Containers

Flexible Intermediate Bulk Containers are, as their name implies, made of flexible materials, and are designed to be handled from above using sling straps that are an integral part of the container design. These containers are intended for use with dry granular materials ranging from fine pharmaceutical powders to crushed stone and, although they are available in any size necessary, are often sized to be half the width of the shipping vehicle, so that they sit two-across in the truck bed. These can be fabricated of a range of fabrics, liners, and coatings – although polypropylene (PP) with various coatings for static electricity dissipation, UV protection, or food contact predominates – and may have a polyethylene or polypropylene liner. FIBC systems may be designed with filling and emptying spouts in the top and bottom of the bag, as well as a variety of lifting sling arrangements to suit the type of handling systems and bag capacity [13].

Institutional Packaging

Institutional packaging is food packaging that is intended to be used in retail operations, restaurants, commissaries, and cafeterias, and is intended to be manually handled. It is often intended for use in quantities approaching those of consumer packaging, although the unit size and labeling may be optimized for efficient use in the retailer's application rather than retail customer appeal, because it is a package that is not often seen. Restaurants, bakeries, creameries, and other food service operations that cannot use truckload quantities of a particular ingredient will typically use institutional quantities to gain more efficiency in storage and product pricing, and these are often delivered in the distribution packaging that is subsequently described.

An ancillary category that is often neglected in the institutional packaging milieu is the home delivery meal segment. These are subscription or order services that deliver consumer products direct to the home (as opposed to a grocery delivery service that simply delivers regular retail items). These may be produced in non-standard sizes, are often frozen, and may be labeled quite differently than retail containers because they will be designed to encourage repeat purchases rather than identifying them as unique among a host of competitive products on a retail shelf.

Bag-in-Box Packaging

In addition to the usual shipping container and large steel can, many ingredients such as cleaning agents, fruit juice, milk, soft-drink syrups, and toppings for hamburger and pizza operations may use a bag-in-box system, allowing pumped application to speed operations. Bag-in-box packaging is most often a corrugated container fitted with a flexible plastic bag and usually a dispensing or emptying fitment. They are typically lined with a high-barrier liner bag to preserve the contents and because of the flexibility of the container are not well-suited to carbonated beverages. These have almost completely replaced the heavy stainless steel syrup containers that were used in carbonated beverage dispensing and are often part of fast food and self-serve restaurant operations. These are seldom seen at the consumer level with the exception of some cleaning agents, juices, and large wine containers (which suffer from a persistent perception of poor quality). Ankerbräu breweries in Nordlingen, Germany, have produced a 25-liter bag-in-box beer distribution system with a claimed 8-month shelf life, but this relies on re-carbonation of the uncarbonated beer at the time of dispensing [14].

Shipping Sacks

The "burlap bag" has always been synonymous with the shipping of loose materials ranging from citrus fruit to grain, but in the last several decades has largely been replaced with mesh, paper, paper-composite, and plastic shipping sacks for bulk materials ranging from dog food to cement. For applications requiring extreme strength and puncture resistance, bags may be made of woven polyethylene or polypropylene, either alone or in conjunction with other layers for lining and labeling. These are traditionally filled and then sewn shut, although heat-sealing, tapes and adhesives have begun to replace these methods to speed production and aid in consumer utilization. Additionally, handles, spouts, zip seals, or other features may be added as required. Sizes are typically limited by the density of the product, with 40kg bags of cement being near the limit of practical use, and less dense items such as dog food available in 20 kg bags.

Jugs, Drums, and Pails

Jugs, drums, and pails are a common method of supplying small quantities of bulk ingredients such as pastry filling or soy sauce to operations such as bakeries and restaurants. Food ingredients may be hot-filled and then shipped for use in the food service operation, and aseptic liners may be added if necessary. Jugs, which often are blow-molded containers made to lay flat on a shelf with a dispenser feature hanging over the edge, can be used to contain and dispense everything from sauces to detergents.

Pallets

Pallets are flat platforms that provide spacing for mechanical material-handling devices to move intermediate loads of goods while assisting in the stability of the load. Most often, pallets are moved by manual pallet jacks or motorized fork trucks that move across the relatively smooth floor surfaces encountered in modern material handling. It is also possible to use pallets with sling lifts, and roller or belt conveyor systems, although these types of uses are less common. Pallets may be made in a variety of sizes and any number of materials, but wood predominates, particularly for reusable pallets, with plastic and paper pallets gaining ground, particularly for one-way trips and specialized loads that may require custom features on the pallet deck.

Pallet Types

Wooden pallets predominate in the market, as previously mentioned, with nearly a half-billion being produced in the United States every year. Beyond this, wooden pallets may vary a great deal in strength, stiffness, wood type, type of load to be carried, and fasteners used in construction. The two most common types of wooden pallets are stringer and block pallets, which will have either a notched, solid side stringer (with a four-way lift capability) or use simple wood blocks as spacers [15]. They may have solid plywood decking and be constructed of new, recycled, or a combination of materials. Simple softwood pallets may be used once and recycled, with more expensive types of pallets generally requiring a deposit and are intended for reuse, often within a “pallet pool” that handles the returns and re-supply on a for-fee basis.

Because of the FAO International Plant Protection Convention’s International Standard for Phytosanitary Measures (ISPM 15), pallets (and other shipping fixtures such as *dunnage, crating, packing blocks, drums, cases, load boards, pallet collars, and skids*) intended for international shipping must be made of materials that are incapable of spreading invasive species. Wooden pallets, because of their capacity to carry agricultural pests such as the Formosa termite must be heat treated to a core temperature of at least 56°C for 30 minutes, or treated with a chemical fumigant such as Methyl Bromide to achieve this standard, and must display appropriate markings indicating compliance. Fabricated wood products such as plywood, paper, and laminates are typically not considered a harbored insect problem, nor are shavings or sawdust because of their thin cross-section [16]. As one might expect, plastic and metal pallets and materials are exempt until such time as plastic- and metal-eating insects appear.

Plastic pallets represent less than 5% of the total pallet market, and are typically constructed of HDPE, PP, or PVC. These may have a high recycled material content and can be produced in any number of fabrication methods, with the most common being structural foam molding. These are more expensive than wooden pallets but are generally considered cleaner and more durable, with the ability to include complex design features for specialized applications such as shipping automotive sub-assemblies. Industry efforts are underway to produce simple plastic pallet from recycled resin, and recycled plastic “lumber” is being examined in traditional pallet construction methods.

Paper-based pallets, made of molded pulp or corrugated and honeycombed paper, are a smaller portion of the market than plastic pallets. Although generally weaker than other types of pallets, they are well suited to light loads that are subject to high weight-based shipping charges such as air freight. Paper pallets are also easily recycled but are susceptible to both humidity and moisture effects and are typically not durable enough for multiple-trip use.

Metal pallets are typically used in specialty distribution systems that require high strength and the ability to resist a great deal of transit abuse. Because of their high cost and weight, they are typically part of a "captive" pallet system, where pallets are returned within the organization rather than being pooled as wooden pallet loads might be. Although heavy and expensive, they are capable of securing heavy, dangerous, and expensive cargos such as automobile engines and ammunition, and eliminate the risk of disastrous fires that may occur with stockpiles of the other types of pallets.

Slip Sheets

Slip sheets are simple, heavy-duty sheets that allow material-handling equipment to slide thin metal plates (fitted to a standard fork truck) under a unitized load of containers without use of a pallet, saving weight, space, and money. These may be used in conjunction with a *push-pull* device that slides the load on and off the tines more efficiently. These systems are best suited for packaged items such as lightweight consumer goods that are in stabilized loads that do not need any sort of support from the pallet. They are typically less than approximately 12 mm in thickness, are usually made of plastic laminated paper or heavy plastic to reduce friction, and will have lips on the edges of the load where handling access is required.

Shipping Fixtures

Shipping fixtures are a category of shipping device that is distinct from the mass-produced containers, pallets, and boxes that have been previously discussed. These are typically used for very fragile and high-value items that require specific support and protection, such as automobile dashboards and aerospace components that will justify their high price. Most of these are designed and built for a single purpose and may include any number of onboard devices including climate and pressure control, as well as active vibration-damping systems. Simpler variations are used to transport large diesel and jet engines for installation and rebuilding, large building installations such as air conditioning evaporators, and fully assembled boats and aircraft sub-assemblies. In nearly all cases, the shipping fixture is intended for reuse, either after return to the manufacturer or as a service stand for the original component.

Wood Crates and Boxes

Once the iconic container for distribution and long-range shipping, wooden crates and boxes have become cost-prohibitive for most items and somewhat unnecessary for long-distance shipping protection with the advent of the intermodal shipping container. Although still used in consumer applications where a wooden case will add marketing appeal, such as with alcoholic beverages, cosmetics, and occasionally fresh fruit, wooden crates and boxes are currently seldom used in food packaging except as bulk haulers in growing operations. The ISPM-15 restrictions on untreated wood being used for international shipment further limit their use. In most cases, wooden boxes have plywood or chipboard panels (eliminating the infestation concern), and crates are made of lumber slats. These are more often used for large machinery shipments and specialty applications that may not be able to travel in standard distribution methods than for low-value consumer goods.

Integration of Distribution Packaging and Manufacturing

In some cases, products may utilize the packaging as part of the manufacturing system itself. The previously mentioned bulk containers replace bulk tanks and bins in many manufacturing operations, and laptop computers can be assembled using their shipping tray as an assembly jig. The food industry has many such examples, because many canned goods rely on the heat of thermal processing as a cooking step to achieve their final consistency or quality, and frozen meals are also assembled in their final service trays. It is unlikely that computer manufacturers' ability to produce a custom product order for the consumer directly from an online request will trickle into the consumer foods arena, because computers are typically in a fixed-form factor and have relatively few options whereas there are many deli service counters and their equivalents available to consumers. Still, integrated Web orders for retail groceries have been seen as a potentially profitable service extension for grocery stores.

Response of Packages to Shipping and Handling

Once products are produced, packaged and shipped, the packaging becomes a large part of protection against damage during shipping. To understand how to prevent damage, it helps to have some basic concepts of how packaged goods behave.

Static Compression Damage

Compression from stacking loads, particularly those intermittently applied over long periods of time in high-humidity conditions, can damage package-product system, which means that the high safety factor described Chapter 4 will come into play. Although it is possible to rely on design data to estimate strength, it is important that a good estimate of the actual stacking strength of containers is known. This can be achieved by compression-testing the final containers, in both loaded and unloaded configurations, to determine how much of the load can be absorbed by the primary or secondary containers, and what the most likely mode of failure will be. Additionally, although there are a number of good compression-testing devices and protocols, careful observation will show that the real-world failures often involve asymmetric load application or palletization that compromises stacking strength by allowing the box edges to hang over the pallet's supporting surface. Products such as fresh fruit, seafood, and meat, which can support little stacking load and produce high levels of humidity, present a substantial challenge in maintaining package stacking strength. Care must be also taken that any shipping or storage damage is not inflicted during the package filling and closing process, and that good design practices are followed, usually involving coated corrugated board or plastic materials to resist moisture [17].

Dynamic Considerations in Packaging

Because packaged goods must get from the producer to market in usable and salable shape, it is important that the producers and transportation providers work together to provide a safe and economical means of transporting the goods. In the United States, a large volume of freight moves via truck transport even though it is less energy-efficient than rail, owing to the relatively difficult and inflexible nature of the nation's rail system, particularly for small loads of goods, but goods can be moved by truck, rail, air, and water, and each of these modes has its own considerations with regard to the dynamic environment.

To ensure that the goods reach the marketplace intact, it may be necessary to engage in some means of testing the package-product system. In order to conduct useful and accurate transportation, it is important to understand the basic concepts behind the shock and vibration environment's impact on packages and how they can be simulated.

In the world of packaging, getting goods to market requires that they be placed in some (usually) mechanical conveyance, each of which will have its own peculiar considerations with regard to dynamic environment and required packaging protection. Although many products are robust enough to survive the distribution system, and others are overpackaged in an expensive attempt at protection, damage to goods in shipping is a huge economic burden and potential safety hazard to shippers, manufacturers, and consumers. To understand how to get products to market in intact and saleable condition, the packaging engineer must have a good understanding of the environment that the product will endure, and must have a grasp of the basic physics of how mechanical devices respond to the shocks and vibrations to which they will be exposed.

Natural Frequency

Nearly all solid objects have a set of frequencies at which they will either amplify or attenuate vibration that they are subjected to. The specific response of the item will be a function of its structural design, materials, and any external constraints that may exist. The resonant frequencies in these may be very low, with a value of less than 1 Hz for large building structures in lateral seismic movement and some kinds of vehicle suspensions, or extremely high as with turbine parts, but the process is essentially the same. For elastic materials, described in more detail in Chapter 2, energy is stored and released in sympathetic cycles, driven by the inertia of the mass acting under some external force.

Fluid systems also oscillate cyclically, sloshing and surging, and exhibit natural frequencies and resonance modes of their own. For this reason, large tank carriers are built with internal baffles or tank separators to prevent or reduce the potential for the fluid movement that can cause the vehicle to capsize or lose control. This occurs because fluid flow tends to dissipate energy rather than store it like elastic solids. Modeling and prediction of this is complex, usually requiring advance computer simulation, and will not be considered in this text.

Viscoelastic systems have very interesting intermediate resonance properties and are often used as vibration dampers both in shipping and engineering applications such as engine mounts and vehicle isolation pads. The mechanics of this will be discussed in this chapter in general terms but are still the subject of a great deal of research.

For very simple systems made of purely elastic materials (without viscous or viscoelastic elements), the mechanical response of systems can be predicted by elementary equations, but for complex, real-world systems, it is often impractical and usually uneconomical to attempt to model the vibration response of the item in question. In this case, it may be necessary to attempt to simulate the transportation environment using vibration simulation equipment (Figure 9.1) and observe the response of the system to determine the best type of packaging for the product, to conduct real-world trials, or both.

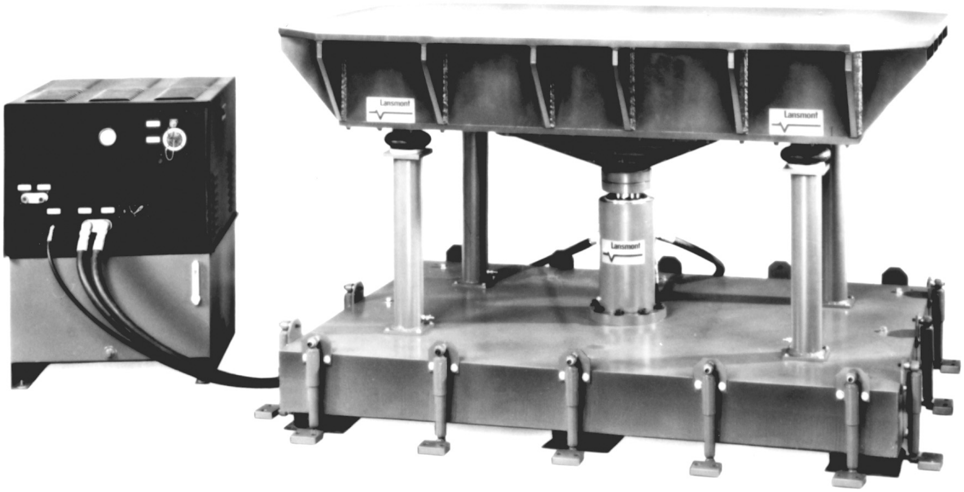

Figure 9.1. Vibration Table
Source: Courtesy of Lansmont Corporation

Resonance

Resonance is the matching of the natural frequency of a periodic system and a corresponding energy input. This results in the reinforcement and amplification of the energy within the structure. Intentional resonance is found and used in many applications ranging from circuit design to aerodynamics and atomic spectrometry. In mechanical systems, unchecked resonance can result in catastrophic failures as more and more energy builds in the system until the structure disintegrates (Figure 9.2).

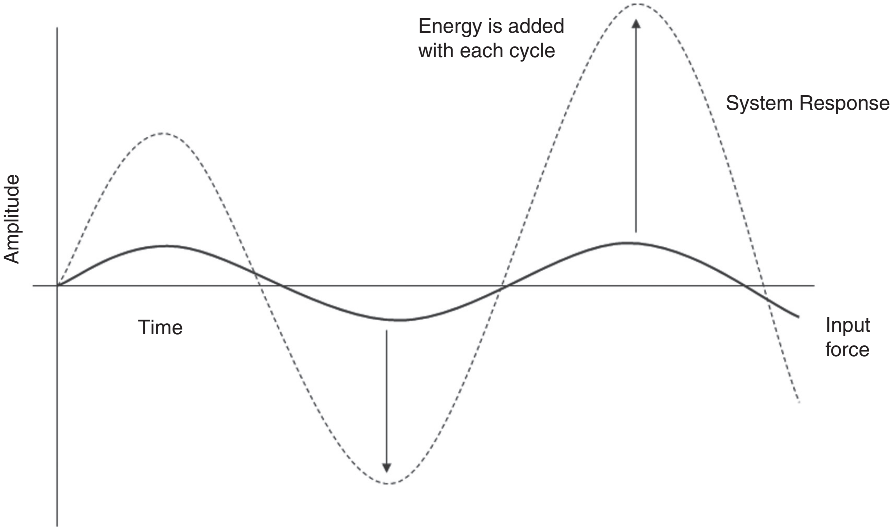

Figure 9.2. Resonance in Vibrating Systems

Because solid materials have both mass and some degree of elasticity, and fluid systems have similar resonance phenomena as previously described, nearly any structure can be said to have some potential for resonance. Reducing or eliminating resonance in structures may require a great deal of engineering effort and is often achieved by engineering a structure that interrupts the forcing energy, incorporates mutually cancelling resonance phenomena, or uses damping phenomena to dissipate energy from the system and prevent catastrophic levels of motion.

Response of Simple Spring-Mass Systems

The equation that describes the motion of a simple spring-mass system is:

$$m\ddot{x} = -kx \tag{9.1}$$

m: mass, kg
k: spring constant, N/m
x: displacement, m
$\ddot{x}$: acceleration, m/s^2

A large value for the spring constant (k) implies a "stiff" spring that requires a great deal of force for a given amount of deflection. A "soft" spring, by contrast, has a low k value and requires less force to deflect. Note that this is simply an energy balance trading kinetic energy of motion for potential energy stored in the spring:

$$\begin{aligned} m\ddot{x} &= -kx \\ m\ddot{x} &= \vec{F}_{\text{mass}} \\ &= m\vec{A} = \text{mass} \cdot \text{acceleration}, \ \frac{\text{kg} \cdot \text{m}}{\text{s}^2} = N \qquad (9.2) \\ -kx &= \vec{F}_{\text{spring}} \\ &= \text{displacement} \cdot \text{spring constant}, \ \frac{\text{m} \cdot \text{N}}{\text{m}} = \frac{\text{kg} \cdot \text{m}}{\text{s}^2} = N \\ &\therefore \\ \vec{F}_{\text{mass}} &= \vec{F}_{\text{spring}} \end{aligned}$$

This may be solved as a second-order homogeneous differential equation:

$$x(t) = \frac{\dot{x}(0)}{\sqrt{\dfrac{k}{m}}} \sin\left(\sqrt{\frac{k}{m}} \cdot t\right) + x(0)\cos\left(\sqrt{\frac{k}{m}} \cdot t\right) \tag{9.3}$$

$x(t)$: position at any time t, m
$x(0)$: initial displacement, m
$\dot{x}(0)$: initial velocity, m/s
t: time, s

and is surprisingly useful for describing many types of packages and other systems. The system's natural frequency (f_n) given by the equation is actually the primary resonant frequency – the frequency at which the system will oscillate when displaced and released. The easiest way to envision this is to imagine a spring with a weight hanging at its end. If the weight is pulled gently, the weight will bob up and down on the spring at the spring-mass system's natural (primary resonant) frequency:

$$f_{\mathrm{n}} = \frac{1}{2\pi}\sqrt{\frac{k}{m}} \tag{9.4}$$

f_{n}: the undamped natural frequency, Hz

It is also possible to calculate the natural frequency from the static displacement – the degree to which the cushioning is compressed at rest, although this may be hard to measure with stiff materials under light loading.

$$f_{\mathrm{n}} = \frac{1}{2\pi}\sqrt{\frac{g}{\Delta}} \tag{9.5}$$

g: acceleration of gravity, typically $\sim 9.82\,\mathrm{m/s^2}$

Δ: static deflection of system at rest, m

These frequencies are often stated in Hertz (Hz), although with large spring-mass systems, the frequency may be fractional, as the structures can take several seconds to go through a complete cycle. In some cases, a *natural period* (Π_n) may be described:

$$\Pi_{\mathrm{n}} = \frac{1}{f_{\mathrm{n}}} = \frac{2\pi}{\sqrt{\dfrac{g}{\Delta}}} \tag{9.6}$$

which is the inverse of the frequency – the time required for the structure to go through a complete cycle – and is usually described in seconds per cycle. This is most useful in the present application when considering the relationship of natural period of a structure to the duration of a shock pulse.

Changing the ratio of the spring's stiffness (k, the ratio of displacement to force) to mass (m) will inversely affect the natural frequency, as shown in Table 9.2.

Harmonics

Harmonics exist as resonance points that are an integer multiple of the natural (fundamental) frequency. Thus, if a system has a fundamental resonant frequency of 15 Hz, it is quite likely that there will be progressively less active resonance points at 30 Hz, 45 Hz, 60 Hz, and so on. Practically speaking, the response at each of the resonance points will decrease significantly as the difference between the forcing frequency and the natural frequency increases. With the

Table 9.2. Frequency Response Relative to Mass and Spring Stiffness

(Mass)/(Spring Constant)	Natural Frequency Change
Increase *Larger mass or softer spring*	Decrease
Decrease *Smaller mass or stiffer spring*	Increase

exception of musical instruments and other very elastic structures with little damping, this decrease will usually render higher-multiple harmonics insignificant.

Damped Systems

Damping adds another term to the equation and represents a force that opposes the instantaneous motion of the vibration. The net effect of this is to remove energy from the system in some manner, usually by conversion to heat either by mechanical braking, current opposition as with induction damping, or hydraulic fluid or air flow with rate-dependent, viscous damping, as shown in the examples below. Without damping, a theoretical spring-mass system will oscillate indefinitely because there is no allowance for the removal of energy from the system.

In practice, this does not occur in nature because energy is lost from all vibrating systems, even though it may be a subtle effect such as the heating of a metal spring as it oscillates or the loss of energy as air-resistance from movement of the system components. The most common explicit device for oscillation damping that is seen in everyday use is the shock absorbers installed in automobile suspensions. These contain a combination of fluid and a one-way valving system that allows the wheel to move upward quickly as it hits a bump, but then forces fluid to travel through small orifices as the wheel re-extends, slowing its return. The net effect of this is to "decouple" or detune the system and ensure that the wheel does not resonate endlessly against the elasticity and rotational energy of the spinning tire after a single bump:

$$m\ddot{x} + c\dot{x} + kx = 0 \tag{9.7}$$

c: damping constant, $\dfrac{\mathrm{N \cdot s}}{\mathrm{m}}$

Again, this can be seen as an energy balance:

$$m\ddot{x} + c\dot{x} + kx = 0 \tag{9.8}$$

$$\begin{aligned}
m\ddot{x} &= \vec{F}_{\text{mass}} \\
&= m\vec{A} = \text{mass} \cdot \text{acceleration} = \frac{\mathrm{kg \cdot m}}{\mathrm{s}^2} = N \\
c\dot{x} &= \vec{F}_{\text{damping}} \\
&= \text{velocity} \cdot \text{viscous damping force, } \frac{\mathrm{N \cdot s}}{\mathrm{m}} \cdot \frac{\mathrm{m}}{\mathrm{s}} = N \\
-kx &= \vec{F}_{\text{spring}} \\
&= \text{displacement} \cdot \text{spring constant, } \frac{\mathrm{m \cdot N}}{\mathrm{m}} = N \\
&\therefore
\end{aligned}$$

$$\vec{F}_{\text{mass}} + \vec{F}_{\text{damping}} + \vec{F}_{\text{spring}} = 0$$

Damping may be considered to range from over-damped, where the structure does not completely oscillate properly when perturbed, to under-damped when it goes through many

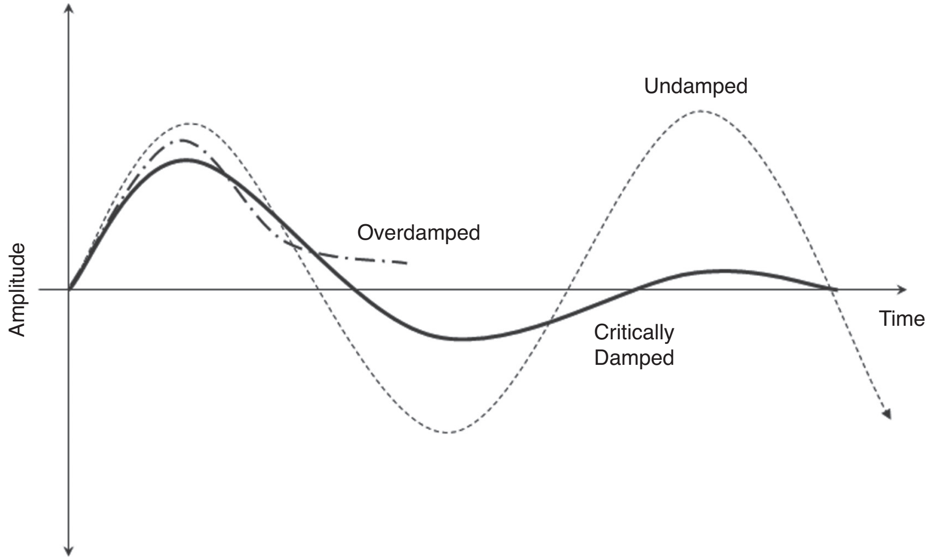

Figure 9.3. Damping in Vibrating Systems

oscillation cycles before settling to a resting state. The damping ratio can be described as:

$$\zeta = \frac{c}{2\sqrt{km}} \tag{9.9}$$

ζ: damping ratio, dimensionless

In general, the higher the value for the damping ratio (ζ), the fewer cycles it will undergo before coming to equilibrium. The damped natural frequency(f_d) of the simple spring-mass system is related to the natural frequency (f_n) by:

$$f_\mathrm{d} = f_\mathrm{n}\sqrt{1-\zeta^2} \tag{9.10}$$

There are typically three conditions of damping that are considered when evaluating or designing vibrating systems, as shown in Figure 9.3.

Under-damped Systems

(ζ too low, with $\zeta = 0$ representing an undamped system)

Under-damped systems typically oscillate excessively before coming to an equilibrium state. The practical implications of this are that the system will not remove energy quickly enough, and may oscillate excessively. This, in turn, can cause divergent oscillation that can cause damage or an uncontrollable device.

Over-damped Systems

(ζ too high)

Over-damped systems will not oscillate at all, but will attempt to come directly to equilibrium, and because of the high degree of damping, may not achieve this. In physical systems, this typically means that the system will not allow phase damping or energy removal.

Critical Damping

($\zeta = 1.0$, or as required)

Critically damped systems will oscillate a minimal number of times before coming to an equilibrium state. Although a mathematically perfect damping ratio is approximately $\zeta = 1.0$, the actual physical system will dictate the damping coefficient required, with vehicle suspensions in the range of $\zeta = 0.2 - 0.4$. In packaging applications, damping may be provided by many types of fixtures and materials, commonly made of dunnage, foam, or plastic film. These will be discussed in detail later, but the energy in these structures is typically given up as heat evolved from the deflection of polymer or other padding and dunnage structures, air displacement, or – if done improperly – deflection or destruction of the product.

Phase Lag

Phase lag is a phenomenon, most often tied to viscous or viscoelastic structures, where the response of a system is delayed in time relative to the forcing frequency (Figure 9.4).

Because destructive resonance and amplification depend on the system responding in phase with the forcing frequency, phase lag may be used as a means of "detuning" the system so

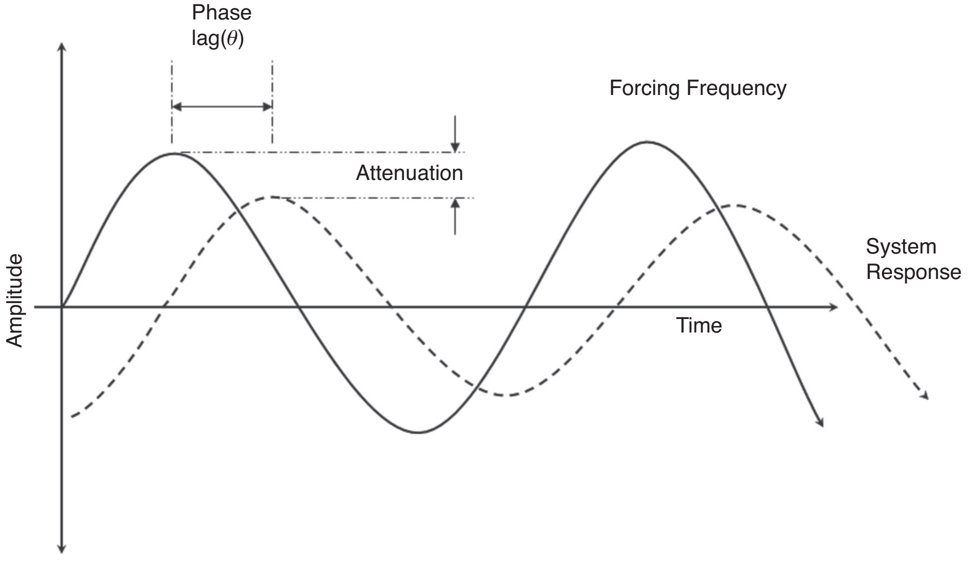

Figure 9.4. Phase Lag in Vibrating Systems

that the system responds in opposition to the forcing energy, and oscillations and vibrations are reduced or eliminated.

Forced Vibration

Forced vibration is vibration that is driven by an external cyclic input that continues beyond the initial disturbance of the spring-mass system, and is much more indicative of real-world situations. The energy of forced-vibration systems generally comes from either environmental sources such as wind turbulence or wheels rolling over bumps in the road, or from engines or actuators in a structure. In nearly every application of vibration analysis, the object is to avoid resonance in the structure under study either by altering the structure or by defining those conditions under which they occur such that they may be avoided.

Simple Spring-Mass Response to Forced Vibration

A simple spring-mass system will respond to forced vibration in one of several ways, some of them important to the design of useful packaging. The general response of a simple spring-mass system to a harmonic force can be given by the equation:

$$\begin{aligned} m\ddot{x} + c\dot{x} + kx &= F_0 \sin \omega t \\ \omega &= 2\pi f_\text{f},\ {}^{\text{rad}}\!/_{\text{s}} \end{aligned} \tag{9.11}$$

$$\begin{aligned} F_0&\text{: harmonic force component}, N \\ \sin\omega t&\text{: harmonic periodic component} \\ &\quad \sin\omega t = \sin 2\pi f_\text{f} t \\ f_\text{f}&\text{: forcing frequency, Hz} \end{aligned}$$

Without considering the variable values, this can again be seen as a generalized energy balance:

$$m\ddot{x} + c\dot{x} + kx = F_0 \sin 2\pi f_\text{f} t \tag{9.12}$$

$$\begin{aligned} m\ddot{x} &= \vec{F}_\text{mass} \\ &= m\vec{A} = \text{mass} \cdot \text{acceleration} = \text{kg} \cdot \frac{\text{m}}{\text{s}^2} = \frac{\text{kg} \cdot \text{m}}{\text{s}^2} = N \\ c\dot{x} &= \vec{F}_\text{damping} \\ &= \text{damping force} \cdot \text{velocity}, \frac{\text{N} \cdot \text{s}}{\text{m}} \cdot \frac{\text{m}}{\text{s}} = N \\ -kx &= \vec{F}_\text{spring} \\ &= \text{spring constant} \cdot \text{displacement}, \frac{\text{m} \cdot \text{N}}{\text{m}} = N \\ \vec{F}_0 \sin 2\pi f_\text{f} t &= \vec{F}_\text{applied},\ \text{cyclic applied force},\ N \\ &\therefore \\ \vec{F}_\text{mass} + \vec{F}_\text{damping} &+ \vec{F}_\text{spring} = \vec{F}_\text{applied} \end{aligned}$$

The sign convention for force in most systems provides that the damping force opposes the direction of motion, because fluid friction opposes the direction of flow and removes energy

Table 9.3. Ratio of Forcing Freqencies to Natural Frequencies and Their Responses

$f_{f\text{ v.}}\,f_n$	Amplification (A)	Phase Relationship	Type of Motion
$f_f \ll f_n$	$A = 1$	In phase	Synchronous Motion
$f_f <= f_n$	$A > 1$	In phase	Amplification
$f_f \cong f_n$	$A \approx \infty$	Indeterminate	Resonance point, amplification determined by available damping
$f_f >= f_n$	$A \gg 1$	Out of phase	Amplification and/or repetitive shock mode
$f_f \gg f_n$	$A \cong 0$	Out of phase	Attenuation

from the system. The implication of this is that an undamped, forced system has the capacity to build energy indefinitely in resonance.

Amplification Factor

The amplification factor during resonance can be seen as a function of the ratio of forcing and natural frequencies and the damping available to the system in Table 9.3. This is also graphically illustrated in Figure 9.5.

In Phase

The force that is exciting the motion and the object being excited are moving in the same direction at the same time.

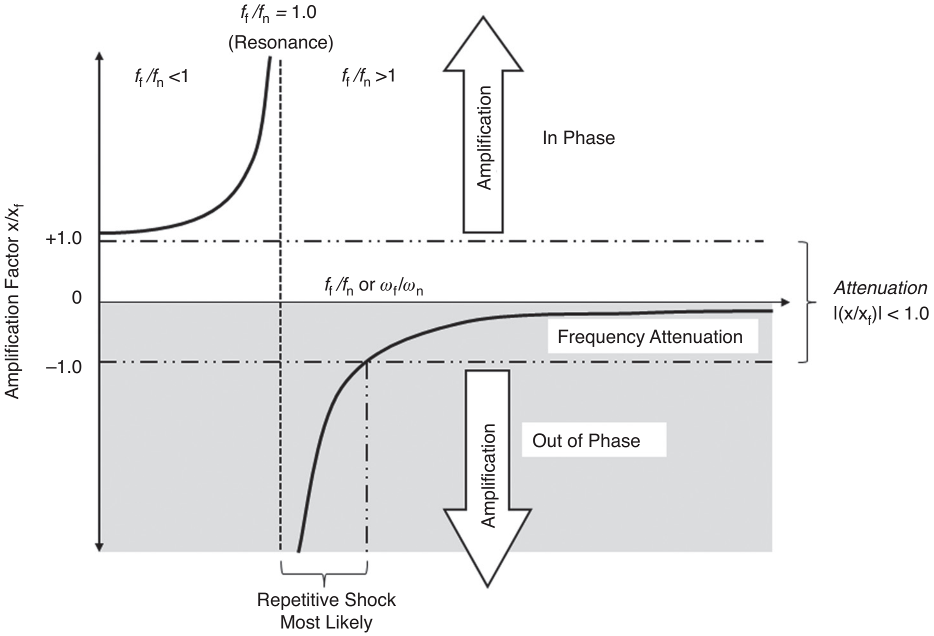

Figure 9.5. Resonance and Amplification in Vibrating Systems

Out of Phase

The force that is exciting the motion and the object being excited are moving in different directions at the same time, usually related by a phase angle φ.

Indeterminate

Although a mathematical solution for phase angle may be constructed for this point, practical experience has shown that the phase and amplitude relationship will be a mathematically chaotic system that is sensitive to both initial conditions and frequency hysteresis (whether the frequency is increasing or decreasing).

Synchronous

The object moves at approximately the same amplitude as the forcing motion.

Amplification

The object is moving at a larger amplitude than the forcing motion due to the energy being stored in the system by its elastic components being synchronous with the forcing frequency and reinforcing it.

Resonance

Object moves at an enormous amplitude, restrained only by the damping force c, if any, because all of the elastic energy storage is being fed back into the system in phase. In theory, an undamped system will continue to increase its range of movement until it disintegrates.

Repetitive Shock

Repetitive shock is the point at which the force that is exciting the motion of the object and the object being excited may be moving in opposite directions at all times. In practical applications, this is typically the top box of a stack, or a container on a floor. During shipping, the amplification is out of phase, providing enough acceleration for the container to “lift off,” and subsequently the opposing motion causes the containers to repeatedly slam together, usually with a specific rate of repetition that may cause further problems with shock amplification.

In packaging dynamic situations, this results in extreme levels of damage and may exhibit facets of both shock amplification and vibration resonance damage. Because of amplification and repetitive shock, as well as lateral shifting of the load, most palletloads of material are restrained by a plastic overwrap, either stretch wrap or a heat-shrink film, or straps of plastic fiber or steel banding.

Attenuation

In the attenuation region, energy is being returned to the system out of phase with the forcing energy, giving the system the ability to reduce amplitude or even remain almost stationary while the forcing motion continues to act on it. This is usually the design goal of dynamic cushioning and damping systems, as well as suspension systems and other damping device designs.

More simply put, the response of an undamped system as the frequency increases will go through an interval of in-phase resonance of increasing amplitude, a resonance point where the response of the system achieves a theoretically infinite value, and an out-of-phase period where the response of the system is at first in the most danger of repetitive shock and then is attenuated to nearly zero. A damped system will show similar responses, depending on the type of damping mechanism used, but with reduced response.

These relationships are shown in more mathematical detail in Figures 9.6 and 9.7 as well.

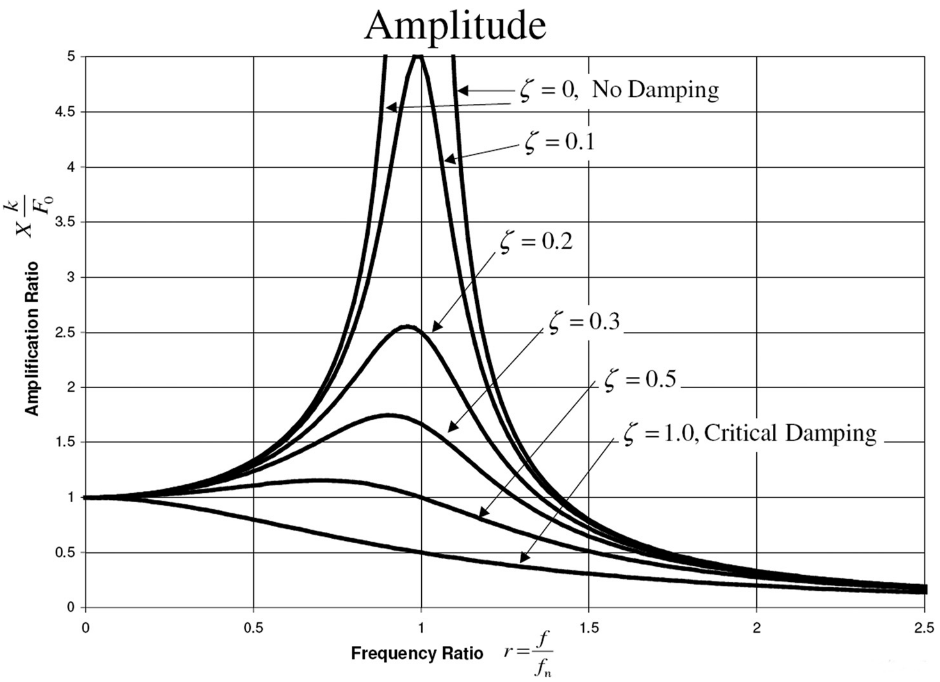

Figure 9.6. Amplificaton Ratio and Damping

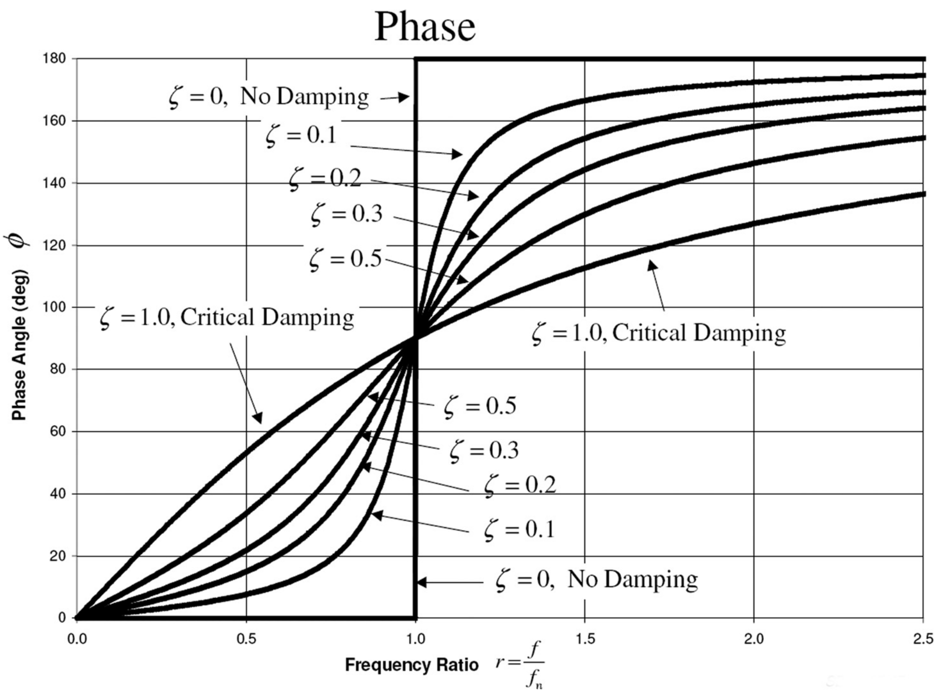

Figure 9.7. Phase Shift and Damping in Vibrating Systems

Clearly, it is advantageous to consider these design factors when designing a package for distribution. The product should not be exposed to undamped or unattenuated environmental inputs that closely match the product's resonant frequency. The result of this would be to have a huge amplification of the products' response with attendant product damage. There are some exceptions to this, where the mechanical action of the resonance might be beneficial, such as with the mixing of reconstituted juice products that are initially made as water and unmixed juice concentrate and then shipped by truck. The motion of the truck during shipping mixes the product thoroughly and results in a shelf-ready product.

Shock, Resonance, and Shock Amplification

Shock is generally taken to mean a single, non-repeating mechanical input, and in packaging applications it usually is unintentionally inflicted during material handling operations and transportation as the package impacts along its vertical axis either as an intentional handling step or by accident. Humping damage is a result of the collision of railcars as they are rolled up a "hump" (a low hill in a rail-switching yard) and then coast downhill to slam couplers together during train assembly, creating a unique, lateral shock hazard that packaging engineers must be aware of if their product is shipped by rail. Typically, similar design methods are used, but are applied to the horizontal axes of the package.

The previously discussed vibration and its related properties also affect how systems behave when they are subjected to a shock from being dropped or bumped during shipping and handling. Because shock inputs do not have a distinct frequency, more often shock analysis is concerned with the amplitude and duration of the shock, with the latter having some correspondence to a half-cycle of vibration.

Shock resonance phenomena may be hard to grasp, but they have a corresponding influence on structures, which can result in anomalous damage levels. The simplest way to visualize this effect is to consider that a shock impulse will comprise several overlapping frequencies, each of which may excite a resonant frequency in the product. If the duration of the shock applied to an object is very much shorter than its natural period, the effects will be minimal, which is one reason that designers will try to provide "soft" springs or cushions to reduce shock damage (Figure 9.8).

On the other hand, if the period of the shock and the natural period of an object are similar, this may result in resonance-induced effects such as breakage that can occur with very little apparent mechanical input. If the shock pulse is considered as a *half-cycle input*, the concept of resonance appears again. If the natural period (as described in Equation 9.6) of the product package system is close to the shock input duration, amplification may occur, damaging a well-padded product more than its unpadded equivalent (Figure 9.9). This paradoxical effect has cropped up in many products, from filament-style light bulbs to audio equipment.

The Soft Cushion Paradox

The soft cushion paradox is the result of the instinctive over-padding of delicate structures that result in more damage being caused rather than less. Sometimes, the cushioning systems induce more damage than having no protection at all. From the previous discussion of spring-mass systems, a "soft" (low k value) spring will have a relatively low natural frequency. If the product to be protected has a similar low frequency, and if the input, whether from shock or vibration, is similarly low (such as the vertical vibration from a truck bed), then amplification may occur

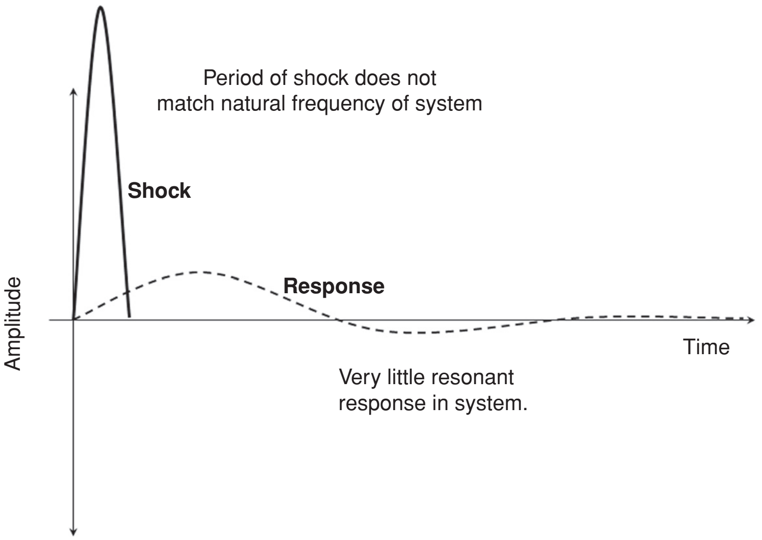

Figure 9.8. Shock Attenuation Phenomena

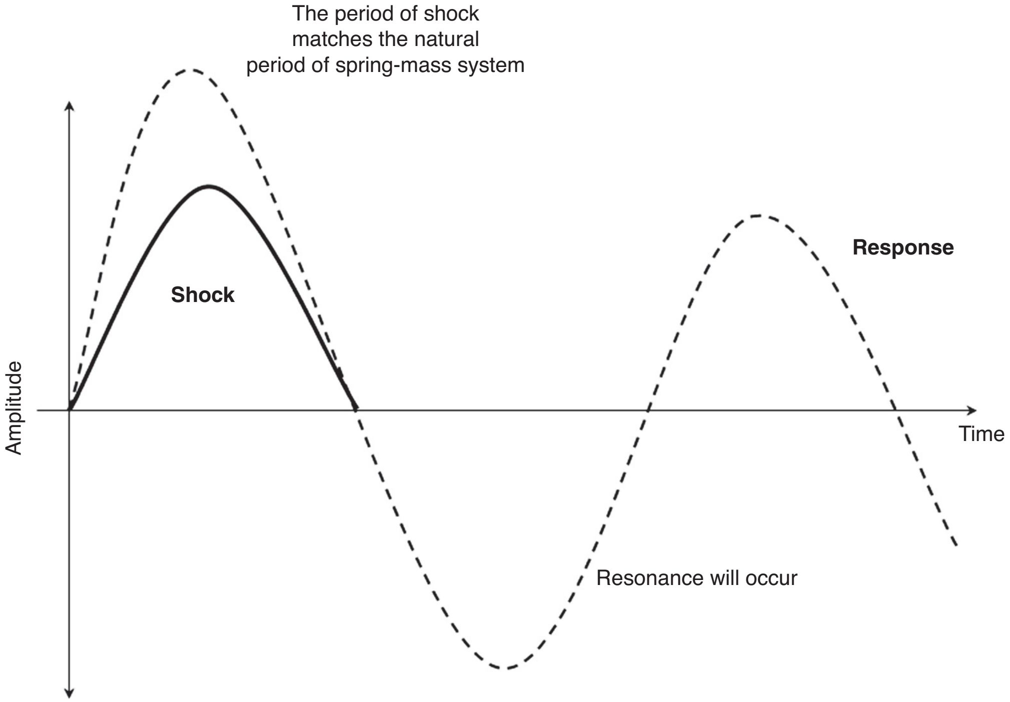

Figure 9.9. Shock Resonance

throughout the system, resulting in damage to the product. The usual solution to this problem is to change the natural frequencies of the packaging system and perhaps the product as well, sometimes in counterintuitive ways.

For example, if a product's critical element has a resonant frequency of 7 Hz, and the package is padded sufficiently against shock to bring its natural frequency in the 7 Hz range, then two things may happen. A shock input may be "tuned" into the correct frequency range by the package cushioning system, causing great damage. More certain is vibration damage from the padding intended to prevent shock, since the 7 Hz input is common in most modes of wheeled vehicle, and will be amplified through the package padding and cause the cascaded amplification to make resonance problems in the product worse.

Packaging Design for the Dynamic Environment

Often, the lowest systemic cost for this kind of protection involves changes in the design of the product, as well as the design of a thoroughly protective package, which is another strong argument for concurrent development of the product and its packaging system. In too many cases, the product is simply handed to the packaging engineer in its finished form, much too late to make substantial and necessary changes for the product to survive distribution. This results in both the delay of product introduction and expensive over-packaging, which reduces the overall profitability of the product line.

Critical Element Analysis

Critical element analysis is a general concept for product quality and testing analysis, and can be used to prevent damage or quality loss. In this section, it will be used in the traditional form of physically fragile components that may cause catastrophic failure of the structure, but the underlying concept can be used in other product quality issues such as shelf-life control and product quality deterioration. Use of critical element analysis can remove a lot of the confusion that ensues from trying to determine the failure mode for a structure – or whether failure has actually occurred at all. The basic steps of critical element analysis are:

1. *Determine the "critical element"*: The critical element is the element that is critical to the function or integrity of the product. This usually involves some preliminary testing or a prior knowledge of the system involved. In an electronics assembly, it may be a component on the end of long wires (one of the reasons for the ruggedness of newer surface-mount electronics), or it may be much more obscure, such as the components that provide the proper product viscosity and texture.
2. *Determine what constitutes failure in the critical element*: This could be mechanical failure, such as an assembly that will not operate, or in a food product it might be product breakage, the separation of ingredients, leaking packages, or a much more subtle reduction in shelf life. Getting an agreement on what constitutes failure, particularly when it involves subtle factors such as flavor or texture rather than something that can be objectively analyzed and quantified, can be one of the more difficult exercises in completing this process.
3. *Determine which hazards cause critical element failure*: In the previous section on product quality, the factors were inputs such as heat, light, oxygen, or other detrimental factors. In distribution processes, the physical hazards are almost always dynamic in nature: shock, vibration, and handling damage.

4. *Reduce or eliminate those hazards*: This may involve creating a better package, but it also may involve changing shipping modes, changing the design of the unit load, modifying the product, or some other subtle change to provide the most effective systemic improvement.

The Dynamic Environment of Distribution

Each distribution mode has its own separate characteristic mechanical frequencies, and within each of those modes, there is tremendous variation between types of vehicles, and between individual vehicles in any particular type. This does not mean, however, that the range of significant forcing frequencies in the dynamic environment is completely random. The basic design of each type of vehicle, along with standardization among components (wheel diameter, propeller shaft designs, and so on), ensures that there is a range of predictable frequencies available to cause damage to a product. For shock damage, there are some broad assumptions that may prove to be useful in designing protection for products as well. Finally, it is important to remember that shock, vibration, and compression may happen at any point in the manufacturing, distribution, and use cycle.

Many efforts at remediating distribution damage are wasted because the product is damaged before it ever leaves the factory, or because it is damaged during normal use by the consumer. Before embarking on any attempt to reduce distribution damage, it is vitally important to ensure that the product is leaving the manufacturing facility in good shape, and that the product design itself is both sufficient to withstand distribution and is satisfactory for customer use after proper packaging is supplied.

Vibration and Repetitive Shock

Vibration in transportation equipment is due almost entirely to rotating components in the vehicle, or in regular features that are a part of the surface that the vehicle travels on. Some examples of the former are wheel and driveshaft rotation, engine vibration, and propeller-shaft imbalance. The latter, surface-related vibration and repeated low-amplitude shocks may be a result of joints or welds in the rails, or expansion joints in the roadway surface. Air turbulence may be included in this type of input, as might runway vibration on takeoff and landing, but these are over a less protracted period that a days-long truck or rail trip. Water transportation suffers less from these latter types of inputs than do the other modes of transport, because water surface features result in very low-frequency movement of the ship, but propeller vibration and structural resonance still exist.

For a typical limited-access highway, road joints that are spaced at approximately 25 meter (82 feet) intervals (although this can vary widely), and for a five-axle truck travelling at 120 km/h (75 mph), each set of wheels will hit a road joint approximately every 0.76 seconds [18]. Given that most semi-trailers have one double set of wheels at the back of the trailer and another just under tractor coupling, this makes for a double set of repetitive shocks that are impacting the load in the truck. Over a long trip, from California to Chicago, for instance, the distance is approximately 3,300 km (2,050 miles), which means that each set of tires on the vehicle will transmit more than 100,000 moderate-amplitude shocks into the loaded trailer. Combining this with vibration from the rotating wheels, suspension, driveshaft and motor will provide a huge and continuous source of shock, vibration, and mechanical energy to damage the products.

Package Design and Testing

Packaging structures and materials, particularly for food packaging applications, must be produced cheaply and provide for a great deal of protection of the product. Industries that produce high-value goods, such as the aerospace industry and the electronics equipment industry, have a very high cost associated with damage occurring during shipping, whereas with the food industry, the product design response to complaints about damage in shipping may actually be counterproductive in the long run.

Food damage during shipping often goes unreported, with small, indicative quantities of broken product containers being discarded by store personnel and being unreported unless occurring in large quantities, and products that become undesirable to the consumer may be discarded by the consumer and will only show up in a slow erosion of consumer sales that may be masked by marketing blitzes, price reductions, and other wide swings in the marketing-driven food industry.

With high-value items such as those mentioned earlier, it is often desirable to design the product to be rugged enough to survive the shipping environment without the need for excessive packaging. If a food product is treated in this manner, it may become so unpalatable that consumers will no longer purchase it, even though it survives shipping perfectly. This has happened in several sectors of the food industry, and the resulting loss of customer sales has proven that "ruggedizing" food is often not a good idea. There have been other instances, however, where the solution to shipping problems, often with dairy or sauce type products, is to modify the product slightly, often by adding a binding or gelling agent or emulsifier to prevent stratification or evolution of excess liquid during shipping. These changes, if properly done, do not affect consumer preferences and will keep the product in an appealing state even after long shipping exposure.

Because packaging in the food industry is most often seen as a cost item to be minimized, rather than an integral part of a complex food safety and delivery system, the designing of food packages to withstand the distribution environment is often overlooked completely or treated in a perfunctory, "palletload-level" manner. Because consumers have been conditioned to accept a certain number of broken products, particularly in brittle goods such as cereal flakes, baked goods, and pasta, there is little benefit for extensive design work to prevent shock and vibration damage. With other products, however, a simple redesign of a tray molding or bottle configuration may prevent substantial losses due to product breakage or liquid motion. The general progression of package designs to protect a product against damage is as follows:

1. Determine Product Fragility
2. Determine Environmental Conditions
3. Calculate Cushion Requirements
4. Build and Evaluate a Prototype
5. Consider Vibration Effects
6. Monitor Performance in The Field

Determine Product Fragility – Damage Boundary Curves

The Damage Boundary Curve (DBC) of a structure represents the limits of shock duration and amplitude that an item can withstand without damage. The usual test procedure is to use a shock tester (Figure 9.10) that can be programmed to control both the amplitude and duration of the

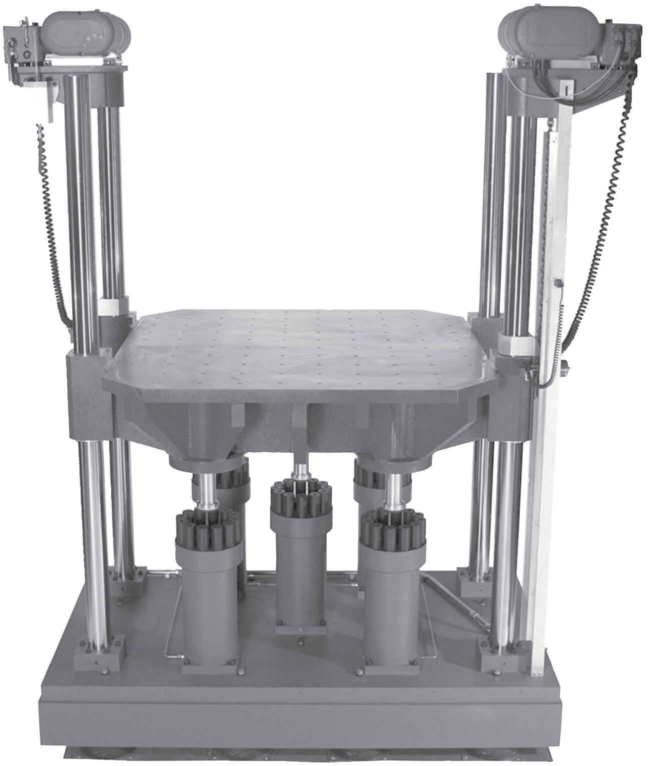

Figure 9.10. Lansmont Shock Machine
Source: Courtesy of Lansmont Corporation

shock pulse imposed on the product. The typical test procedure will involve constructing two variables of increasing severity, first holding the pulse duration at an approximately constant level while increasing the peak amplitude of the shock pulse, then varying the pulse duration while holding the amplitude constant. Both of these tests are performed using "new" products for each separate trial.

The data provided by this test method will allow the construction of an approximate DBC that will describe the levels of shock intensity and duration that the product can withstand, as shown in Figure 9.11. The test protocol usually does not take into account several factors that can affect the final accuracy of the curve provided: repeated shock and period-dependent shock amplification.

Effects of Repeated Shock and Shock Amplification

Repetitive shock – the repeated application of shock pulses to the same item – may have cumulative effects that modify the existing damage boundary curve. The considerations of repeat shocks provide a third parameter to be considered when describing the fragility level of a test sample. Further complicating the issue is the concept of shock amplification, as previously described. If the test sample has a resonant periodicity that matches the velocity change impulse

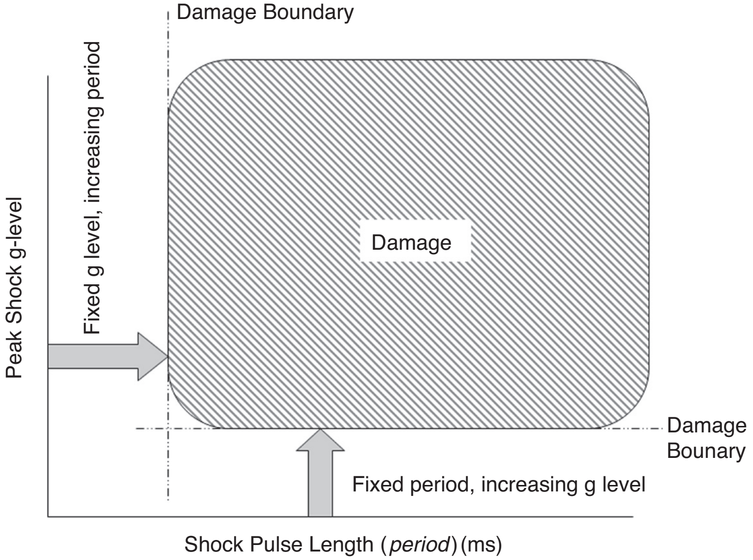

Figure 9.11. Damage Boundary Curve

duration, the shock amplification may distort the "velocity change" axis significantly. Also, it may be possible that a very high rate of peak acceleration may be survivable at particular ranges of velocity change values that provide attenuation rather than transmission or amplification – in effect, creating "safe zones" behind the damage boundary curve. Research on this last issue is lacking and may or may not have practical significance.

Determine Environmental Conditions

To develop a working system to protect the product against distribution damage, it is necessary to understand the kinds of hazards to which the product will be exposed. Whereas it may be enough to estimate the likely drop height and use an estimate for design purposes, as shown in Figure 9.12, it may also be necessary to go in the field and measure actual handling conditions and the kinds of damage that they are inflicting on the product.

Shock and Vibration Indicators and Recorders

Electronic recorders that use accelerometers based on a small mass on a piezoelectric quartz crystal to produce an electric voltage when acceleration results in deflection of the crystal structure are often the most accurate. These systems have shown a huge price drop as accelerometers, often incorporated into a monolithic circuit component, have begun to be incorporated in everyday electronics, and particularly video game controllers and toys. Piezoelectric accelerometers typically are tested or designed to have a very high resonant frequency, minimizing the resonance effects of most common transportation frequencies. It is important to understand that these high frequencies *do* occur in aerospace environments (and very rarely in other types of transportation modes such as steam-turbine-driven ships) as a result of turbine and propeller operation, and thus there may be some high-frequency amplification that occurs.

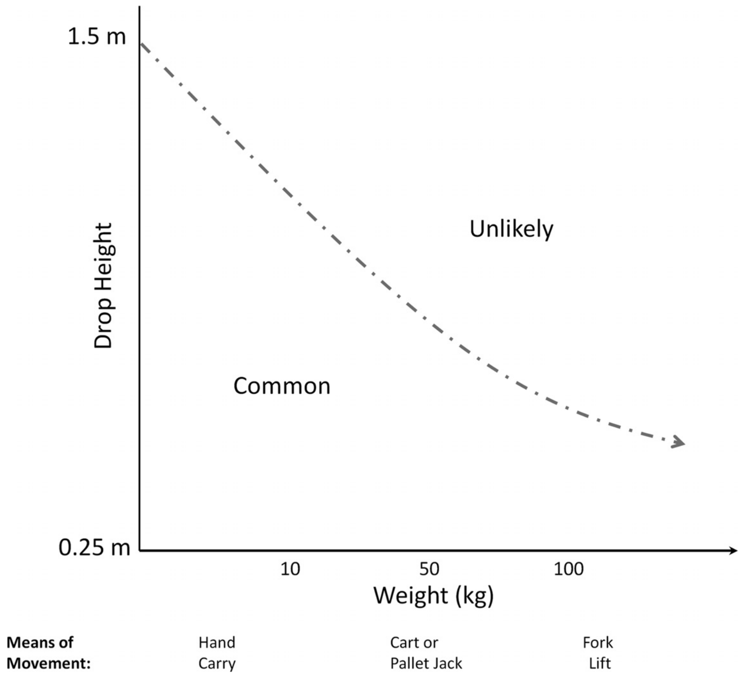

Figure 9.12. Drop Height versus Weight and Transport Method

On-Package Recorders

There are any number of shock and vibration recorders and indicator devices available on the market. Some of these are simple tubes that stick on the outside of a container and supposedly rupture at a particular shock level; others contain a spring-mass system that draws a trace on a slowly moving piece of paper; and still others are electronic systems that contain piezoelectric accelerometer systems that record data in digital format. Although not common, it is possible to instrument packages, or intermodal shipping containers with systems that will record both position (using GPS based navigational fixes) and the dynamic environment, which may help engineers pinpoint particular locations where damage occurs.

The effects of some of these devices may be more psychological than physical. An expensive piece of equipment with a highly visible abuse indicator on it will likely receive more careful handling than one without.

Resonance-Induced Errors

Because shock and vibration recorders have natural frequencies in the same manner that package and product systems do, it does not take a great leap of imagination to see how resonance might occur in such a device. What is less intuitive is the sort of erroneous damage indications that may occur when the indicator or recorder has a very different natural frequency than the product-package system does. A common type of damage indicator is a self-adhesive label containing a tube and a dye capsule with a frangible barrier. The barrier ruptures at an approximate shock amplitude value, indicating that the container has been dropped or otherwise abused. Because the natural frequency of the indicator itself is very high, due to its few rigid components, the indicator may not indicate a shock of long duration and low amplitude. If the product has a low resonant frequency and is subjected to a drop with the same approximate period, or is subjected to long-term low-frequency vibrations, the indicator will not show that any damage should have occurred, yet the product may be ruined.

Similarly, resonance can produce false-positive readings. In the case of a spring-loaded mass that draws a trace on a moving piece of paper, the resonant frequency of the spring-mass systems driving the recorder stylus is usually low enough that they will resonate at lower frequencies, amplifying the amount of vibration or shock transmitted through the stylus's structure and producing large pen deflections when the actual mechanical input may have been rather small. Worse, if the resonant frequency of the product is very high, there is likely to be little resonance damage, but the indicator will show large shock and vibration inputs, leading to the conclusion that damage may have occurred.

Calculate Cushion Requirements

Cushion design has traditionally been concerned with various types of resilient materials, but the principles can be used to design packaging structures of many types and materials. Initially, fragile items were packaged in straw, wood shavings, or other natural materials. These were supplemented with materials such as rubberized boar's hair matting and elastic bungee cords. These materials, though very elastic and capable of absorbing shocks, highlighted the problems with resonance in package structures that has been alluded to previously.

Newer package cushioning materials have been made of viscoelastic materials that, if properly designed, can be tuned to damp out both shock and vibration to within tolerable limits. Although the majority of these materials are of foamed polyolefins, there have been several clever developments that use items suspended between sheets of plastic film under tension in an open frame of corrugated board. This allows the film to be used as an inexpensive viscoelastic damper, and the material may be recycled once the films have been separated from the corrugated.

Calculating the proper cushioning criteria for foam materials is, in its simplest form, a matter of determining the maximum level of acceleration that the product should be subjected to, then choosing and sizing a cushioning material to provide that level of shock reduction at a particular drop height. Manufacturer's data is usually supplied to make this a relatively easy process, but it is also important to test the prototypes and to monitor the performance of the design in the field to take into account any previously unforeseen damage sources.

When choosing a cushioning material, manufacturer's data will typically be supplied that provides a "cushion curve," showing the transmitted G force relative to the static loading on the cushion surface (Figure 9.13). The design process usually favors the selection of high static loadings in the acceptable range of values in order to use as little material as possible, and to reduce the exterior shipping container and reduce materials costs, but it may become a trade-off between large areas of thin cushioning and small, thick pads, although these will require a larger shipping carton and take up more volume.

Additionally, the effects of end-on shocks or being dropped upside down should be considered. With large, monolithic objects such as electronic assemblies, the design has evolved to a more or less standard end-cap, usually made of Expanded Polystyrene (EPS) foam and designed to protect in all three axes. This presumes that there is little flexural deformation in the chassis of the assembly, which does not apply to many types of consumer items and food products.

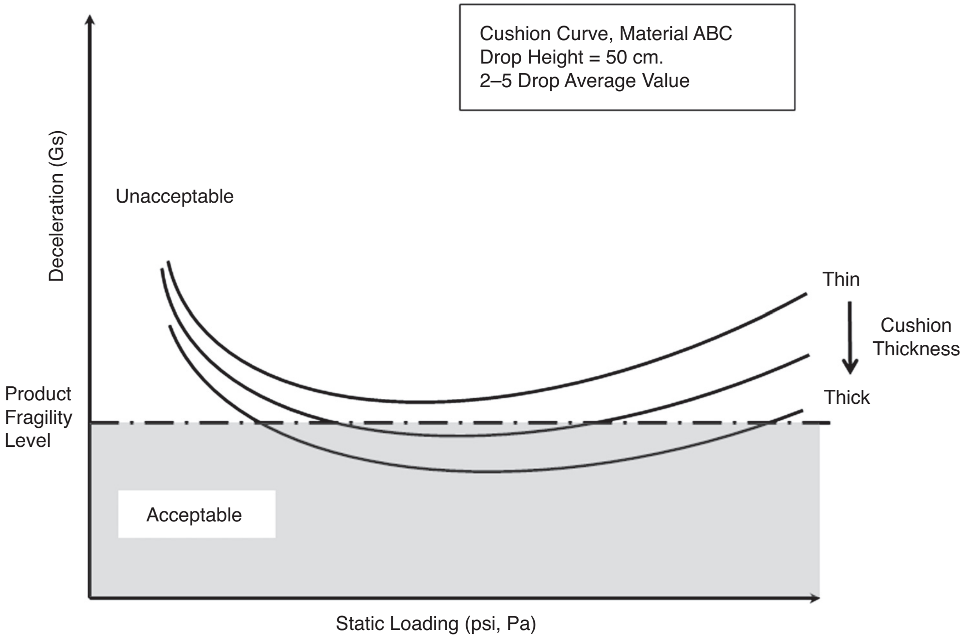

Figure 9.13. Generic Cushion Curve

Additional Cushion Design Factors

Once the cushion design has been developed, it must be examined for other design constraints, the most common of which is buckling, where the cushioning material deforms in non-axial manner such that its linear cushioning capability is severely compromised. This often makes another argument for more surface area and thinner cushioning materials because they are less likely to buckle, but it must be checked, usually against buckling criteria relating thickness and static loading. Some other factors that must be considered are temperature, creep, and variability in materials.

Temperatures will directly affect the viscoelastic properties of padding materials, with the result that a cushion that performs well in the laboratory may be too stiff in cold weather and too soft when transported in hot climates, drastically changing its performance. When stored for long periods of time in hot weather, creep, as described in Chapter 2, can permanently deform the cushion structure and compromise its effectiveness. Finally, with the increasing use of recycled materials, the variability in the materials properties should be considered, because studies have shown that incorporating recycled materials will provide a padding structure that may be softer than the original [19].

Design, Build, and Evaluate Prototype

Although the packaging of fragile, expensive items such as instrumentation assemblies and aircraft components may justify the expense of complex foam pads or support frames, the extreme price pressures on food items makes the likelihood of anything beyond minimal padding for most food items unlikely. This is not to say that cushion design principles cannot be included in the design of food packaging, but it must be done using existing materials and structures. Further, it may be difficult to justify the expense of dynamic testing to ensure the survivability of the product-package system until after a problem comes to light.

Design of food packaging to minimize dynamic input may include the use of well-designed trays or boxes, the reduction of mobility of the item in the container so that it does not have enough freedom of movement to be damaged, or the redesign of the product itself. This last step, though often an inexpensive solution to the problem, can have unintended consequences in that the product may gradually become so mechanically durable as to be unpalatable, and sales of the (undamaged) product could suffer.

Design of Protective Packaging for Shipping Food Products

The design of packages that can prevent mechanical damage to food products must include several design features:

1. They must be strong enough to resist compression damage, although the shipping container often bears the majority of the load during stacking and shipping.
2. They must restrain the product so that it does not have enough freedom of movement to be damaged during shipment. A product that is sufficiently well restrained will usually have a higher frequency than the one that has some freedom of movement inside the package. One opportunity that is seldom used for providing restriction of movement of products is to design an interlocking stacking pattern such that each package provides partial restraint of the product underneath. This allows the product to be easily taken from the container by the consumer, but when in a packed shipping container, will help prevent damage from excessive movement. One of the simple examples of this is the nesting trays that are used to display produce in supermarkets.
3. There should be some allowance made for the prevention of shock damage. Although it is often not economically attractive to do in-depth analyses of the shock response of package-product systems, careful observation of the dynamic environment and of the types of product damage that occur may yield opportunities for improvements.

Consider Frequency and Resonance Effects

As previously mentioned, the shock impact of dropping an item does not have the continuing periodic inputs that vibration in moving vehicles and conveyors provide, but resonance effects can and do occur. The other, often destructive frequency effect is the soft-cushion paradox, previously described. Sufficient padding to counteract shock inputs may lower the natural frequency of the product-package system to the point where it will resonate and be damaged in shipping. Although it may not be feasible to do vibration testing on the finished design, the design data of static loading, static deflection, and product mass can be used to roughly estimate the primary natural frequency, using Equation 9.5.

Monitor the Performance of the Packaging System

Once the design is put into production, it should be monitored for actual damage during distribution. Obviously, if the final design is inadequate and damage is excessive, it should be corrected. On the other hand, the complete absence of any kind of damage may be an indicator of over-packaging. This will depend on the type of product, the cost of damage, and the hazards, costs, and impacts associated with damaged product. At this point, the opportunity to reduce materials use and cost may present itself by redesigning the package so that an acceptably small, non-zero loss rate is achieved. Damage should also be examined for co-factors such as particular handling locations or carrier routes, anomalous abuse, and excessive environmental conditions such as direct exposure to rain because these will alter the apparent source of observed damage and the apparent ineffectiveness of the package design.

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Chapter 10

Food Regulation, Safety Systems, and Security

Food and Packaging Regulation History

The history of food regulation dates beyond recorded history – The Code of Hammurabi (ca. 1760 BC), one of the earliest western legal documents, contained sections on fair pricing of drink at taverns, Chinese case law records food contamination litigation as early as 200 BCE, and the Magna Carta, as described in Chapter 2, addressed grain and wine measurement [1]. Archaeological and more modern records indicate that standardization of weights and measures of precious metals in currency, as well as guilds of food-related craftsmen such as brewers, millers, and bakers were among the first to apply standards of production and to be held responsible for consistency of product quantity or quality. These systems, as well as consumers' skeptical self-reliance while purchasing goods from doubtful sources, persisted well into the era of food mass production. With the advent of large-scale, mass-produced package foods and drugs, the producer and contents of products were obscured to the point where large-scale adulteration and contamination of foods became a substantial problem. In parallel with this trend, understanding of both the microbiology, chemistry, and, to some extent, toxicology of food-borne illness grew to contribute understanding of the sources of the problems that were occurring.

During the 1800s, armies began to experiment with the replacement of unpalatable dried meats with heat-sterilized jars and then sealed metal cans of "bully beef" (from the French, "boulli" meaning "boiled" after the method of sterilization in use at the time) to extend their capacity to travel without depending on local rations. Although canned goods were hand-produced at that point and production proved to be too slow and expensive to make a large impact in the Napoleonic era, later campaigns in the American Civil War and Spanish-American war, Britain's Crimean War, and the Franco-Prussian wars motivated high-volume mass-production of canned goods.

In the United States, the food supply was changing rapidly as well. From a barter and self-sufficiency food distribution system to the doubtful products carried in local general stores, the nature of the retail markets was beginning to change at an accelerating rate. P. T. Barnum, recalling his days as a clerk bartering doubtful goods for dubious furs in a "country barter store," wrote: "Nearly everything was different from what it was represented. Our ground coffee was as good as burned peas, beans and corn could make, and our ginger was tolerable, considering the price of cornmeal." [2]

The advent of packaged and pre-prepared food goods and the expansion of rail infrastructure across an enormous continent began to demand that the consumer trust a producer that they did not know. Indeed, the producer could not know many of the early manufacturers as there was no requirement that the producers identify themselves, the actual contents of the product, or the

Food and Package Engineering, First Edition. Scott A. Morris.

actual weight or volume of product. This distrust produced a tremendous marketing opportunity for early packaged foods producers, most notably Ferdinand Schumacher and the American Cereal Company (which later became Quaker Oats) in Akron, Ohio [3]. He turned consumer mistrust into a sales tool by carefully identifying the manufacturer and contents, offering a money-back guarantee, and tying them into some of the first national food marketing campaigns based on panacean health claims. This latter marketing twist was the start of campaigns that have continued unabated by most manufacturers to this day, and which have prompted both a continuing escalation of regulations and their continuing circumvention.

The Pure Food and Drug Act of 1906

The first US federal legislation broadly regulating food in the nation, the Pure Food and Drug Act of 1906, was the result of a long history of regulation at the state and federal level of smaller issues such as contaminated drugs and the various foods, both toxic and otherwise, made from the output of a burgeoning chemical industry that created synthetic food materials that often drove more wholesome, naturally produced foods out of the marketplace. This is a debate that continues into the present, with issues like the escalating use of high fructose corn syrup and various additives, preservatives, and packaging materials' extracts in foods, as well as dietary supplements [4].

The tipping point was reached by a military inquiry ordered by General Nelson Miles into "embalmed" beef rations that were contracted by the Secretary of War, Russell Alger, from Chicago meat packers for use in the Spanish-American War in spite of recommendations to purchase local beef near army camps in the field. Allegations of the use of preservatives that were suspected to include borates and salcylates in the canned meat were dismissed by a military court in a controversial inquiry that eventually censured Miles, but questioned the safety and methods of the meat packers and the contracting practices of the Secretary of War [5, 6, 7].

In the interim, enough questions had been raised to motivate the sponsorship of the author Upton Sinclair to write an exposé of the anti-labor operations of the beef-packing "trust" (cartel) in Chicago in the early 1900s. The "Army Meat Scandal" and Sinclair's exposé of the unsanitary practices of Chicago's meat-packing industry that became the bestselling book *The Jungle* prompted inquiries by European governments and their rejection of imported meat products, both because of the use of boric acid and other chemicals as preservatives, and because of inspection policies that favored the Chicago beef producers [8]. The absence of a comprehensive food purity bill in the United States, and the loss of business by producers exporting products to Europe (and particularly Britain), which already had such legislation in place, added urgency to the legislation. Although much of the objection could be seen as protectionist trade policy by the countries involved, a comprehensive bill protecting consumers in the United States (and its foreign trade markets) was long overdue by the time of its passage. A pure-foods bill was initially submitted (and patterned) after the 1875 British Pure Foods and Drugs Act but was stalled in Congress for decades because of industry influence and debate over the constitutionality of the legislation.

When the Pure Food and Drug Act of 1906 was finally passed, it provided the basic requirements for the listing of manufacturer, weight or volume of contents, and ingredients for any food or drug produced for sale in the United States, and implemented penalties for the production of unfit, mislabeled, or contaminated foods both for domestic consumption and for export [9]. It also contained the "Beveridge Bill" (named for Indiana senator Albert J. Beveridge), strictly regulating practices in the beef industry that was passed under the threat of making public a report conducted by Commissioner of the Labor Bureau Charles P. Neill, and Assistant Secretary of the Treasury James B. Reynolds into practices Chicago's beef-packing operations [10]. Intriguingly, the Congress also approved boric acid as a meat preservative almost immediately after adopting the Act, thereby approving one of the pivotal alleged contaminants for further use. These regulations have been periodically updated and expanded as the industry and science have evolved to include food, drugs, cosmetics, medical devices, and many other items.

Whereas original legislation was concerned with simply eliminating harmful contaminants, and considered food as adulterated or unfit "if it contain any added poisonous or other added deleterious ingredient which may render such article injurious to health," it did not set specific levels for contamination or trace materials, most of which were below the detection limits of the analytical methods of the era. As analytical techniques improved, the concept of "any added poisonous or other added deleterious ingredient" inevitably collided with modern analytical techniques and equipment sensitive enough to detect trace contaminants into the parts-per-trillion range. This has required making decisions about the minimum acceptable level of contamination for both direct and indirect food additives. These levels have been subject to occasional changes and a good deal of debate as analytical techniques, medical knowledge of the substance's effects, and considerations of total dietary intake have shifted. As a part of most country's regulatory policies, food packaging must not represent a source of "contamination" of the food, and in most cases may not be used as a means of adding a food component that is not properly represented in the label statement. It remains to be seen what sort of labeling requirement will emerge for active packaging materials that become an integral part of the food production process, such as those which react with foods during storage to remove lactose or perform other functions, as described in Chapter 8.

Further regulations by other government agencies have been implemented to regulate toxic materials that may be released into the environment. Packaging materials are also regulated because they are food contact substances and can release *indirect additives* – materials that will contaminate food after it is processed and packaged – into a food product. This may be a beneficial effect, such as the antioxidants that are incorporated into butter and margarine overwraps to reduce oxidation of fats, but the largest concern is with harmful contaminants such as lead from soldered can seams, carcinogenic monomers from plastic materials, and organic solvents from printing inks. More modern, contentious issues such as the issue of correlation of teratogenic effects (teratogenic substances interfere with normal fetal development, and may cause birth defects or later problems in maturation and sexual differentiation) and endocrine disruption with low-level chemical exposure to plasticizers contained in polymeric packaging components continue to be a source of debate.

Food and Packaging Laws and Their Related Agencies

Although food or packaging law can (and has) become an entire professional specialization, this chapter will attempt to outline some of the more consistent requirements of packaging legislation in the United States' laws without belaboring the minutiae of any of them considering that they represent a mountainous volume of material, some of which will inevitably be subject to periodic change. Rather, the intent is to outline the general intent of the legislation and technical requirements to illustrate the legal framework within which the food processing and packaging operates. European Union regulations rely more on a coordinated panoply of member country's internal regulations, overseen by the European Food Safety Authority for food hazards, as well as specific acts of EU legislation such as the European Parliament and

Table 10.1. Food Production Laws and Standards of Selected Countries

Country/Region	Document	Access
Australia & New Zealand	Australia New Zealand Food Standards Code	http://www.foodstandards.gov.au/thecode/foodstandardscode.cfm
People's Republic of China	PRC Food Safety Law (2008)	http://www.euchinawto.org/index.php?option=com_docman&task=doc_download&gid=449
EEU	EU – Food Safety From The Farm To The Fork	http://ec.europa.eu/food/index_en.htm
EEU*	Product Labelling and Packaging	http://europa.eu/scadplus/leg/en/s16600.htm
India	The Food Safety and Standards Bill (2005)	http://mofpi.nic.in/foodsfty.pdf
Japan	The Food Safety Basic Law (Tentative Translation)	http://www.fsc.go.jp/sonota/fsb_law160330.pdf

*Also recommended: Heckman, Jerome H. (2005), "Food Packaging Regulation in the United States and the European Union." *Regulatory Toxicology and Pharmacology* 42: 96–122.

Council Directive 94/62/EC of 20 December 1994 on packaging and packaging waste [11]. A strict correlation of function between US agencies and EU or other countries' similar entities would be the subject of several more chapters, if not several books. A table of Web-accessible English-language references to other countries' food safety and packaging regulations is listed in Table 10.1.

Whereas the usual description of food packaging regulations goes into excruciating detail about labeling requirements for food packaging, it is also instructive to see how many systems of regulation can affect packaging in various ways. Because packaging is a globally integrated field, drawing from nearly every segment of both science and commercial practice, the list of involved agencies is enormous and can be described here only briefly.

National Institutes of Standards and Technology (NIST)

The general principle that predominates with most products is that protection of the consumer means that measurement error must be minimized during filling. The method used by all US agencies (unless otherwise specified by special circumstances) for checking the net contents of all types of packaged goods is given in NIST Handbook 133 [12]. Additionally, NIST publishes or is involved in nearly all standards of measurement and purity at some level, from weights and measures to standardized test substances and the traceability of measurement back to known standards.

Federal Trade Commission (FTC)

The Federal Trade Commission regulates deceptive packaging and unfair trade practices in non-food products and may be involved in food products that are mislabeled in terms of quantity or package type. Additionally, the FTC is responsible for marketing claims such as "Sale" or "Economy-Sized," as well as environmental claims such as "Biodegradable" and "Ozone Friendly." In general, this means that the size of the package relative to its contents, as well as many of the label statements, is covered by the FTC. Excessive headspace, false bottoms, and "outage" (loss or reduction of product during transportation and storage) are typical concerns in terms of package size and are the reason that a disclaimer such as “product is sold by weight not volume – some settling may occur” is often put on products that settle in shipping, such as breakfast cereals. Under-filled packages that exceed the limits of filling error as well as intentional deception can be the cause for product recalls or consumer reimbursement.

United States Department of Agriculture (USDA)

The USDA regulates production, labeling, and packaging of fruit, vegetables, meat, and poultry products that are not subject to the Pure Food and Drug Act. The typical label must contain: a statement identifying the product, net content weight, list of ingredients in descending order of predominance (this is not required for whole-muscle products such as chicken breasts), and the name and place of business of the producer, as well as the inspection legend and establishment number, if applicable, and safe handling instructions. Nutrition labeling is voluntary for single-ingredient products such as steak or chicken breasts and may be provided as point-of-purchase information. Nutrition labeling is mandatory for those other products that are supplemented (have additional added ingredients). As of March 16, 2009, Country of Origin Labeling (COOL) is required of retailers of meat and poultry and retailers of fresh and frozen fruits and vegetables with an invoice value over $230,000 annually [13]. COOL is required on:

- Muscle cuts and ground meat of beef, lamb, chicken, goat, and pork
- Fish and shellfish
- Perishable agricultural commodities (fresh and frozen fruits and vegetables)
- Peanuts, pecans, macadamia nuts, and ginseng

Retail establishments such as restaurants, delicatessens, salad bars, and the like are excluded, as are many processed foods and game meats [14].

United States Food and Drug Administration (FDA)

The Food and Drug Administration is the agency with the primary responsibility of enforcing the current version of the original Pure Food Act, now the Federal Food Drug and Cosmetics Act (FFDCA). This has been amended frequently as the agency contends with more issues and as the technology and level of scientific knowledge changes.

The FDA currently regulates biologics, cosmetics, drugs, foods and beverages, medical devices and materials, radiation-emitting electronics, and veterinary products and devices. For food and beverage products, there are some exemptions, many of which are intended to reduce regulatory burdens on small businesses, which are often overseen by state agencies. Small businesses with fewer than 100 employees and fewer than 100,000 units/year sold are typically exempt from federal oversight, although they may be overseen by state agencies. Facilities that produce food for immediate consumption, such as restaurants and delicatessens, are also not regulated by the FDA, although they are usually under the scrutiny of state and local food service inspection systems.

In grossly oversimplified terms, FDA regulations are concerned with the safety of the food formulation, the proper labeling of the product in terms of its nutrition and health effects, and the longer-term interactions between the product and food contact substances, including the package. Additionally, it requires that the producer (or, more commonly, the distributor) of the product is identified on the package. In order to eliminate pointless testing to ensure that every commonplace ingredient and material such as clean water and properly prepared grains are safe even though they have been used since prehistoric times, the agency lists "Generally Recognized As Safe" (GRAS) ingredients and food contact materials for exclusion from approval. As new or previously unlisted ingredients and materials are developed for use with food products, they must be proven safe by the manufacturer, often after extensive testing, usually in animal-model studies. For an ingredient that is likely to see large-scale use, such as a new artificial sweetener, these tests may be extensive if it is a synthetic product such as cyclamates, or less stringent for a plant-extract material such as rebaudioside A, a purified stevia plant extract. Obviously these tests may be expensive and have historically been time consuming – an issue that the FDA contends with on a continuing basis.

For packaging materials, the major concern is the extraction of packaging materials into the product, which often presents a much smaller hazard. The approval process for new packaging materials and some additives has several faster options available, provided that the dietary exposure to the extracted material is small and the material is non-carcinogenic. These approval paths, the Threshold of Regulation and Food Contact Notification, are outlined later in this chapter.

The food labeling originally begun with the Pure Food and Drug Act of 1906 required the identification of a product, its net weight, the manufacturer's name and address, and an ingredients list in descending "order of predominance." The subsequent 1938 Federal Food Drug and Cosmetic Act added the regulation of production and distribution of food, set food Standards of Identity for common items such as catchup and orange juice, and set quality standards and acceptable levels of fill-in containers. Standards of identity were developed to promote a minimum standard of manufacture for particular items that were commonly produced by many manufacturers in order to ensure that consumers received acceptable products regardless of the source. This has had some interesting side effects, in that one of the compromises agreed to in the legislation was that if a product met the minimum Standard of Identity, it was allowed much more leeway in making advertising claims. The predictable result of this is that although many essentially identical Standard of Identity products such as ketchup are on the shelf, they compete for the consumer's dollar with claims of "better" or "thicker" or "more flavorful" without verification [15]. Another sometimes contentious effect is that certain foods such as children's breakfast cereal hover just below the requirement for labeling as "candy" because of the extraordinarily high sugar content.

Amendments such as the 1973 Nutrition Labeling Regulations, which began listing nutrients on a voluntary basis, were later supplemented with the requirement for sodium labeling and the revisionary 1990 National Labeling and Education Act (NLEA) that required nutritional labeling for most foods (those that neither make a nutritional claim nor have an added nutrient are often exempt), and was quite specific about how and where the labels were to be presented. It additionally clarified the requirements for making claims about the foods both in terms of health benefits and other more consumer-oriented statements such as "light" or "fat free."

The NLEA also prohibited states from enacting laws that differ from federal laws regarding items such as standards of identity, labeling, and packaging, but in turn allowed states to bring action under federal statutes in an attempt to unify the regulation of food manufacturing.

Current food labels describe "serving sizes" (which seemingly have little bearing on the amount that consumers typically eat or the calories they consume) and is based on "typical portion sizes (from food consumption surveys), ease of use, nutrient content, and tradition (of use in previous food guides)" [16]. The labels must bear ingredients in descending order of percentage of content. The nutrition information panel contains both mandatory components and voluntary components, as shown in Table 10.2. Voluntary components become mandatory

Table 10.2. NLEA Required Food Package Label Components

NLEA Nutrition Information Panel Components[i]	
Mandatory	Voluntary
Total Calories	Calories from Saturated Fat
Calories from Fat	Polyunsaturated Fat
Total Fat (g)	Monounsaturated Fat
Saturated Fat (g)	Potassium
Cholesterol (mg)	Soluble Fiber
Sodium (mg)	Insoluble Fiber
Total Carbohydrate (g)	Sugar Alcohol – usually a sugar substitute such as sorbitol or xylitol
Dietary Fiber (g)	Percent of Vitamin A as Beta Carotene
Sugars (g)	Other Essential Vitamins and Minerals
Protein (g)	
Vitamin A	
Vitamin C	
Calcium	
Iron	

[i] *Source*: The Food Label. http://www.cfsan.fda.gov/~dms/fdnewlab.html

if a claim is made about any of the optional components or if a food is fortified or enriched with a component.

NLEA and Health Claims

In July 2003, the FDA issued two guidance documents regarding "qualified health claims" on food labels. A qualified health claim is one that is accompanied by a qualifying statement to indicate that there is some degree of uncertainty regarding the scientific validity of the claim.

The FDA will approve qualified health claims in situations where the scientific evidence supporting the claim falls short of that required for an unqualified health claim under the Nutrition Labeling and Education Act of 1990 (NLEA). Under NLEA, for an "unqualified" health claim to receive authorization, it must be supported by the totality of publicly available scientific evidence. There must be "significant scientific agreement" (SSA) among qualified experts that the claim is supported by such evidence. One example is that of soluble fiber and reduction of heart disease. The Food and Drug Administration Modernization Act of 1997 (FDAMA) provides a second way for the use of a health claim on foods to be authorized. FDAMA allows certain health claims to be made as a result of a successful notification to FDA of a health claim based on an "authoritative statement" from a scientific body of the United States, such as the US or other credible government source, or the National Academy of Sciences, among others. Dietary supplements, a distinct class of edible materials in the eyes of the FDA, are subject to a great deal less scrutiny and are allowed a great deal of latitude in poorly substantiated claims of health benefits. Because of the low level of required scientific evidence and regulatory compliance, and often enormous profitability, both food and drug manufacturers continue to explore this area in many markets. EU regulators have taken steps to enforce the 2006 Nutrition and Health Claims Regulation on many of these products that are sold based on dubious or unproven health claims, much as British Parliament led pure food regulation in the United States by several decades.

Structure-Function Claims

Structure-function claims have historically appeared on the labels of conventional foods and dietary supplements as well as drugs. These claims describe the role of a nutrient or dietary ingredient intended to affect normal structure or function in humans, for example, “calcium builds strong bones.” For a structure-function claim, the manufacturer is responsible for ensuring the accuracy and truthfulness of these claims. Structure-function claims are not pre-approved by the FDA but must be truthful and not misleading. If a dietary supplement label includes such a structure-function claim, it must be labeled with an often-seen disclaimer: “This statement has not been evaluated by the FDA. This product is not intended to diagnose, treat, cure, or prevent any disease”.

Food Additive Petitions

Food additive petitions are the oldest and most difficult means of getting a new material approved. This can be an extremely arduous process for a new food ingredient such as a synthetic sweetener or fat substitute, and may require years of testing before approval is granted.

For packaging materials, the regulations hold that “[a]ny substance used as a component of articles that contact food shall be of a purity suitable for its intended use,” as well as:

> “Food-contact material must not transfer substances to food that may render the food injurious to health and, therefore, adulterated within the terms of Section 402 (a) (3) of the Federal Food, Drug, and Cosmetic Act (FFDCA) The food-contact material must not impart a taste or odor to the food that causes it to be unfit for consumption and, therefore, adulterated within the terms of Section 402 (a) (3) of the FFDCA.”

Because of this, it is incumbent on the manufacturer to prove that new materials are safe for their intended use, and this must be accompanied by a substantial amount of scientific data demonstrating that no contaminants will be extracted from the packaging material into the product. Thus, to file a petition for the use of an indirect food additive, extractability studies usually must be performed. For packaging materials, this usually involves exposure of materials to food simulant, a solvent that approximates the type of product the packaging material will be exposed to. To simplify testing somewhat, simulants are broken into several simple categories generally outlined in Table 10.3 [17]. There are many exceptions and variations on this general protocol depending on the food type, toxicity of the material involved, dietary exposure, and intended use. If new data indicate a lower level of acceptable exposure to a substance, that

Table 10.3. List of Food Simulants for Extractability Studies

Food Type	Recommended Solvent
Fatty Foods Meats, High Oil Content Foods	Food Oil (Corn Oil, Fatty Triglycerides, or coconut oil)
Aqueous or Acidic Foods Pickles, Sauces, Fermented Products	10% Ethanol (EOH) solution in water
Low Alcohol Products (EOH < 15%) Beer, Wine, Fermented Alcoholic Beverages	10% or actual EOH concentration in water
High Alcohol Products (EOH > 15%) Distilled Spirits, Flavor Extracts	50% or actual EOH concentration in water
Exposure time is most often 10 days at 40°C	

also needs to be taken into consideration even in evaluating a material with long-standing FDA regulatory clearance.

Because of the extraordinarily long approval period and expense of testing, the FDA has created two alternate systems that may apply to low-level, non-carcinogenic extractables: the Threshold of Regulation Request and the Food Contact Notification.

Threshold of Regulation (TOR) – 21 CFR 170.39

Requests are made through the Threshold of Regulation Program of the FDA to allow an exemption for food contact substances if it is determined that the consumer will not ingest a large amount of the product or migrating compound. A dietary concentration of 0.5 parts per billion (ppb) is a typical upper level for TOR approval, and 0.5 ppb is the dietary concentration threshold for most food contact substances, provided that the substance is not carcinogenic. If no new data is necessary (usually because of previously published studies) the approval process can be very fast, often less than 120 days. Dietary concentration is calculated by applying appropriate reduction factors (i.e., food-type distribution and consumption patterns) to the measured or calculated worst-case migration values. Thus, the threshold of regulation can be met even if the migration level is much higher than 0.5 ppb. The Threshold of Regulation exemption, once granted, does not grant any proprietary rights to the filers and effectively provides clearance for all manufacturers of a particular material.

Food Contact Notification (FCN) Sec. 409 [21 USC §348]

Food Contact Notification filings can be submitted for any substance that is properly classified as a "food-contact substance" and has largely superseded the TOR program. There are exceptions for some substances for which the calculated dietary exposure exceeds 1 part per million (ppm), but generally speaking, for substances whose dietary intake exceeds 0.5 ppb, some amount of toxicity data will be needed to demonstrate the safety of this level of exposure. For low dietary intakes – up to 50 ppb in the diet – this means submitting reports of *in vitro* genotoxicity assays such as an Ames test, mouse lymphoma, or chromosome aberration study. These can be studies performed by the notifier or obtained from the public literature. Of course, if these studies do not provide uniformly negative results, this will complicate the review process. If the dietary exposure is higher than 50 ppb, it may be necessary to submit more extensive toxicity data such as oral sub-chronic study in rats/dogs. These studies must demonstrate a clear No Observed Adverse Effect Level (NOAEL), and the NOAEL must exceed the calculated dietary exposure by a safe margin, usually 1,000 times. The advantages to the filing entity are that the FDA has only 120 days to complete its review of the notification, and in the absence of an explicit FDA objection by day 120, the notification automatically becomes effective. Additionally, the notification only approves the food-contact substance of the manufacturer/supplier listed in the FCN, which may offer an incentive for filing for approval in a competitive market. Of course, this does not prevent others from submitting their own notifications to get approval of similar, competitive products.

National Marine Fisheries Service (NMFS)

Although the FDA and USDA are the primary sources of regulation for seafood, the NMFS offers inspection services and legally recognized certification of seafood and related processing operations [18].

Bureau of Alcohol, Tobacco, Firearms and Explosives (ATF)

The Bureau of Alcohol, Tobacco, Firearms and Explosives (the acronym omits the "E" for recently added responsibilities with regard to explosives), which is administered by the US Justice Department, regulates – as its name implies – the manufacture, labeling, transportation, and packaging of alcoholic beverages, tobacco products, firearms, explosives and related materials, as well as some aspects of advertising for wine, distilled spirits, and malt beverages. Tobacco products and alcoholic beverages are subject to a variety of regulations in terms of specific labeling about the type and number or volume of product as well as health warnings about their use. Although the interstate transportation of explosives and ammunition is outside the purview of this book, it is useful to remember that high-proof alcoholic beverages may be quite flammable and require specific marking of containers and placarding on vehicles that transport them.

Department of Transportation (DOT)

The Department of Transportation oversees the transportation of goods in nearly every mode of conveyance imaginable. Because of the differing modes of transportation for different types of materials, the responsibilities for enforcement of these regulations are further delegated to the Federal Highway Administration, the Federal Railroad Administration, and the Federal Aviation Administration. Marine shipping is the responsibility of the DOT's Maritime Administration as well as the Federal Maritime Commission, under the Department of Commerce. With the Surface Transportation Board (STB) of the DOT replacing the previous Interstate Commerce Commission in 1996, and taking over the regulation of certain parts of the truck, rail, bus, and pipeline transportation of goods, many of the rate and classification systems for non-hazardous freight have been left to several industry groups discussed subsequently.

The most familiar face of DOT regulations in packaging are the distinctive system of hazardous materials markings illustrated in Figure 10.1.

Figure 10.1. Hazardous Material Placard

The Department of Transportation oversees the transportation of goods, and particularly hazardous goods, as specified in 49 CFR§172 [19]. The Hazardous Materials Table contained in 48 CFR§ 172.101 specifies the type of packaging, marking, documentation, and surface vehicle placarding used for an extensive list of various types of hazardous chemicals.

Air shipments of hazardous materials are regulated by the Federal Aviation Administration (FAA), which is concerned with the safety of the aircraft involved as well as the passengers, considering that most airlines fly mixed freight/passenger routes. Further shipping rules are put forth by the Air Transport Association in the United States and by the International Air Transport Association internationally. Thus, the shipment of particular materials that are generally detrimental to airframes (such as strong bases and mercury) and flammable, explosive, or other destructive materials may be prohibited or strongly regulated by the FAA; other less hazardous materials may covered be under the rules put forth by the respective industry groups.

Shipments of materials into space, although certainly a specialty market at this point (typically, 20–25 commercial launches per year worldwide), are also controlled in the United States by the FAA, who licenses commercial space transportation [20]. Given the extraordinary costs involved in getting material into low suborbital flight, there is always an enormous premium placed on the weight and material efficiency of payload design and resistance to the acceleration and vibration encountered during launch (and re-entry for missions that return material rather than leaving it in orbit). There is little need for extensive packaging regulation at this point considering how few commodity-level goods are shipped in this manner so far.

The Environmental Protection Agency (EPA)

While the FDA and USDA concerns about food packaging have to do with the effect on the product and the consumer, EPA regulations address concerns about the package and its contents' effect on the environment. Thus, concerns about post-consumer effects of packaging on the environment have lead to such things as the prohibition of many toxic metals, particularly those used in printing and polymer production and stabilization in significant concentrations, that may leach into groundwater supplies or otherwise affect public health.

Because the EPA is generally responsible for pesticide and antimicrobial environmental regulation, and some types of food packaging have been developed with antimicrobial and insecticidal properties as well as antimicrobial additives to foods themselves, an agreement was reached in the Food Quality Protection Act of 1996 giving the Food and Drug Agency jurisdiction over antimicrobials in food packaging, which would otherwise be considered as pesticides and be under the jurisdiction of the EPA, as shown in Figure 10.2.

Additionally, state regulations in nineteen states (California, New Hampshire, Connecticut, New Jersey, Florida, New York, Georgia, Pennsylvania, Illinois, Rhode Island, Iowa, Vermont, Maine, Virginia, Maryland, Washington, Minnesota, Wisconsin, and Missouri) prohibit the intentional use of lead, cadmium, mercury, and hexavalent chromium in packaging or individual packaging components, such as coatings, inks, adhesives, or labels above a level of 100 ppm, with some exceptions for recycled-content, reusable containers, and recycled packages [21]. Because these prohibitions affect a very large percentage of the national market, they have driven a national effort to reduce these metals in packaging materials that are used in national distribution.

Additionally, the EPA regulates permissible discharges from processing operations, which may be a concern with residual processing chemicals, as well as biological oxygen demand

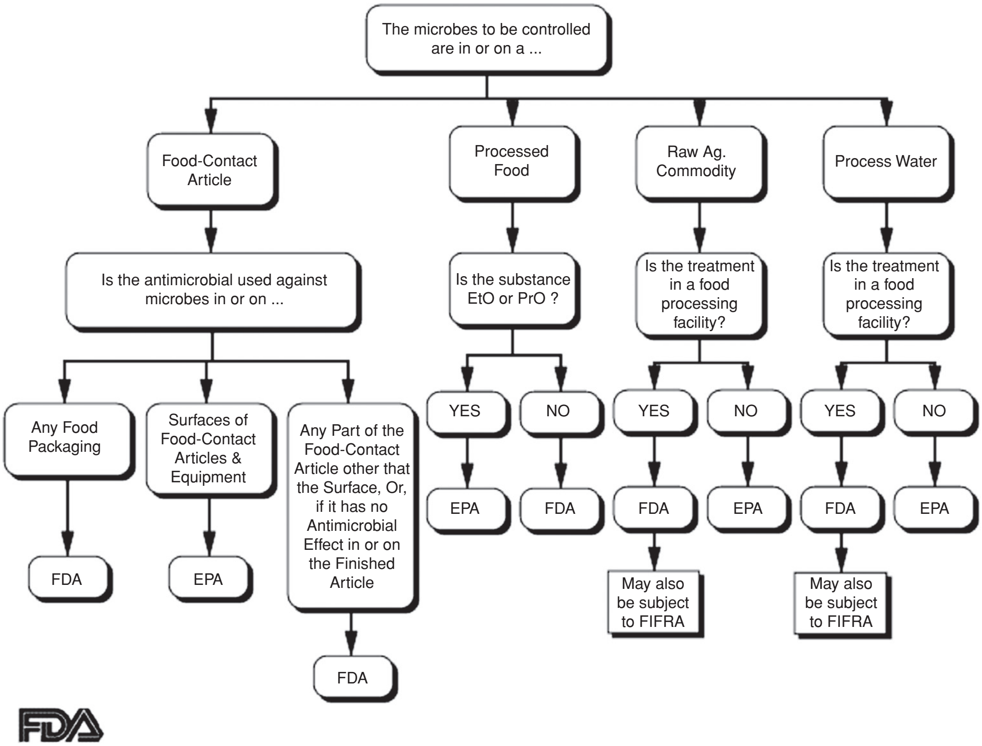

Figure 10.2. FDA Antimicrobial Flowchart
Source: FDA

(BOD) from food-processing waste and large-scale animal processing facilities, among other concerns.

Department of Homeland Security (DHS)

DHS was established to coordinate and assimilate functions from many pre-existing departments of the federal government, as well as to create a unified security structure for national defense. Although the general requirements for security will be discussed in a subsequent part of the chapter, in general, DHS oversees most of the concerns regarding bioterrorism, product and package tampering, and disruption of the food supply in coordination with the USDA, FDA, and Health and Human Services' Centers for Disease Control, among others. Although best known for luggage screening at airports, the DHS has been assigned the task of overseeing both commercial and private activities that might constitute a threat to the security of the country, including the food processing and packaging industries. This has led to increased security surrounding food processing facilities, among other changes.

Department of Defense (DOD)

The Department of Defense oversees military and related operations in the United States. As such, it is also responsible for the large-scale purchasing of materials and supplies for use by the military. The requirements for these are often much more stringent in terms of safety, damage prevention, and, for food and medical supplies, shelf life and quality extension. The Meals Ready to Eat (MRE) rations that have replaced canned rations must survive for three years of storage (and are often stockpiled beyond that) as well as being air-dropped without a parachute. Ordnance, instrumentation, and communications gear must often survive shipping and deployment conditions far in excess of that seen by consumer items, with the result being that the DOD and its agencies may have distinct and stringent requirements for processing and packaging of products, and sub-industries have sprung up to assist in both understanding and fulfilling these requirements. Packaging requirement codes are given by MIL-STD-2073-1E in a standardized form that may describe wrapping material, unit container levels, and other requirements, with other requirements and standards used on a contractual basis, although specialized items and devices may also carry specifications for specialized packaging for deployment.

United States Post Office (USPS)

The United States Post Office led the way to the mass-distribution of goods in the United States that barely had a transportation infrastructure by implementing the Rural Free Delivery system. This allowed the creation and explosive growth of “modern” catalogue-order retailing operations that have since metamorphosed into our current online ordering and rapid delivery industry. It remains the major conduit for written communications and carries a staggering number of goods and documents, although it competes with private carriers for the latter. For obvious reasons, the post office sets both limits on what can be sent and the manner in which it must be packaged. There are substantial limitations on hazardous, restricted, and perishable materials, as given in USPS Publication 52, and maximum weight, labeling, and sealing are all subject to minimal strength and integrity standards [22, 23].

For large quantities of materials to be handled by the Postal Service, such as a mail-order operation, the local USPS station may work with the customer to provide approved bins, trays, or other means by which goods can be presorted or otherwise fitted into the facility’s workflow.

United States Patent and Trademark Office (USPTO)

The USPTO, a unit of the Department of Commerce (DOC), is the office in charge of documenting and regulating patents, trademarks, and copyrights, which puts it squarely in the midst of most of the modern media-usage debates and any number of other contentious intellectual property disputes. Patents typically protect the inventor for an initial period of 17 years, and extensions can be filed. There is a substantial risk, however, because filing a patent requires public disclosure of the nature and method of the invention. Much industrial research is concerned with *patent breaking* – creating a similar product without violating the exact terms of the patent, and often using the disclosure inherent in the patent filing. Because of this, many businesses do not file patents, preferring to rely on their own internal security measures as well as contractual non-disclosure agreements and confidentiality agreements for protection.

Trademarks and service marks are marks, logos, or other content used to distinguish a product. A *trademark* is a word, phrase, symbol, or design, or a combination of words, phrases, symbols or designs, that identifies and distinguishes the source of the goods of one party from those of others. A *service mark* is the same as a trademark, except that it identifies and distinguishes the source of a service rather than a product.

> *For goods*: the mark must appear on the goods, the container for the goods, or displays associated with the goods, and the goods must be sold or transported in commerce.
>
> *For services*: the mark must be used or displayed in the sale or advertising of the services and the services must be rendered in commerce [24].

The "in commerce" stipulation requires that the trade or service mark is actually used rather than simply being pre-emptively filed in order to prevent others from acquiring it and preventing further use, as has often been done with Internet domain names.

Trademarks and service marks offer the benefits of constructive notice nationwide of the trademark owners' claim, and the legal use of the® and **SM** symbols, respectively. The jurisdiction of federal courts can be invoked in disputes over trademark and service mark issues and the ownership can be used both as the basis of filings for foreign equivalents and of registration filed with U.S. Customs Service to prevent importation of infringing foreign goods. Trade and service marks have a ten-year renewal cycle and typically may be used as long as they are for products or services rendered in commerce.

Library of Congress – Copyright Registration

Copyright filing with the Library of Congress will regulate "Rights to Copy" of media. These are effectively the right to use, distribute, sell, and make derivative works from original "material," which may be any type of idea, information, or media content that can be kept in any kind of substantial form [25]. Traditionally thought of as protecting written works and music, copyrights also cover many other types of intellectual property such as architectural designs, boat hull designs, and even choreography. Whereas copyright law is at the heart of much of the controversy around the disruption of traditional media distribution (such as digital online music sales), for commercial applications such as food manufacturing and packaging, the concern is more often with the marketing information that is part of the overall brand identity and sales campaign.

Copyrights usually extend for the life of the original author(s) and can be renewed for very long periods of time (often 50–100 years). Increasingly stringent enforcement provisions such as the Digital Millennium Copyright Act and the 1996 treaties of the World Intellectual Properties Organization have criminalized the act of distributing some types of copyrighted material, particularly those related to mass media and software. This has led to some ludicrous enforcement actions against individuals who copy purchased music for their own use or perform live copyrighted music in small, nonprofit venues, but it is also a necessary part of preventing fraud and counterfeit goods production and distribution.

Consumer Product Safety Commission (CPSC)

Most often thought of in its role of recalling defective and unsafe consumer products, the CPSC regulates many different types of products that are not under the jurisdiction of other government agencies. It also has issued the Poison Prevention Packaging Act in 1970, subsequently amended, which requires child-resistant packaging for household substances that it deems hazardous (including foods, drugs, cosmetics, and fuels) [26]. The technical testing specifics are more fully discussed in Chapter 4, and the original provisions of the bill have been amended to include some requirements for certificate of manufacture, which are a matter of some controversy. There are exemptions based on whether the product is expected to be used in the house, is a pharmaceutical to be repackaged by a pharmacist, and similar occurrences, but the end result is that thousands of household poisonings of children are prevented each year. While child-proof packaging is the butt of many jokes (and is claimed to be adult-proof as well), and there have been concerns about adults leaving them off at the risk of poisoning children, the benefits are substantial [27]. The CPSC also tracks the approximately 6,000 emergency room visits for lacerations and punctures caused by trying to open obstinate packages with sharp tools [28].

Occupational Safety and Health Administration (OSHA)

OSHA, under the Department of Labor, has been mentioned in conjunction with several other particular aspects of packaging and food processing, but in general is concerned with preventing workplace-related injuries and health problems, and ensuring compliance with the Occupational Safety and Health Act of 1970. The more general involvement in the packaging and food processing industries have to do with OSHA regulations requiring proper safety equipment and training as well as adequate safeguards on operating machinery. Printing equipment and packaging machinery can be particularly dangerous if the operating mechanisms are left unprotected, and requirements demand guards on nearly any accessible part where contact with moving or dangerous equipment may occur.

Personal protective equipment, permissible exposure limits (PEL) to a substantial list of chemicals, "Right to Know" communications about chemical products, and process safety management standards may also come into play, although many of the latter are targeted at the chemical and petroleum industries. Because many of the hazards are made known by employees or other non-management personnel, there are also whistleblower protection provisions as well as authorization to access information, particularly where an accident has occurred [29].

The National Institute for Occupational Safety and Health (NIOSH), which develops safety procedures and ergonomic standards, is not administered by OSHA but by the Department of Health and Human Services. Even though the two institutions have approximately the same mission, and OSHA makes use of NIOSH information, the latter is considered to be more research-related and deals with a variety of unusual issues, from Alaskan aviation to "body art" [30].

Private Carriers

The National Motor Freight Classification dictates the type of packaging to be used for truck transport, and is a set of tariffs originated by the now-defunct Interstate Commerce Commission (predecessor of the DOT) and now managed by the American Trucking Association's National Motor Freight Traffic Association [31]. Item 222 of the National Motor Freight Classification (NMFC) lists the specifics of packaging mandated by the tariffs both by box type and by corrugated board type and strength. Additionally, the NMFC lists "general packaging definitions and specifications, specifications for packages that have been approved expressly for the transportation of certain commodities, and performance-based packaging criteria."

The National Railroad Freight Committee's Uniform Freight Classification (UFC) Rule 41 provides similar (and often identical) tariffs for rail freight in the same manner. Although this may seem restrictive, the requirements are minimums that allow a good deal of latitude for packaging design, and may avoid problems with accusations of insufficient packaging in the event of damage claims being filed on a shipment.

Private delivery carriers such as United Parcel Service and FedEx require compliance with Rule 222 for most commercial manufacturers and may have additional requirements in their tariffs if the shipment is to be transported by air. For small consumer shipments, the requirements may be simply to be well packed as assessed by the counter personnel, and to not be carrying a list of proscribed materials such as explosives, biohazards, or dangerous chemicals. These may have some additional latitude in "Surface Only" shipments that avoid the more stringent air carrier safety standards, but will take longer to arrive.

Food Safety and Security Systems

Although food safety has always been a concern with fresh and preserved food products, recent political concerns with the security of food, particularly imported food, that travels large distances very quickly has generated another layer of complication that may force information technologies to stretch in order to trace and account for shipments. Additionally, food processing facilities have quietly become much more secure, limiting unsupervised access because the introduction of a dangerous component into a centrally located food facility could have far-reaching consequences, as recent instances of contaminated imported and domestic food ingredients has shown.

Food safety, defined here as the unintentional contamination of food, has been a concern throughout history, considering that nature has all sorts of microscopic organisms, vermin, and toxins that are capable of rendering food inedible or poisonous. The commercial agricultural and food distribution system has been dealing with these issues for some time with a high degree of success, as have the agrarian societies that preceded them. Current political developments have prompted a great deal of concern about the food security, which refers to both to the intentional contamination or destruction of a food supply via asymmetric warfare, terrorism, or hostility, and also refers to ensuring that a population has a sufficient food supply in the face of natural hazards or geopolitical conflicts.

Because of the nature of agriculture, the food supply is very accessible to external environmental inputs from any conceivable direction. Insect or chemical contamination can occur very easily, and it is difficult to provide any sort of meaningful security for vast expanses of farmlands. In tandem with this, the effect of a small contamination or infestation incident, if detected, will be easily contained and quarantined. As crops are concentrated and processed, the stakes of such actions begin to increase and the concern with safety increases as well. Finally, there is an "hourglass effect" for contamination incidents, with crops and retail distribution having the lowest effect and ingredient-level contamination being the most hazardous.

The hourglass diagram in Figure 10.3 illustrates that the most concentrated point of influence in the food production and distribution system would be located where operations and materials

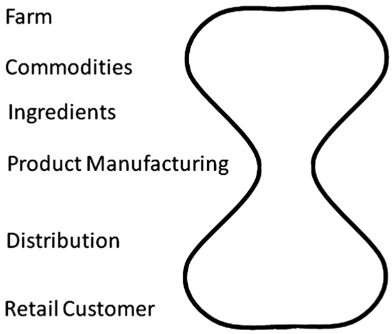

Figure 10.3. Security Hourglass

are concentrated, and then widely redistributed. Because of this, food production and distribution operations are being subjected to more intense security requirements, and producers and distributors themselves are faced with larger concerns about the products that they manufacture and distribute. Food ingredients have also become a matter of great concern because of the broad influence that a food additive that was used in a large number of products could have. Additionally, increased outsourcing of food ingredients to international suppliers can result in the complication of validating the received material as being genuine and safe.

HACCP

Current manufacturing practice usually involves the development of a Hazard Analysis and Critical Control Points (HACCP) plan to prevent hazards and contamination during the manufacturing process and to efficiently use resources rather than simply inspecting the final product for quality conformance. HACCP plans may be effective if designed and implemented correctly, and can save the manufacturer from serious processing failures, but there have been objections that some manufacturers are simply repackaging their existing hygiene programs as a HACCP plan for the appearance of conforming with requirements [32].

HACCP systems usually involve at least seven basic components [33]:

1. Hazard Analysis
   Potential biological, chemical, or physical hazards associated with a food and measures to control those hazards are identified.
2. Critical Control Point Identification
   Identification of the points the production system from raw materials to packaged product where the potential hazard can be detected, controlled, or eliminated.
3. Prevention
   Development of preventative methods with critical control limits to relevant specifications (such as temperature, pressure, and water content) for each control point.
4. Monitoring
   Development and implementation of monitoring procedures for each of the critical control points.
5. Remediation
   Development of remedial actions to be taken when a critical measure has not been achieved, such as under-cooking or over-dehydration of the product.
6. Validation
   Develop a system to verify that monitoring equipment is functional, accurate, and is being properly used as required.
7. Recording
   Implement archival records that document operation of the HACCP system. This should include records of hazards and their control methods, the results of monitoring of safety requirements, and any corrective action taken.

Product Recalls

For the food manufacturing and distribution system in most economies, there is usually some tracking and identification system in place to identify particular batches of processed product that may be contaminated or defective. Recently, contamination incidents with products such as ground beef and fresh spinach have highlighted a more “brittle” response – the kind that paralyzes a whole segment of the market – when grocers removed that entire particular product category from sale as a safety margin. This often has much more to do with the maintenance of consumer confidence than it does with a strategic elimination of hazardous products, and as such is inefficient and extremely costly in the long run. In any event, the ability to track individual batches of product using either open or closed coding types, as well as other means such as flagging particular UPC codes, indicates that the infrastructure already supports a moderately flexible response system. For a food product, regulatory agencies such as the Food and Drug Administration in the United States have a mechanism for issuing recalls, usually with a multistep approach [34]:

Class I recalls for dangerous or defective products that predictably could cause serious health problems or death. Examples of products that could fall into this category are food items found to contain botulism toxin, food with undeclared allergens, a label mix-up on a life-saving drug, or a defective artificial heart valve.

Class II recalls for products that might cause a temporary health problem or pose only a slight threat of creating a more serious problem. One example is a drug that is under-strength but that is not used to treat life-threatening situations.

Class III recalls for products that are unlikely to cause any adverse health reaction, but that violate FDA labeling or manufacturing regulations. Examples might be a container defect (plastic material delaminating or a lid that does not seal); off-taste, color, or leaks in a bottled drink, and lack of English labeling on a retail food item.

Recall management systems are a common feature in many operations, particularly in the food and pharmaceutical industries, and there are consulting firms that can assist smaller operations when needed. For manufacturing or processing defect issues, the response-and-recall system has been shown to be most effective when the companies involved are willing to immediately and effectively take ownership of the issue and then proactively drive the process. Delaying or denying the problem can result in an enormous illness or death, loss of consumer confidence, and the resulting loss of sales. In general, the four basic steps for managing product recall are [35]:

Planning

A recall plan and necessary acceptance infrastructure should be in place before any actual incident occurs. Simulated and test recalls can help highlight problems in the system before an actual recall occurs.

Response Time

A rapid response aids in dealing with the actual problem and will minimize any loss of consumer confidence in the product and the company. Additionally, a rapid response may reduce liability by restricting the infiltration of the contaminated product into the marketplace by holding them during distribution or at the retail level.

Effective Communication

Immediate and effective communication to all concerned parties is critical in a product recall. Communicating of the necessary identification and remediation instructions to the actual handlers, sellers, and customers of the product is of the utmost importance. Communication of the company's response to the problem is also critical in maintaining (and in some cases increasing) consumer confidence in the company and product line.

Follow-Up

Following up a recall event with analysis of the problems (and successes) of the response system will highlight any potential problems or areas that need to be addressed in the response strategy. Additional follow-up in re-marketing a product that has suffered a catastrophic loss of market position because of the effects of a recall may be required as well.

The actual steps to be taken in the event of a recall will vary considerably with the product. In the computer software industry, current problems are usually handled by “patch” downloads, arguably the most cost-effective means possible considering that the distribution is automatic and the installation is handled by the consumer. For other consumer products, the solutions will vary widely, ranging from additional repair parts being sent from the manufacturer allowing service personnel to remedy the problem and service recalls in the automobile industry, to food recalls where the product is removed from sale and the consumer is urged to not use that product for a short period. This last method is often catastrophic to a particular product or type of product and it may require careful management to re-establish consumer confidence in a useful time frame.

Food Security

All of the scenarios discussed so far have been those developed for use in response to a defective product that has unintentionally created a hazard, either through a fault of design or an oversight in manufacture and processing. The intentional hazards that make up food security issues have the additional factor of careful forethought and a degree of planning, but the same mechanisms that assist in “accidentally” contaminated product recalls can assist in providing a flexible response to an intentionally contaminated product, because there is little difference between the two events. The complete prevention of product problems by a clever and determined party may be nearly impossible, but an acceptable level of security can be provided by quality control checks and the understanding of the influence of a single contaminated ingredient at the “pinch point” of the hourglass. Paradoxically, for food products, the most influential contamination ingredients would be those used in the largest number of products, such as high fructose corn syrup and vegetable oil, but the large quantity used would mean that creating a broad contamination would be very difficult because of the large volume and number of suppliers. In the instance of manufacturers knowingly shipping contaminated product, there is little difference in final effect between that action and a politically motivated malicious attack. Recent problems with peanut butter contamination highlight the extraordinary delay, negligence, and lack of response by inspectors and local health officials, even though similar problems had occurred in nearby operations and had caused widespread illnesses [36]. This creates a system ripe for abuse, with the potential (as was shown) for widespread illnesses and several deaths.

Security Concepts

While the security industry utilizes a large number of increasingly technical solutions for both real and perceived potential threats, some basic concepts and questions underlie most of the solutions and policies. Assets to be protected are effectively “something you value.” This can range from personal property and bodily safety to something a good deal more abstract such as a computer password or the goodwill of a brand line [37]. Threats to these assets can result in actual “attacks” that can be foiled, mitigated, or recovered from. For any security measure that is to be implemented, as with any change in technology, one must consider what the actual threat is, what the costs of prevention are, and what further problems may be propagated by implementing those solutions [38]. The unintended consequences of many types of security changes can be significant, ranging from consumer inconvenience removing the inner seal from a bottle of ketchup to being arrested as the result of false identification by a criminal database. Additionally, security systems exhibit *emergent properties* – characteristics that occur as complex systems interact in unexpected ways.

Asymmetric warfare refers to conflict between parties where their power, numerically, technologically, or strategically, differs by a significant amount. This term has been adapted to refer to asymmetry of strategy or tactics, and currently the term often describes a military or civil-conflict situation in which parties of unequal power interact and attempt to take advantage of their opponents' weaknesses using widely differing tactics [39].

One of these tactics would theoretically include sabotage of infrastructure and the creation of distrust and fear within one of the parties' civilian population. Interestingly, this is often less of a concern in modern conflicts that are symmetrical in more conventional ways – the Cold War of the late 20th century saw little ongoing concern for the integrity of the food supply.

The popular impact of food contamination fear has been extensively shaped by previous incidents in the United States with product tampering, most notoriously the Tylenol poisonings in the 1970s. More recent problems with so-called *counterfeit goods* have highlighted the susceptibility of the supply chain to goods that have been counterfeited for financial gain. Unfortunately, it would be relatively difficult for each farm and each retail store to have the sorts of security that one typically faces at an airport, and the costs would be enormous. So a trade-off has been made in favor of increased security at the "pinch points" of the system – in the production facilities rather than in retail outlets, farms, restaurants, or fishing vessels.

In general, bioterrorism requires an infectious or poisonous agent, a means of dispersal (*vector*), whether it be insect transport or physical distribution, and a host that the agent can infect or poison. Usual bioterrorism controls seek to sequester the infectious agents before they can be dispersed, and will occasionally address the host directly with protective vaccines or other measures. Although the risk of bioterrorist attack is very low – the largest incident in the United States so far being the intentional contamination by the members of a religious cult in Oregon who were seeking to influence a city election, and the most deadly apparently being from a single person distributing anthrax through the mail – the potential for actual harm and general panic is enormous [40, 41].

The Bioterrorism Act of 2002 and subsequent amendments and modifications have added a significant amount of registration and oversight to the food production system which was, by comparison, very lax in its ability to import process and distribute food. Prior to the act, the chief concern was with the final product, and this has shifted somewhat by requiring registration of facilities, safeguards, and identification within production facilities, prior notice of imported materials, and allowing detention of raw and intermediate products before they are distributed [42].

The Role of Identification and Information Technologies in Food Security

The basic terminology of identification when used in a security context is important as many of the concepts are used interchangeably when they have distinct meanings. Identification is usually based on something that an item or person intrinsically has (a fingerprint, for example), something it is assigned (such as a name), something that it "knows" (such as a password), and something it might extrinsically carry (generically referred to as a "token," such as an identification card) [43].

Authentication of an identity occurs when the verifier compares an identifier against a different knowledge set looking for a match. Authentication allows a process to go forward, whether it be admittance to a work area or the acceptance of a shipment of materials. A good example of this would be the examination of the identification card of a student trying to get into a college bar. Comparing the picture on the identity card against the person attempting to identify themselves with it gives a rough means of verification and admittance to the establishment, although this is obviously circumvented on a regular basis.

With all types of identification used for authorization, the risk of both fraudulent and mistaken misidentification can be matched to the rewards from doing so. State drivers' licensing offices are frequently the subject of investigation as the sale of drivers' licenses can be worth several thousand dollars apiece, and an inattentive examiner can similarly mistakenly authenticate an identity document.

Counterfeit goods that have been produced to intentionally misrepresent themselves, either as a known commercial product or as having an inflated quality or safety level, are a profitable item for the sake of commercial gain, and have always existed. A good deal of ancient trade was based on the value of the quality of a product, and so misrepresented, sub-standard products always represented a chance at profitability. Recently, because of the inordinately high value of some items – pharmaceuticals and aircraft parts, for example – counterfeiting has been of great concern. Similarly, counterfeiting has been used to encompass intellectual property such as illegally copied music and software that is easily reproduced and distributed without paying fees and royalties.

Counterfeiting the identification of a particular food ingredient may be similarly desirable considering that misrepresenting the quality or safety of a particular item can bring enormous increases in financial gain. This is particularly true for items that are difficult for the average user to distinguish, and which vary widely in price. Ordinary seafood is routinely sold as more expensive species because it is hard to discern one fish from the next after processing. Misrepresentation of vintage wines is a relatively common occurrence, and more usual consumer items that have a high markup value based on quality attributes, such as extra virgin olive oil, are regularly the subject of fraud, often on a shipload scale [44,45,46]. With this in mind, a lot of the security features that are commonly advocated to safeguard the food supply are little more than window dressing in the face of an entity that is determined to gain access. Further, these offer the potential of allowing reliance on gadgetry rather than observation and common sense. Because of the highly developed distribution network for food products, in theory it should be possible to track shipments and to verify whether these are legitimate or not. What is not so certain is whether the system, already optimized for extreme low cost, will be willing to bear the expense of doing so.

Transparency is a critical component of safety as well, and one that is currently not required of food producers. The Heinrich Accident Triangle holds that each major harmful occurrence follows a certain number of minor occurrences – a principle that can hold true in nearly every security scenario, although unfortunately too often done in hindsight. With current food safety regulations, many of these incidents are never revealed by manufacturers because they are not required to do so (and are allowed to refuse inspector's requests for information). This has the effect of compounding the extent of safety and security problems because they can be well into distribution and incorporation into other products before a response even begins. In the event of malicious or intentionally fraudulent production of dangerous ingredients, the results can be a widespread event of sickness and even deaths before a response even begins, and the results can be destructive both to consumers and to the other, legitimate producers of similar items.

Information-Based Security Systems

The technological basis for an information-based security system has its roots in the cryptography sector that has been working to develop secure information transmission systems. In essence, many of these systems depend on a validation system where the information carried has no meaning to the casual (or intrusive) observer, but that can be unlocked with a key and mathematical algorithm to yield the validation code or message. This is the basis for the critical security features of nearly all electronic commerce, banking, Web-based purchasing, and credit card data transfer, and is often used to encrypt software and media files.

In essence, most security and encryption schemes rely on a linked two-part system: encryption and decryption (Figure 10.4). Historical methods required that these methods have the same method or algorithm, and the same *keys* for encryption and decryption. These keys are sequences used to scramble the *plaintext* message into apparently random characters, signals, or numbers termed *ciphertext* that have no apparent meaning or even pattern of information.

Recent developments have resulted in two-part keys based on large prime numbers, which produce so-called *public key* systems that allow encryption with one key and decryption with another. The most famous of these is the RSA algorithm based on modulo encoding using very large prime numbers, and which derives security from the computational difficulty of factoring these. In essence, the sender and receiver of information do not have the same key, and the use of one key does not make the other vulnerable, though the decryption key obviously must be kept private. Moreover, intercepting the ciphertext, whether it is electronic data, a printed label, or some other communications means, is useless without the ability to decrypt it.

The application to a food security system can involve validation at various points in the distribution system, verifying products' information against a validation key carried in a scanner, or other separate means. Because of the increased amount of information that can be carried in systems such as data-matrix optical coding schemes and RFID systems, the potential for a moderately secure, fairly complex, yet easily translated validation system has emerged.

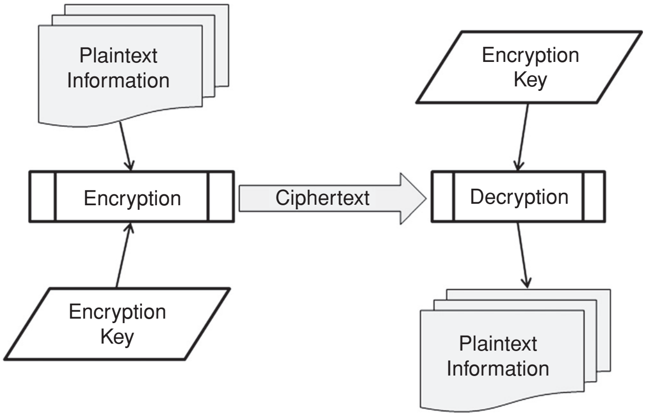

Figure 10.4. Encryption Flowchart

Other types of validation have been proposed, using printed interferometric methods, holographic validation seals, and other methods such as the inclusion of inert "validating" materials – even DNA fragments – in foods as a means of ascertaining whether they are genuine or not. Concerns about complexity, safety, and cost will often make these methods less attractive, and the time and the fragility of many validation systems as well as their susceptibility to *lifting* – removing the validation token from a legitimate item and transferring it to a counterfeit one – can render these only marginally useful for large-scale commodities such as food items.

Food System Response to Threats

Regardless of the identification, verification, and tracking systems used, once a problem, intentional or unintentional problem is identified, the food distribution and retail must respond in a rapid, appropriate, and flexible manner. Workers in systems security consider many response scenarios to be *brittle* – that is, when a system has a credible threat, the response requires the entire system to stop functioning or to be extraordinarily restrictive. A good example of this is current airport security system that often closes an entire airport's operation if an uninspected passenger enters a secured boarding area. The problem is not that this is an inappropriate response to an actual threat; rather, it is an inappropriate response to the perception of a threat. If the entire food distribution system of a country shuts down upon the detection of a single product tampering or contamination threat, every false alarm would be disrupting and expensive, and would result in a system that was completely dysfunctional. Worse, this kind of exaggerated response can be used to create a *denial-of-service* attack, which is the equivalent of setting off all the fire alarms in a building in order to keep legitimate users out, and might prove more harmful than more direct attacks.

As discussed in Chapter 8, the base-rate fallacy problem continues to apply: In a system with a large population (in this case, a large volume and diversity of products) that has a very low level of actual occurrences of some hazard, even a moderate number of false alarms can result in a maddening number of delays and shutdowns if the system is not adequately prepared to respond flexibly to varying levels of threat. Because of biological hazards that the food preservation systems were originally intended to defeat, and chemical contamination that occurs periodically, the threat of food safety problems have already created a fairly good system for responding to problems with particular food products.

More useful is the careful design of flexible response, where small segments of a particular system are shut down to contain a potential threat. Additional, judicious safeguards on the quality of the food supply both with regard to intentional and criminal contamination, as well as accidental errors in processing or formulation, when coupled with rapid methods of detection of contamination and a rapid response by the distribution chain, will probably justify the additional cost and complexity required to achieve these results.

As previously discussed, the current recall system is already a selective and responsive means to that end if used promptly and properly. Accurate, transparent, and responsive safety system allows the rapid containment of emerging threats before substantial harm is done and without paralyzing whole segments of the economy.

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Chapter 11

Closing the Loop – Disposal, Re-use, Recycling, and the Environment

In the packaging cycle that provides the framework for this book, the continuing path of the materials used in packaging after its first use lies within the consumers' decision to discard, recycle, or re-use the package, as shown in Figure 11.1.

Industrially developed countries have considered disposal of smaller containers as a traditional solution, although recycling is becoming more popular because of a combination of motivating factors that will be discussed in this chapter. Many ancient cultures and those in developing countries often re-use packages and transportation containers whenever possible because of the difficulty and expense of replacing them – a viewpoint that finds renewed relevance as manufacturers begin to consider not only the entire life cycle of the product, but the continued sustainability of their operations in a more global perspective.

The decision that the consumer makes is a complex one, touching on both pragmatic economic and technical realities and more idealistic social goals, although many times they are not aware of the process at the time. Similarly, setting societal expectations in the form of regulations, economic incentives, and social awareness is a complex problem that requires a broad understanding of the materials, economics, and public perceptions involved. Some of these factors will be discussed in this chapter, although this is by no means a complete treatment of the factors involved.

Bottles and other types of beverage containers have had some success in re-use either because of their design for re-use, ease of cleaning, and legislation requiring beverage manufacturers to take back containers ("Bottle Bills"), or because beverage manufacturers find it economically viable to put a deposit on their containers so that they can re-use them. Some of the examples that are used for industrial and distribution packaging were discussed in Chapter 9.

Whereas this solution may work as an incentive for re-use of glass containers and some specialized plastic beverage containers, most plastic and metal containers must be taken backward several steps into "raw" materials for recycling of the basic material into newly fabricated containers. Most other packaging types fall into the recycling category as well, although there is a patchwork of legal requirements and many types of technical and economic complications involved in recycling packaging. The materials-recycling solution is also gaining in popularity for containers and materials that are more obviously not reusable, as well as other durable and non-durable goods. As the infrastructure for transportation, reclamation, reuse, and marketing of these materials increases, the viability of re-use of even larger quantities of materials grows as well. The combination of diminishing resources (with an attendant rise in prices), legislative changes, and the difficulty of disposal has been a strong motivator for industries from

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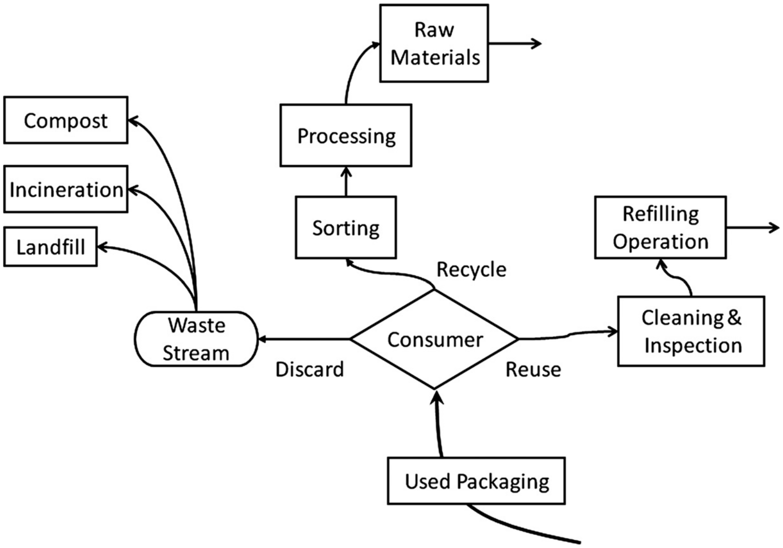

Figure 11.1. Flowchart of Materials after Package Use

automobile manufacturing to consumer electronics to begin to examine the complete life cycle of their products and the consideration of the sustainability of their operations. Finally, traditional disposal methods – dumping or burning – can no longer be seen as easy solutions because of public concerns with groundwater and air contamination, land use, and health effects. It is no longer possible to simply dig a hole in the ground and fill it with any sort of garbage in most developed countries – the town dump has largely disappeared. In its place, large and technically complex (as well as expensive) landfill sites have sprung up to fill the need for disposal space. Similarly, incineration has grown in complexity from the "burning barrel" stage to large-scale operations fitted with pollution control equipment and often capable of operating as an electric-steam co-generation facility. In the end, then, packaging that makes up a large and very visible portion of the discarded materials produced in most civilized countries will take the path of least resistance, either for economic, regulatory, or social reasons, but the path that it takes may be quite complex.

Re-use of Containers

The re-use of many types of food containers is currently impractical and unmarketable in a mass-marketing society. For a variety of sanitation and esthetic reasons, few consumers would bring empty soup cans to a store or factory to be re-filled even if it were technically possible, even though a moderate percentage of sturdy containers such as glass jars and steel cans are re-used for other purposes around the home. Re-use of containers demands an entirely separate handling system for the return, cleaning, and refilling of containers. This limits their applicability to containers that can be designed for many trips through the use cycle before degrading to the point where they cannot be used again. "Bottle Bills" – involving mandatory fees paid on purchased containers that are refunded to the customer when the container is returned – currently exist in 23 states and provinces in North America and provide a framework where this sort of utilitarian re-use works. Glass beverage containers and specially fabricated plastic bottles in several operations in Europe have been designed for this type of durability, but other, less durable containers that are returned under Bottle Bill requirements – plastic soft-drink bottles and aluminum cans, as well as many types of glass containers that are not designed for re-use – are typically recycled for their material content.

To provide for a sustainable bottle return system, there must be economic incentives in place as well as public infrastructure to support it. In a typical Bottle Bill state, retailers must set aside space to return and store containers, and either provide space and utility connections for automated return devices or provide employees, facilities, and space to accept and store returned bottles. Additional requirements range from backhaul capacity for the empty containers to filling lines or recycling operations, and the ability to process the empty containers either by reducing them into scrap or washing and re-shipping them must be provided and maintained. The financial cost to producers is substantial, mostly in the capital investment in returnable containers that are often more costly than disposable ones, but washing and handling facilities have to be maintained. This cost is usually reflected in a higher per-unit price for beverage products in deposit states.

The political price is often high as well – container manufacturers who have invested in the production of large quantities of disposable containers will not want to lose the revenue that producing one returnable container instead of ten to twenty-five equivalent disposable containers will represent. The loss of jobs that this production changeover entails represents a political liability, unless a clear case for equivalent “green” employment can be made. This has had the result of making Bottle Bill legislation both very contentious and their opposition typically very well funded by retailers, bottlers, and container manufacturers.

Technical Aspects of Package Re-use

For food containers to be safely re-filled and re-used, they must be thoroughly cleaned, typically by a combination of water and alkali solution washes, and then inspected for physical defects. For plastic bottles to be re-used, they must also be inspected for the presence of residual contaminants that may have migrated into the plastics as a result of consumers using them for storage of non-food materials such as gasoline, waste motor oil, or insecticides. This has typically been done with frequency-specific infrared or near-infrared (NIR) sensors that are responsive to specific key wavelengths of typical contaminants. Because of the speeds required for such inspections, it is currently not possible to check for every possible contaminant, but those that are most likely (fuels, oils, household and gardening chemicals) are typical targets. Future implementations of these kinds of inspections may allow for a broader range of target spectra.

Containers used in re-fill systems are typically sturdily constructed and may have design features that mask the wear and tear on the container as it repeatedly travels through the filling and distribution system. Glass containers are typically quite robust and may be standardized to distribute inventory in a bottle pool among brewers or bottlers in a given region. Plastic containers, although less brittle than their glass counterparts, are typically much more prone to cosmetic damage from abrasion and must either be designed in such a fashion that the abrasions and scratches do not significantly detract from the container, or must accommodate the problem in some other fashion, such as a replaceable overwrap label.

Re-use of other containers

There is a vast assortment of re-usable containers for other types of packaging, particularly for distribution and non-consumer packaging such as aseptic IBC containers as have been previously described in Chapter 9. Most of these combine a sturdy, re-usable physical support with some kind of disposable sterile inner container (usually a multiwall bag). For non-sterile use, most production facilities use re-usable bins unless the cost of transporting the empty bin or container between the parts or ingredient manufacturer makes it impractical for economic reasons.

Recycling

Recycling at its simplest is the re-use of the materials in a package without using the intact package again. Typically, this is the result of the decomposition of the material back to an intermediate state (resin particles, wood fiber, glass shards, or metal fragments) and the subsequent reforming of the container from all or part of those materials. Some materials, typically highly cross-linked thermoset polymers such as car tires, will require decomposition back to a very basic chemical state in order to be reused as anything other than relatively inert filler materials. The costs and energy input for this can be considerable, with the result that many of these types of materials are being investigated as fuel rather than material sources, and the final economic outcome is often very changeable.

The implementation of this takes any number of different forms, as shown in Figures 11.2–11.4, ranging from the now-common recycled office paper to multilayer plastic containers that encapsulate the recycled content in a layer of virgin resin. The typical requirements for recycling involve separation of waste into material-specific components, reduction of volume, transportation, and either the incorporation of recycled material in the production of new material, such as incorporating recycled paper into the production of "new" rolls of paper, or reforming the material so that it can be used in the production of new items such as recycled plastic resins that may have been pelletized in an extruder.

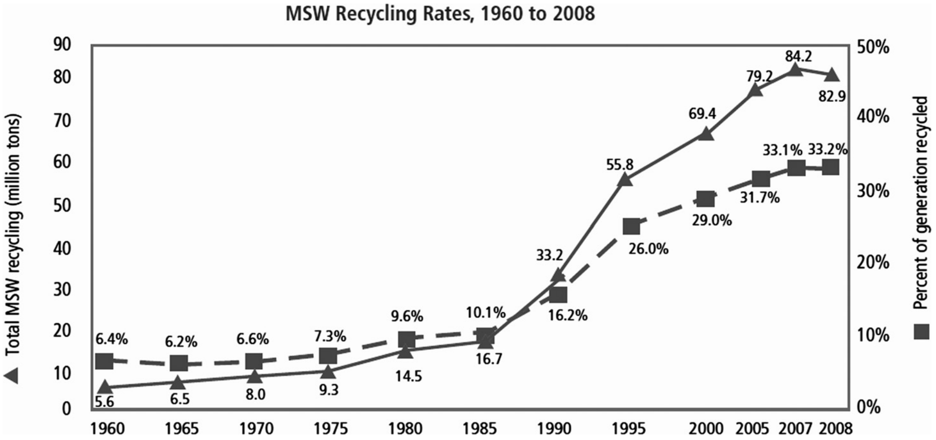

Figure 11.2. US Recycling Rates
Source: EPA

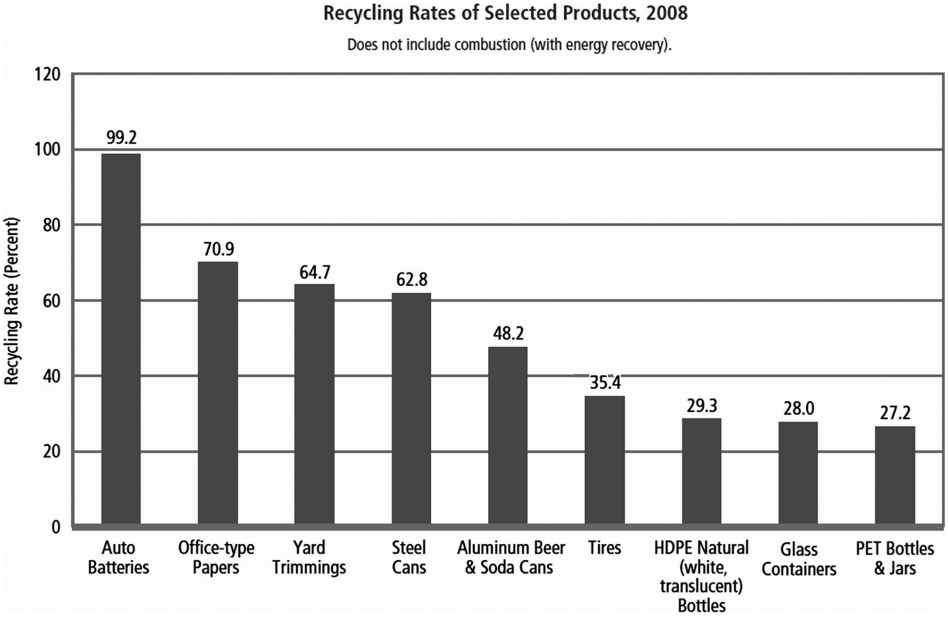

Figure 11.3. US Recycling Rates of Selected Products
Source: EPA

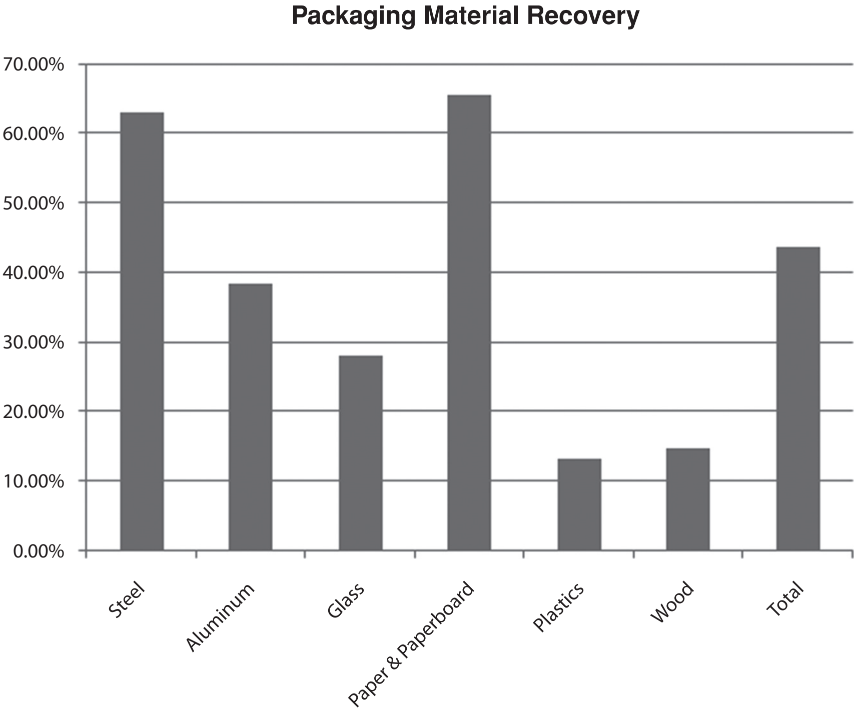

Figure 11.4. US Packaging Material Recovery Rates
Source: EPA

Recycling Segregation

Waste separation is often accomplished as a combination of efforts by the consumer, who may segregate waste to a certain extent by separation operations – both manual and automatic – at a primary receiving or transfer station, and by the final recycling operation such as a steel mill or plastic pelletizing facility. The extent of pre-sorting and separation will be a function of the community's size and the facilities and markets for recycled materials that are available to it. Large, crowded communities near economically viable materials-recycling operations may have a more complex sorting policy and operations than a small rural community that may seek only to remove a certain specific types of materials. In general, systems operate as single-stream (complete mixture), dual-stream (usually fibers such as paper, and glass, plastic aluminum and steel containers), and multistream (requiring a high degree of consumer presorting).

Much as landfills have moved to larger, more efficient operations, the trend in recycling separation has begun to move to larger, more automated separation that can allow the recycling operation to go to a more mixed material stream. Some of the separation technologies include the following.

Airflow Separation

Airflow systems separate materials by density, usually allowing glass to fall to the bottom of the sorting process and removing paper and aluminum in the airstream.

Star Screens

Star screens are conveyor systems that use rotating star-shaped cogs to transport material from one end to the other by pushing it along from underneath. Small material fragments fall out between the cogs and between the fingers while larger material is transported through to the other side.

Trommel Screens

Drum-shaped screens that rotate around the direction of material flow, sifting smaller pieces of material out through the grating as they move along and are tumbled. This can be combined with a magnetic separation system that pulls ferrous materials from the tumbling waste.

Eddy Current Separator

Current-flow devices that induce a counteracting magnetic field in electrically conductive materials by providing a high magnetic flux density using spinning magnets or applied alternating electric fields, then catching the materials as it is levitated off the end of a moving conveyor. Because most non-magnetic metals such as aluminum and stainless steel are sufficiently conductive, eddy current separators are typically implemented after ferrous, magnetic materials are removed by standard magnets.

Plastics Separation

This is often done by hand, but there are a number of different automated separation systems, most based on some aspect of the polymer's response to light or X-rays. Light-based separation develops sorting criteria from NIR and visible light to ascertain color and, in the case of

NIR, composition. Newer systems combine NIR and visible sensors into a single module to provide both polymer identification and color separation. X-ray systems are based on absorption or Energy Dispersive X-Ray Fluorescence and by targeting specific responses to distinguish material types.

Volume Reduction

Volume reduction can take many forms, depending on the type of material involved, the amount of transport necessary, and the markets for the particular materials. Metals can be crushed, with larger items such as automobiles and appliances crushed or shredded, paper is typically compacted and baled, glass is sorted for color and crushed, and plastic is usually compacted or shredded before any shipping occurs.

Recycled Materials Processing

Steel and other ferrous metals are typically recycled in an electric arc furnace as described in Chapter 3, and incorporate ferrous scrap of all types, from packaging to vehicles and structural steels. This recycled steel is then treated as any other steel source and is then used to fabricate new items of all types depending on the quality of the final product, including structural building components. Recycled materials have begun to be a requirement of new building construction, particularly with government buildings [1] and those projects that wish to qualify as a "green building" [2].

Aluminum is recycled in similar fashion, with empty containers baled and shipped to a recycling furnace operation. From there, the cans are shredded and burned free of organic decorations and labeling in a dedicated furnace and re-melted along with salt and potassium fluoride to assist in the removal of oxides, then cast into ingots or billets for rolling or extrusion. Recent furnace designs have also incorporated energy recovery from the coatings and decoration residue [3]. There is an ongoing concern with the quality of scrap aluminum that is returned for recycling, both in terms of moisture content that can cause separation problems, and heavy metals that might be incorporated into the food contact surface of a can [4]. Recycled aluminum requires only a fraction of the energy to be re-cast when compared to converting raw ore (10 MJ/kg versus 220 MJ/kg), so the economic incentive has been enormous (and is increasing with the increase of energy costs), and aluminum has enjoyed a high recycling rate for some time.

The incorporation of recycled material in glass production is simply an extension of the traditional re-use of pre-consumer cullet that is the result of breakage and other waste in the glass manufacturing process. Recycled glass is typically sorted for color, either by hand or with the aid of particle imaging sorters, and fed to the charge of the glass furnace.

Recycled paper fiber is incorporated at the vat stage, and usually must face some separation processing to remove adhesives and other contaminants (including an increasing number of electronic devices such as anti-theft and RFID tags). Separation is usually accomplished by reducing the recycled paper to pulp and then subjecting it to several stages of cleaning in order to remove large, dense contaminants such as staples, and then using screening and hydrocyclones to remove less dense contaminants such as adhesives, tape fragments, and waxes. The presence of these lighter contaminants is an ongoing concern for the paper industry because they will clog screens and slow paper output, though presorting and the separation processes have managed to control defects.

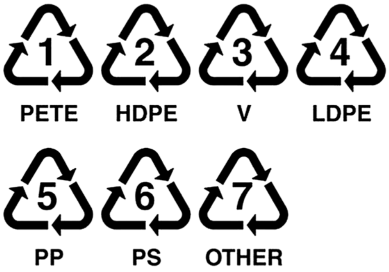

Figure 11.5. Plastic Recycling Symbols

Plastics are typically sorted for content according to the recycled material label incorporated into most plastic moldings (Figure 11.5) and will usually be separated, finely shredded, pelletized, and even depolymerized then repolymerized for use in extrusion and molding equipment.

One of the ongoing challenges for recycled polymers, and particularly PET from drink containers, is that there is concern about contamination from materials either included in the waste stream and not removed by cleaning, or materials sorbed into the polymer structure and desorbed from the surface of the new container. Depolymerization will overcome many of these problems, and in other cases, manufacturers have constructed multiwall containers that incorporate virgin PET resin as the food contact layer and recycled resin either as an encapsulated or outer layer. Currently, the United States approves the use of recycled content on a case-by-case basis through the Food and Drug Administration, which issues “No Objection Letters” for processes that can be regarded as not exposing consumers to hazards above the threshold of regulation (TOR) as described in Chapter 10. Work has been conducted to model and validate recycling processes to accommodate a modest amount of contaminants based on the idea that they will be diluted and encapsulated in the finished product, and will not desorb enough material to constitute a health hazard [5]. Considering that both plastic and recycled plastic content are somewhat controversial among some food consumers, this is likely to be an item of debate for some time.

Composite materials provide an ongoing challenge; paper laminated to foil and plastic film does not have a distinct material type to use, and this has been an ongoing criticism of the materials used in structures such as aseptic packaging and MRE military rations. The obvious solution is to incinerate the materials to recover the energy content, but this option is not always possible, so these materials often wind up in landfills. The conflict between composite materials’ difficulty of recyclability and the advantages offered by these types of materials structures has caused some conflict in the implementation of some types of packaging in certain markets, because many of these containers require less energy and material than more traditional structures. The preferred method for “recycling” of these laminate structures is given as pulping the cartons to recover the paper fiber, although no description of the fate of the foil or polymer layers is given, and one must assume that it is disposed as waste either by landfill or incineration [6].

Recycling Regulations

Recycling regulations in the United States have been a patchwork of local and state requirements that are not unified, nor is there a national standard for recycling requirements, although many of the existing regulations have been pushed into a de facto standard to consider the most stringent case and then producing to that standard. In other countries, recycling exists in a wide range of forms ranging from materials purchased from garbage pickers in huge municipal dumps to the attempts of the EEU to begin to standardize recycling as discussed elsewhere in this chapter.

Disposal and Landfills

"We're Running Out of Landfill Space!!" This was a complaint that was recorded in 1889 and probably dates back to the time of the first cities, as waste disposal is always a problem where people congregate [7]. This is currently something of an overstatement; in fact, developed countries are not running out of landfill space, but the days of simple and inexpensive garbage dumps are largely over in many developed countries because of the intersection of many social, environmental, and legal demands. Fortunately, modern cities do not usually have to deal with some of the disposal problems of older ones – thousands of tons of manure and many dead draft animals every day. According to industry sources, American states have future capacities ranging from less than 5 to more than 20 years, with states on the East Coast facing the most immediate shortfalls [8]. All states with the exception of Hawaii ship municipal solid waste (MSW) across state lines, which adds to both the cost and complexity of waste disposal, particularly in an era of inflating fuel costs. The longer-term implications of this are that areas with large tracts of unpopulated land or disadvantaged communities may develop economies around the operation of landfill or waste-handling operations disposing of material from other states. This is already occurring to a limited extent and can only increase along with the attendant public concern over economic, health, and safety issues.

Waste Production in the United States

Waste production in the United States is made up of five major components, and packaging makes up the largest (and most visible) percentage of those (Figure 11.6).

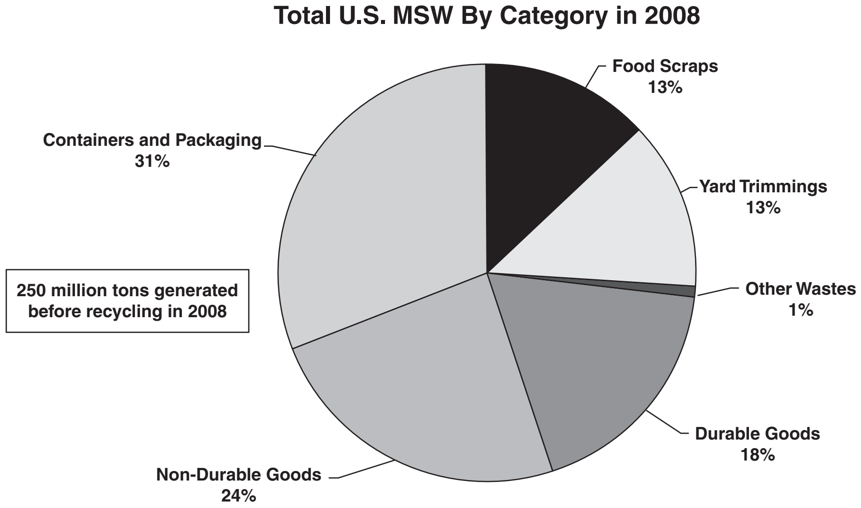

Figure 11.6. Municipal Solid Waste Categories
Source: EPA

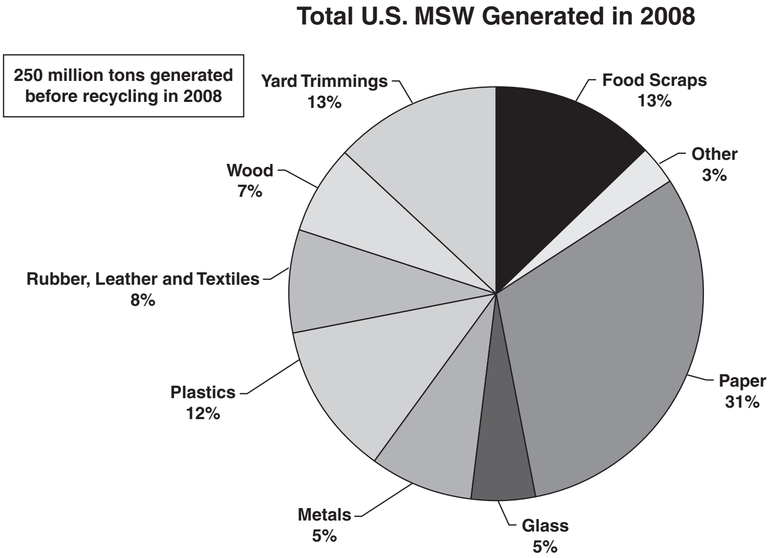

Figure 11.7. Municipal Solid Waste Materials Content
Source: EPA

What is less well understood by the general public is that the rest of the waste stream is also composed of:

Durable and Non-durable Goods

Durable and non-durable goods having a service life of three years or more for the former – usually items such as refrigerators and automobiles, and consumables that have a service life of less than three years for the latter.

Yard Waste

Yard waste that is increasingly either prohibited from municipal garbage collection or diverted into composting operations.

Food Scraps

Food scraps that generally represent a small percentage of the overall MSW stream and may be composted, although this is less common than with yard waste.

Central food processing facilities generally have an economic incentive to both use as much of the raw product as possible and to process their own waste to minimize tipping or sewage fees. Developing countries may have a very different composition of municipal waste, most notably with regard to food waste, because these countries use fewer centrally processed foods and discard the waste, both in trimmings and spoiled foods, directly into the municipal landfill, and may have fewer durable and non-durable goods to dispose of [9].

Landfill Construction

Historically, it was acceptable to simply let waste pile up, or dig a hole in the ground and push in any kind of discarded materials without regard for the consequences of materials leaching

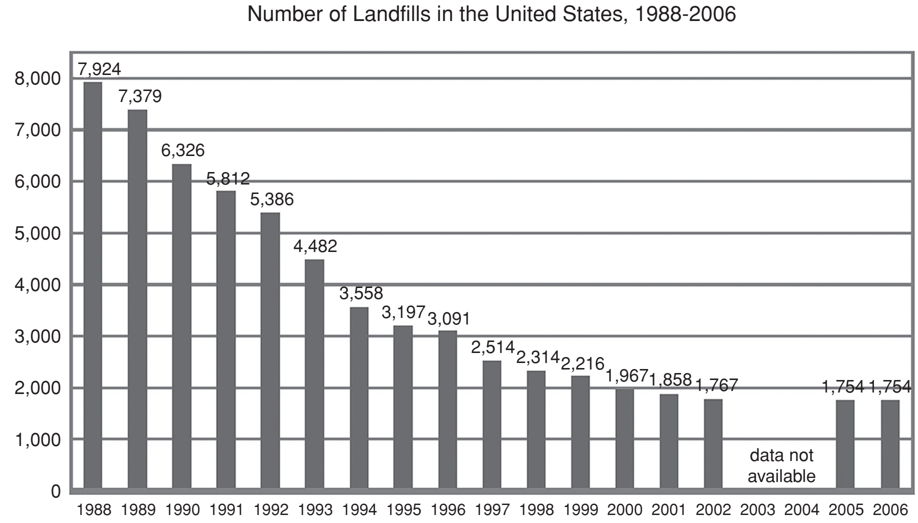

Figure 11.8. US Landfills in Operation
Source: EPA

into the soil or groundwater. The discovery of groundwater contamination by a vast range of pollutants contained in landfills, as well as changes in people's willingness to have disposal sites in their vicinity, has changed the legal, social, and economic framework of garbage. There will not be a shortage of landfill sites nationally, but the days of conveniently located and inexpensive disposal of materials are over, as shown in Figure 11.8, which is one of the motivating factors in many recycling schemes.

Currently, new landfills must be designed to minimize or eliminate groundwater contamination, because any rainwater that percolates through the accumulated garbage will extract many components from the MSW contained in the landfill and transport them into the groundwater supply. These can include lead and cadmium from batteries, pesticides and cleaning agents, and solvents and components used in paints, petrochemicals, and household chemicals. Sites based on industrial activities, such as chemical refining and munitions fabrication, have faced similar concerns. Constructing a landfill that will protect the groundwater supply usually requires building a clay and geotextile liner structure under the fill site, providing drainage and monitoring wells as well as gas vents, and carefully filling and monitoring the site to ensure that it is not contaminating the surrounding environment (Figure 11.9).

A longer-term problem is that materials are never lost from landfill sites. Because the materials are usually deeply buried, there is little air available for aerobic digestion of waste materials, and because there is little water available, efficient anaerobic decomposition of organic materials does not occur either. Archaeologists who explore modern landfills find food materials that are still recognizable (if not edible) after half-a-century [10]. The result of this is that, in effect, modern landfills are sarcophagi for our municipal waste, preserving it forever. Although some energy recovery is done via the promotion of biogas generation in the landfill, and this may be used to fire boilers or operate motor vehicles and specially constructed diesel-electric generators, material recovery costs are still too high to re-open landfills to mine the raw materials that they contain. Most communities in the United States are involved in some form of pre-separation and segregation of solid waste – compostable garden waste is almost

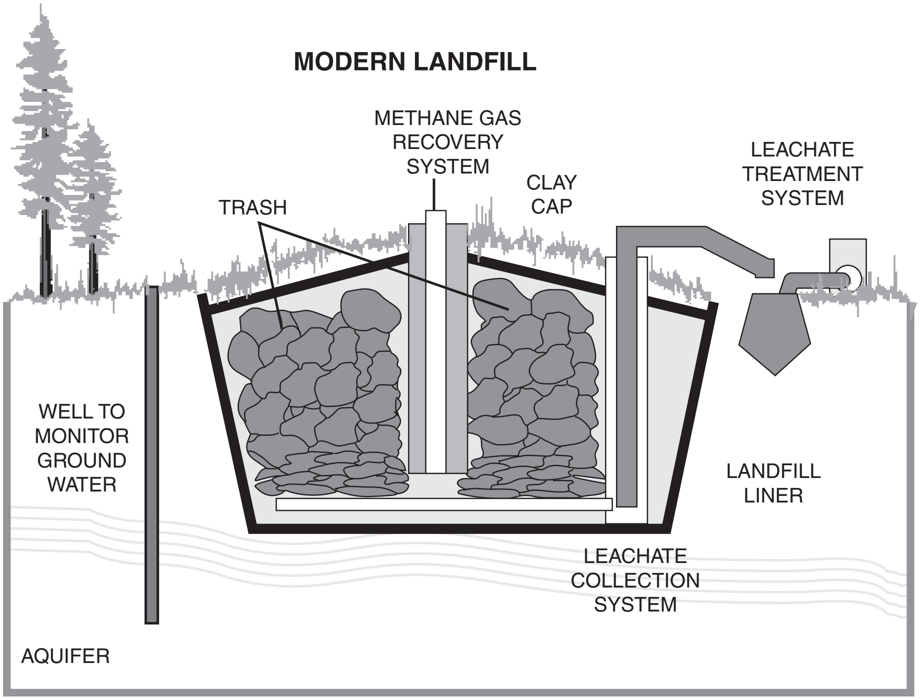

Figure 11.9. Landfill Cross-Section
Source: EPA

universally excluded from landfills – but post-landfill operations are virtually non-existent. In Europe, where both fuel and landfill costs are very high, biogas as a means of energy recovery is receiving a great deal of scrutiny [11]. Current regulations require substantial protection against groundwater contamination by leachate, but nine states are currently studying the operation of properly constructed facilities as "bioreactor landfills" that inject water to accelerate anaerobic decomposition to reduce volume and produce methane as fuel from organic content. An added bonus to the water-injection bioreactor landfill method is that landfill post-closure care is reduced significantly, reducing overall operating expense.

The end result of this combination of factors is that disposal costs for municipal solid waste have grown tremendously, and the availability of convenient disposal sites has been curtailed sharply because of the high cost of constructing and maintaining a properly operated solid waste facility. *Tipping fees* – the fees charged to dump materials in landfills – have increased dramatically and represent an important factor in the overall economic equation that motivates recycling in many areas (Figure 11.10). Items eliminated from the waste stream and recycled for their materials become one less cost that is incurred in disposal irrespective of their value, and may represent a significant factor in determining whether recycling is economically viable in any particular area.

Other Disposal Methods

These have been the occasional subject of public debacles over the years: garbage barges that are not allowed to offload in any port, or loads of toxic wastes that are shipped to developing

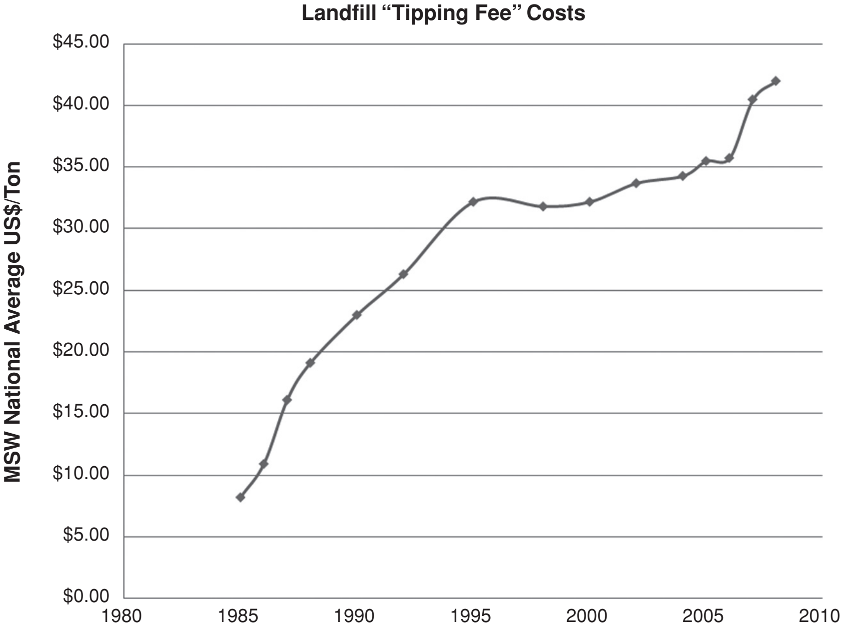

Figure 11.10. Tipping Fee Costs
Source: Generated from National Solid Waste Management Association data

countries to be handled badly, stored in inadequate facilities, or simply dumped among the local population [12, 13]. As global economic development accelerates the production of toxic materials, and rapid communication and disclosure of unacceptable disposal situations accelerates, these problems will become more visible and must be dealt with in a more proactive fashion. Typically, illegal disposal results from poor oversight, a lack of convenient or economic disposal alternatives, or simply a lack of concern beyond the immediate situation. The Basel Convention, first convened in 1989 as a response to improper waste shipments, and continued as an ongoing set of working groups and conventions, has sought to establish global protocols for cross-border waste handling among its 170 signatories, although lax local enforcement may make many of these moot [14].

Packaging Waste Programs Outside the United States

European Directives on Packaging and Packaging Waste

The European Parliament and Council Directive (1994/62/EC, of 20 December 1994, finally codified as Directive 2006/12/EC) on packaging and packaging waste demands that member states comply with the following directives [15]:

- By no later than June 30, 2001, between 50% and 65% by weight of packaging waste to be recovered or incinerated at waste incineration plants with energy recovery;
- By no later than December 31, 2008, at least 60% by weight of packaging waste to be recovered or incinerated at waste incineration plants with energy recovery;

- By no later than June 30, 2001, between 25% and 45% by weight of the totality of packaging materials contained in packaging waste to be recycled (with a minimum of 15% by weight for each packaging material);
- By no later than December 31, 2008, between 55% and 80% by weight of packaging waste to be recycled;
- No later than December 31, 2008, the following targets for materials contained in packaging waste must be attained: 60% by weight for glass, paper, and board; 50% by weight for metals; 22.5% by weight for plastics; and 15% by weight for wood.

Additionally, there are targets for heavy metals (specifically lead, mercury, cadmium, and hexavalant chromium) incorporated into packaging to be reduced over a five-year period (with the exception of leaded crystal).

In addition to this, there is a vast range of country-specific listings within the regulation that attempt to make accommodation for the member countries' different approaches to achieving these targets, including energy recovery via incineration. The European Parliament and Council are to have set further recycling targets for 2009–2014 as well. Portugal, Ireland, and Greece (the so-called P.I.G. countries) will get special dispensation because of rural, island, and isolated areas and do not have to comply with the targets until 2011, and new member states (Czech Republic, Estonia, Cyprus, Latvia, Lithuania, Hungry, Malta, Poland, Slovenia, and Slovakia) have extensions until the end of 2012. There is often a good deal of disagreement among the member countries, because their requirements may have different wording or different standards. The current trend is toward reconciliation of these differences in order to further the growth of pan-European markets for recycled materials and products [16].

The actual implementation of this is somewhat more complex, with each of the member countries having its own standards for compliance and reporting, and there is a vast regulatory literature that exists in both the EEU and each country for this. It is illustrative to reproduce Annex II of document 31994L0062**,** The European Parliament and Council Directive on packaging and packaging waste as it gives the most useful definitions and impression of the legislative intent for the production of recoverable, non-toxic packaging:

ANNEX II

ESSENTIAL REQUIREMENTS ON THE COMPOSITION AND THE REUSABLE AND RECOVERABLE, INCLUDING RECYCLABLE, NATURE OF PACKAGING

1. *Requirements specific to the manufacturing and composition of packaging – Packaging shall be so manufactured that the packaging volume and weight be limited to the minimum adequate amount to maintain the necessary level of safety, hygiene and acceptance for the packed product and for the consumer.*
   - *Packaging shall be designed, produced and commercialized in such a way as to permit its reuse or recovery, including recycling, and to minimize its impact on the environment when packaging waste or residues from packaging waste management operations are disposed of.*
   - *Packaging shall be so manufactured that the presence of noxious and other hazardous substances and materials as constituents of the packaging material or of any of the packaging components is minimized with regard to their presence in emissions, ash or leachate when packaging or residues from management operations or packaging waste are incinerated or landfilled.*

2. *Requirements specific to the reusable nature of packaging. The following requirements must be simultaneously satisfied:*
   - *the physical properties and characteristics of the packaging shall enable a number of trips or rotations in normally predictable conditions of use,*
   - *(The) possibility of processing the used packaging in order to meet health and safety requirements for the workforce,*
   - *(Must) fulfill the requirements specific to recoverable packaging when the packaging is no longer reused and thus becomes waste.*
3. *Requirements specific to the recoverable nature of packaging*
   (a) *Packaging recoverable in the form of material recycling Packaging must be manufactured in such a way as to enable the recycling of a certain percentage by weight of the materials used into the manufacture of marketable products, in compliance with current standards in the Community. The establishment of this percentage may vary, depending on the type of material of which the packaging is composed.*
   (b) *Packaging recoverable in the form of energy recovery Packaging waste processed for the purpose of energy recovery shall have a minimum inferior calorific value to allow optimization of energy recovery.*
   (c) *Packaging recoverable in the form of composting Packaging waste processed for the purpose of composting shall be of such a biodegradable nature that it should not hinder the separate collection and the composting process or activity into which it is introduced.*
   (d) *Biodegradable packaging. Biodegradable packaging waste shall be of such a nature that it is capable of undergoing physical, chemical, thermal or biological decomposition such that most of the finished compost ultimately decomposes into carbon dioxide, biomass and water* [17].

The German Green Dot System

German Green Dot regulation was a groundbreaking innovation in recycling, both in terms of regulation and economics, and has been used as a loose example by many other countries including most of Europe, Croatia, Turkey, the United Kingdom, Canada, and Iceland. More interestingly, it has urged American packaging manufacturers, who have been averse to recycling legislation, into voluntarily adopting a modest level of recycling content into their own packaging, although this is also influenced by state ordinances, public goodwill, and materials cost savings. The Packaging Ordinance of 1991, last amended in 1998, obliges manufacturers and retailers to take back and recycle packaging, and establishes the basis for deposits on nonreturnable bottles. The nonprofit company, Duales System Deutschland (DSD), was established in 1991 to handle fees and logistics to help industry meet this requirement. DSD does not handle waste itself, but contracts local companies to collect and sort packaging materials, and pays for these services by a small surcharge on each item displaying the Green Dot (Gruener Punkt), which indicates that it is allowed to be handled by the DSD-compliant system. Because manufacturers and retailers are responsible for the return and recycling of packaging regardless of whether they belong to the DSD system or not, the complexity and expense of setting up one's own individual system is a powerful incentive to join the DSD system. DSD has been successful because of customers' presorting of materials, and helped propel Germany to an astonishing recycling rate of 77% for all packaging and a reduction of packaging by 20% between 1991 and 2002. Although the results for the DSD scheme have been remarkable, there has been criticism in the European Commission as well as with German regulators of its near-monopoly position, and alternative collection methods are now more easily permitted [18]. DSD has also restructured its advisory board to exclude waste management firms and is examining energy recovery consistent with the goals of recycling 36% of plastic packages [19].

Canada

Recycling and disposal in Canada is distributed among several government agencies and is largely left to the individual provinces and territories and their municipalities to construct and administer. Canada has recycling and return systems as previously noted, and a strong set of programs for the administration of internal and external cross-border waste movement, particularly with regard to the Basel Convention, but has left more local concerns for municipalities to deal with. The Federation of Canadian Muncipalities (FCM), similar to the CONEG group in the United States, is a consortium of Canadian cities that confer to share information and establish and document reasonable requirements for waste management and recycling [20]. Because of the relatively sparse population in the region's northern provinces, and broad geographic diversity, the waste and recycling requirements will vary widely, but the national exchange has promoted a high rate of beverage container capture within Canada, as well as a strong recycling and prohibited content system in all provinces and territories except Nunavit (which has a population density of fewer than one person per 66 km^2).

Japan

Japan, with its scarcity of natural resources as well as space for landfills – it has only 1.5 years left for industrial landfills and 11 years for municipal sites – has created one of the most meticulously detailed recycling plans of any country [21]. Municipal solid waste is separated into burnable and non-burnable categories, and recyclable sub-categories such as metal and glass, with larger items such as appliances handled separately. Cities in Japan may issue further directives to specifically sort particular items into distinct categories, with the large city of Yokohama having 10 and the small village of Kamikatsu (which seeks to completely eliminate garbage by 2020) having 44 distinct categories of recycling to be sorted. The results have been instructive in that the increased sorting has decreased the amount of material going to incineration (which handles approximately 80% of Japan's waste) at approximately the same cost [22]. Japan enacted the Containers and Packaging Recycling Law in 1995 that requires businesses to recycle their containers, but designates the Japan Containers and Packaging Recycling Association as a recycling-fee handling organization that allows manufacturers to pay fees and have the recycling handled by third parties, much like the German DSD system. In spite of this, Japan has a relatively low recycling rate of approximately 16% of its total MSW, although this is balanced by the relatively low per-capita production of waste (410 kg/year/person for Japanese versus 740kg/person/year for Americans). Japan is also the first country to enact legislation – the Home Appliance Recycling Law – requiring producers of durable goods (specifically air conditioners, refrigerators, washing machines [and presumably dryers] and televisions). The fees for this are borne by consumers who pay for the return of used appliances, as well as additional collection and recycling fees at the time of purchase [23].

Developing Countries

In general, public waste collection and recycling is much less formal in developing economies. Lack of understanding of waste volume and composition and lack of consideration of environmental impact of improper disposal work together with inadequate and poorly organized landfills and recycling programs to produce an inefficient (and often corrupt) disposal and recycling systems [24]. Although it is tempting to regard these problems as something confined to developing countries, the continued presence of scandals surrounding the waste management practices of developed countries, as well as the urban equivalent of garbage pickers – ragpickers, kabaris, and pepenadores – in some of the most affluent cities on Earth, remind us that it is just a matter of degree.

An optimistic view, based on experience, is that as economies develop, and standards of living increase, there is usually an increased demand for some type of remediation of hazardous municipal and industrial waste. This occasionally leads to social unrest, such as the protests against industrial pollution in Dongyang, China, in 2005 [25]. The final results of these are often mixed, but usually result in some improvement of waste handling practice and thus better protection of the population and environment.

India

Although projects for incinerators and gasification systems are underway, India's municipal recycling efforts often lie, literally, in the hands of *kabaris*, who broker waste from garbage pickers who extract materials from dumps under hazardous conditions. Although efforts have been made to curtail the practice, recovery from large dumps and trash bins is often done manually [26]. Larger quantities of materials, such as industrial recycling of scrap, may find a more direct market, and hazardous waste has been shipped from India to the United States for re-processing as a result of vocal environmental concerns [27].

People's Republic of China

China's economy has grown so explosively that the need for basic resources and materials has driven the import of recycled and discarded material, typically as "backhaul" in otherwise unused shipping containers that have been used to export manufactured goods. Basic materials such as copper are extracted from used wire, and recycled plastic containers are being imported from landfills in the United States amidst controversy that the materials are simply being dumped in China. This claim is disproven to some extent by examining the market for used materials in China – ads for scrap plastic and other materials are common. Paper is recycled in backhaul shipments as well; Nine Dragons Paper Holdings has become one of the world's largest producers of paper on the strength of its ability to return paper and packaging from goods exported to the United States and re-process it into paper for a dynamic Chinese economy [28]. Other locally discarded materials are returned in a system similar to that of India, often by small entrepreneurs who pay ragpickers for small quantities of product. Other types of recycling have flourished as well, reprocessing electronics and other goods from the United States and elsewhere among substantial concerns about toxic working conditions and environmental impact. Overall, China suffers from the combination of enormous growth, often underwritten by foreign investment, little or no effective regulation, and the inevitable results of having the regulatory bodies and agencies being the primary investors and shareholders in many of the polluting companies.

Taiwan (Republic of China)

Although Taiwan's economy is much more mature than that of The People's Republic of China, it is included with this segment as a contrast to the disposal and recycling practices in the P.R.O.C., because the populations and geographic regions are so similar, with differences being largely political and economic. Taiwan has had an ongoing series of regulations beginning with the (Solid) Waste Disposal Act in November, 1988 that promotes recycling as a resource-conservation measure rather than one of waste remediation. The Republic of China Environmental Agency (ROC EPA) has promoted a 17-point plan, the Hsi-Fu Recycling Project – Hsi-Fu refers to the sparing use of one's wealth or resources (this title was changed to Urban Waste Recovery and Monitoring Project in 1991 but the term is not generally used). In this system, either the customer or manufacturer (and occasionally both) bear the economic burden of materials with surcharges on various items. For some items such as tires, this is usually added at the time of purchase, whereas with aluminum cans, a surcharge is placed on the manufacturer and the consumer is not directly charged. Recovery, recycling, and re-use capacity is high, with many plants licensed to collect and reprocess waste.

Problems exist with separation processes as well as competition between domestic and imported goods and their fee structures, but Taiwan's efforts have been very good regionally.

Mexico

Mexico, with very little regulation over MSW systems, suffers from the results of increased consumption of consumer goods brought on by expanding economic affluence, population concentration in urban centers, and a lack of well-planned and regulated landfills. During the 1990s, significant gains were made in diverting the waste stream from open/illegal dumping and uncontrolled dumping to sanitary landfills, but recycling rates remain extremely low and often in the hands of *pepenadores*, who scavenge dumps for glass, metal, and PET bottles (if there is a market for them) [29, 30]. Some progress toward recycling has been made in the area of specific materials such as PET bottles, but the system struggles from a lack of investment and enforcement, as well as substantial barriers to properly managed disposal and recycling processes related to both economic level and habit [31].

Incineration

Although incineration can be a useful method of disposal, many communities do not want the possibility of exposure to toxic contaminants from the municipal waste stream. Conversely, some communities see these facilities as a source of economic development. Although it might be intuitively obvious that burning municipal solid waste is a good source of fuel for electrical generating plants, in fact, the variability of the materials contained in these waste streams, as well as changeable moisture levels and differing levels of toxic contaminants, make waste-fired power plants a difficult proposition. Department of Energy research projects have been focusing on the combination of municipal solid waste with coal and limestone to produce a high-efficiency power plant that produces very low levels of emissions.

Incineration beyond the backyard burning barrel presents both an ongoing challenge for waste disposal and a convenient method of reclaiming some of the energy content of packaging materials. Because of the mixed nature of the municipal waste stream, the raw material going into the incinerator may contain toxic materials (most notably, thermally stable metallic toxins such as lead, mercury, and cadmium) as well as other hazardous materials such as polychlorinated compounds and even direct biohazards, although high incineration temperatures tend to make these organisms more of a problem of perception than an actual hazard in a properly operated system [32, 33]. These hazardous materials are seen as a risk both from gaseous dispersion in the flue gasses and from the ash that may be dispersed with the flue gasses or must be disposed of in landfills and may leach toxins into the groundwater [34]. Several ingenious schemes for incorporating non-hazardous incinerator ash and other solid waste as building materials such as drywall, as road building materials, and other re-use schemes that render the materials somewhat inert are under evaluation [35]. Under current regulations, ash is required to be sampled and analyzed regularly, and ash that is determined to be hazardous must be managed and disposed of as hazardous waste.

Public reaction to the construction of incinerators often falls into one of two arenas: one concerned about the environmental or other negative effects, and the other concerned with the income or other benefits that may accrue from locating the incinerator in the community. Not surprisingly, these tend to segregate along economic lines, with further debate occurring around the ethics of targeting low-income urban and depressed rural areas as potential incinerator sites.

Electric power generation, recovering a good deal of the energy content of the MSW stream, has been a facet of the incineration equation for some time. Initial problems with the heterogeneity of the feedstock and boiler operation have given way to efficient generation of electricity using both MSW gas production from landfills, mentioned elsewhere in this chapter, and direct incineration of MSW using moving-grate incinerators as the boiler heat source (Table 11.1).

Additionally, diesel-generating equipment manufacturers have overcome some of the initial difficulties encountered with operation on impure methane, and they are now producing durable

Table 11.1. Heat of Combustion of Biomass Fuels

Average Heat Content of Selected Biomass Fuels

Fuel Type	Heat Content	Units
Agricultural By-products	8.248	Million Btu/Short Ton
Black Liquor	11.758	Million Btu/Short Ton
Digester Gas	0.619	Million Btu/Thousand Cubic Feet
Landfill Gas	0.49	Million Btu/Thousand Cubic Feet
Methane	0.841	Million Btu/Thousand Cubic Feet
Municipal Solid Waste	9.945	Million Btu/Short Ton
Paper Pellets	13.029	Million Btu/Short Ton
Peat	8	Million Btu/Short Ton
Railroad Ties	12.618	Million Btu/Short Ton
Sludge Waste	7.512	Million Btu/Short Ton
Sludge Wood	10.071	Million Btu/Short Ton
Solid By-products	25.83	Million Btu/Short Ton
Spent Sulfite Liquor	12.72	Million Btu/Short Ton
Tires	26.865	Million Btu/Short Ton
Utility Poles	12.5	Million Btu/Short Ton
Waste Alcohol	3.8	Million Btu/Barrel
Wood/Wood Waste	9.961	Million Btu/Short Ton

Source: Energy Information Administration, Form EIA-860B (1999), "Annual Electric Generator Report – Nonutility 1999."
http://www.eia.doe.gov/cneaf/solar.renewables/page/trends/table10.pdf

Table 11.2. US Energy Production from Municipal Solid Waste

Source	2005
Municipal Solid Waste	299×10^{12} Btu
Landfill Gas	148×10^{12} Btu
Other Biomass	130×10^{12} Btu
Total Heat Generation	577×10^{12} Btu
Electrical Generation from MSW and landfill gas*	20×10^{9} kWh

*Note that the electrical generation is included in the preceding Btu figures – much of the heat energy produced from MSW and landfill gas is used for electrical generation.

Source: Energy Information Administration http://www.eia.doe.gov/cneaf/solar.renewables/page/mswaste/msw.html

equipment for direct on-site generation of electrical power at landfills. Microturbine and fuel cell generating facilities are being evaluated for use with both landfill gas and sludge digestion in sewage plants. Both MSW direct incineration and landfill gas in the United States produce an estimated 577 trillion Btu of total energy (Table 11.2), including 20.0×10^9 kWh of electrical energy generation as well as a limited amount of fuel for vehicle operations, typically LNG/CNG-converted vehicles used in the landfill as well as a limited amount of sales to the public [36].

Composting

Composting represents a useful way of recycling easily biodegradable organic materials into fertile humus material that is most often re-used in agricultural operations or redistributed for home, commercial, and highway landscaping and gardening use. Because of its applicability both for packaging systems and food-processing waste, the material here is somewhat more extensive than some of the other sections in this chapter. Composting can be used for many types of materials and is most often used to deal with the lawn and garden and other organic waste components of municipal waste streams, often termed *Source Separated Organics* (SSO). Other sources of compostable materials are from food processing facilities and a limited range of packaging materials, most usually paper- and bioplastics-related.

The economic impetus for composting is persuasive – in the Everett, Washington-based Cedar Grove composting facility, tipping fees are approximately \$25/ton versus landfill costs of \$115/ton. This cost differential, as well as an operating facility that has cleared the hurdles for environmental impact, attracts compostable materials from Portland, Oregon – more than 325 km away [37, 38].

Although composting generally refers to nearly any kind of decomposing plant or animal matter, in most commercial applications it refers to operations that depend on lower-odor aerobic digestion, which in turn depends on the previously mentioned co-factors as well as a proper carbon-nitrogen ratio to provide the necessary decomposition and lack of ammonia formation. Commercial composting facilities typically will have the capacity to aerate the decomposing biomass as well as adding necessary water to promote aerobic microbial proliferation.

Compost Processing Methods

Windrows, forming long piles or heaps of SSO material in open areas, are a common and initially inexpensive method of managing composting where sufficient land is available. Aeration usually depends on a mechanical windrow turner. These can range from small, simple devices usually attached to a front loader or tractor that is used to form the windrows, to larger, self-trailering machines. The turner will churn the material in the compost windrow to allow proper aeration of the material and therefore assist in odor control. Organic material that is too dense to promote rapid aerobic digestion may be mixed with wood chips or other material to promote better air circulation. Water may be added with sprinkler systems or naturally occurring rainfall may suffice. Although this method is relatively simple, it requires a large land area and often a high operating cost because of the necessity for turning-vehicle operation.

Biologically, composting goes through three stages:

1. Consolidation, when SSO materials are mixed with water and bulking agents such as wood chips, formed into a windrow, and the bulk density of the windrow is established;
2. Active, when the core temperature is maintained ideally between 50°C and 60°C and the breakdown of the SSO organic material begins.
3. Curing, when the core temperature drops and nutrients are released in the inorganic form. In a mature compost, microbes have converted the readily available organic matter into humic acids and microbial cells. Immature composts may have partially developed compounds that prove unsuitable for agricultural use.

Other composting methods of processing SSO materials can represent a larger initial investment but may prove to be more efficient in the longer term because of reduced processing costs. These include variations on the windrow method that can include forced aeration methods that reduce the necessity for turning machinery, enclosing the composted material in buildings or dedicated containers either for capture of odors or control of other environmental factors such as temperature or moisture content, or various sorts of in-vessel composting that allows control and transport of composting materials. Additionally, there are mechanical drum (*digester*) systems that agitate the compost and are typically used to combine materials and initiate compost digestion, with the exception of small household units that are not used for the complete composting cycle.

Composting Optimization

Compost digestion operates within an imprecise range of values for the critical factors affecting microbial conversion of SSO to low-odor compost; carbon-nitrogen ratios, moisture and oxygen availability, and temperature. Carbon-nitrogen ratios of approximately 30:1 provide the best ratio for operation, whereas too little nitrogen will result in undernourished microbial action and slow composting, and too much nitrogen will result in excessive ammonia and odor formation. Moisture is typically best maintained at approximately 35–40% of the total weight of the compost material for optimal microbial growth. Oxygen availability for the compost material is critical as well, and insufficient oxygen availability will result in anaerobic digestion of the compost material, which is much less efficient and will produce undesirable odors. Occasionally over-ventilation will occur, which may remove moisture from the compost and result in slower microbial action. Managing the combination of moisture, which tends to compact compost material and make it more difficult to aerate, and oxygen is an essential part of compost management. Temperature can be critical as well, as composting operates most efficiently at a relatively high temperature (50-60°C). Although this is self-regulating to some extent, exceedingly high temperatures can accelerate moisture loss, microbial species may be deprived of oxygen and moisture, and the system may self-sterilize, causing microbial action to cease prematurely. Low temperatures will slow microbial action and in severe climates may result in the cessation of microbial action altogether. Because there is a lot of biogenic heat produced in aerobic composting, insulation management in cold-weather operations may be sufficient for the process.

Odor Control

Although composting operations typically produce a low odor level if properly maintained and managed, the incoming feedstock (animal manure or food processing plant waste) or close proximity to urban areas may require additional steps to control odors. These may include the use of covered facilities with odor control machinery, dedicated composting vessels based on drums or steel shipping or waste containers, or the use of ventilation structures combined with selective permeability membranes that allow gaseous emissions to be vented while retaining the heavier organic compounds that then condense and are recycled back into the compost to be broken down further [39].

The Economics of Waste Handling

No matter which disposal or recycling method is considered, the basic laws of economics will eventually determine whether the system will be maintained. Generally, one can see the equation as a combination of factors, but each situation will have its own unique concerns, as shown in Table 11.3, often having to do with difficult-to-quantify social factors or future concerns, or costs that are often hard to predict. An efficient and environmentally sound disposal system can lead to a better disposition of materials, but the attendant increase in costs may also accelerate the removal of material into recycling or incineration schemes or even the improper dumping of materials.

Note that several of the methods for dealing with waste produce both revenue and a reduction of cost. For example, removing a plastic bottle from the waste stream not only returns the value

Table 11.3. Composting Costs and Revenue Sources

Revenues	Costs
Collection Fees	Labor
Recycled Material Sales	Transportation
Subsidies, direct and indirect (taxes, bottle deposits)	Tipping Fees
Reduced costs from waste diversion (composting, container reuse, recycling) and compaction (evaporation, mechanical compacting)	Facilities Costs (both landfill and intermediate transfer stations)
Composted materials sales	Requirements for specific material content in packaging
Energy generation and sales	Sales and distribution costs
Goodwill – community acceptance of waste handling method.	Capital investment in returnables and infrastructure

of the plastic in that bottle but will also incrementally reduce the amount – and therefore the cost – of material that must be interred in a landfill. Also, note that often the determining factor in a waste handling scheme, particularly for large, rural populations or for systems that ship waste over long distances, is the transportation cost. This is often a major factor in determining whether a smaller or more distant community can recycle all types of materials or only select ones that have enough value to make it worthwhile to transport them over long distances.

An additional problem arises when municipal waste is collected by private companies but recycling efforts are publicly funded. The expense of the programs is borne by the taxpayer, while the reduction of landfill fees paid by the private entities is often not reflected in reduced billing [40].

Sustainability

Sustainability is a term that originally referred to the simple concept of continuity of processes, but has expanded to encompass the idea of a larger, if not global, system of operation and life that is sustainable on an ongoing basis. Further definitions include quality of life and ecosystem conservation. The ongoing collision of expanding population and rapid economic development of highly populated countries such as India and China against the older ones of the United States and Europe, finite energy and other natural resource supplies in a competitive globalized economy, and mounting evidence of man-made irreversible changes in various ecosystems have highlighted the need for a change from the immediate, parochial view of industrial manufacturing, marketing, and business.

In a much broader sense, sustainability has been taken in a broader context to mean a variety of things ranging from source reduction and low carbon emissions to complete, low-tech lifestyles. Given that the term originated with researchers studying large-scale agricultural systems perched on the edge of failure, it is easy to see how this interpretation might arise. For an industry concerned with high-speed, minimum-cost manufacturing of disposable goods, implementing sustainability becomes somewhat more indistinct.

Many of the things that can contribute to sustainability in product lines (and their packaging) stem from commonsense implementation of the simple principles outlined earlier, recycling, efficiency improvements, and source reduction. Source reduction includes minimizing the use of materials in both product and packaging manufacture in order to reduce their overall amount before they enter the MSW management system. Examples of source reduction activities are [41]:

- Designing products or packaging to reduce the quantity or the toxicity of the materials used or make them easy to reuse.
- Reusing existing products or packaging, such as re-fillable bottles, re-usable pallets, and re-conditioned barrels and drums.
- Lengthening the lives of products such as tires so fewer need to be produced and therefore fewer need to be disposed of.
- Using packaging that reduces the amount of damage or spoilage to the product.
- Managing non-product organic wastes (e.g., food scraps, yard trimmings) through on-site composting or other alternatives to disposal (e.g., leaving grass clippings on the lawn).

Indeed, as previously mentioned, the “lightweighting” of consumer goods and packaging have contributed to the flattened rate of per capita waste production in the United States that can be seen in Figure 11.11.

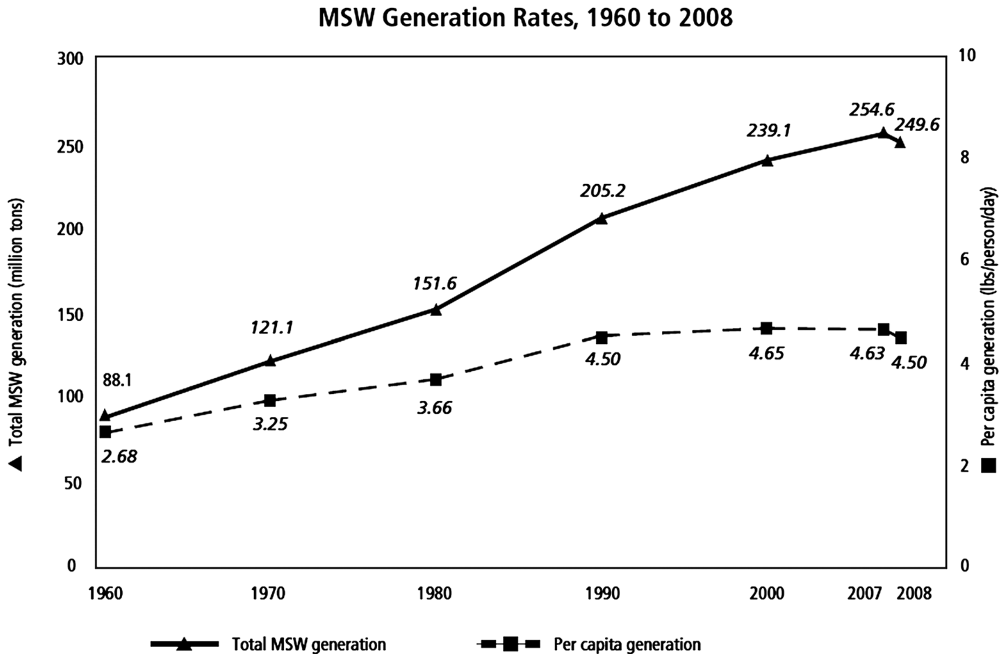

Figure 11.11. US Municipal Solid Waste Per Capita
Source: EPA

From an economic standpoint, sustainability can be managed to not only produce hard-to-measure benefits for society, but can be used to generate a higher rate of profitability by reducing or eliminating waste, re-using materials, and conserving energy. In an economy that concentrates on short-term gains, it is often difficult to focus on longer-term sustainability until a tipping point of resource scarcity, economic shift, or other stress occurs and provides sufficient incentive to overcome the resistance to change from systems that may have been designed for a static model rather than one that recognizes that adaptability and evolution is a key component of economic sustainability. This resistance can range from a time-lag in response because of the complication and investment required to change a large institution, to a complete lack of response based on the belief that the current system is the best available. The food industry, being marketing-driven, often takes a comically over-reactive approach to change in its positioning of products, but is extraordinarily static in its fundamental methods of production. The concept of sustainability has proven to be an agent of change in and of itself, however, helping overcome reluctance to change, and promoting investment in longer-term strategies to cope with increasing changes in the materials and energy systems.

Many of the broader concepts of sustainability can be applied to business operations without significant penalties, and in fact, these may result in long-term profitability and maintenance or improvement of competitiveness [42]. Productivity improvements beyond simple short-term fixes often require capital investment in infrastructure as well as design optimization that often proves more costly. The packaging machinery industry, notoriously stodgy, has begun to implement more efficient integration strategies, though it still lags behind other manufacturing sectors. The food processing industry has always made as much use of raw materials as possible. The industry has capably adapted to rising energy prices in the past by examining resource re-use such as burning waste products to produce energy, but the processing units themselves, already burdened by the demands of cleanliness, flexibility, and immediate production demands and usually without investment capital, are often not integrated and optimized for resource or energy sustainability.

Packaging Sustainability

According to the Sustainable Packaging Coalition, sustainable packaging [43]:

1. Is beneficial, safe, and healthy for individuals and communities throughout its life cycle.
2. Meets market criteria for performance and cost.
3. Is sourced, manufactured, transported, and recycled using renewable energy.
4. Maximizes the use of renewable or recycled source materials.
5. Is manufactured using clean production technologies and best practices.
6. Is made from materials healthy in all probable end-of-life scenarios.
7. Is physically designed to optimize materials and energy.
8. Is effectively recovered and utilized in biological and/or industrial cradle-to-cradle cycles.

Many, if not all, of these goals are focused on economically optimized strategies, which is a constant and unremitting concern in the marginal-expense world of food processing and packaging. Also, few technically complete discussions of how these goals are to be achieved (or who will pay to achieve them) are made. Further, the economics of how the changes will be implemented, and how older production facilities will be treated, had been a matter of vigorous debate. One option, not yet explored in the packaging industry, is the cap-and-trade option of environmental credit trading, similar to carbon, sulfur dioxide, and nitrous oxide emissions trading in the power generation industry, where older facilities are allowed to continue if they buy emissions credits from newer, more efficient plants. This creates an economic incentive for substantial improvement in (or the closing of) older plants, as well as inviting investment in low-emissions designs for newer plants [44]. Additionally it creates an incentive to implement effective partnerships between energy companies and users to conserve sufficient energy to eliminate the need for new power plants altogether. The implementation of this sort of scheme in the packaging industry in a regulatory climate that seeks to minimize government involvement in business affairs may be difficult.

Externalities

The term "externalities" has come to mean the longer-term, more obscure and extended effects of a particular course of action, and is relevant to the concept of sustainability. More formally defined, it means that an externality is a cost or benefit resulting from an economic transaction that is acquired by parties indirectly involved in the transaction. When considering the economic and social outcomes of sustainability in packaging, it is necessary to consider many widely dispersed causes and effects, both economic and otherwise. For instance, the global effects of outsourcing production of plastic resin or container manufacture may be to reduce cost, but it will also inevitably outsource the economic benefits to another location, and will also relocate the resulting pollution, health problems, and secondary economic effects, both good and bad. More strident critics of globalization have pointed out that many countries have essentially exported their problems along with their factories, leaving other communities to deal with the unpleasant secondary effects of the move, often without benefitting from the arrangement.

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Chapter 12

Future Developments and Technologies

Predicting the future is always a doubtful undertaking because it is always based on the extrapolation and interpretation of current and past events. It is appealing to create a wishful list of great technological leaps that will enhance our lives in some manner, but examining historical documents, books, or movies that predict their future (and our present) is always fertile ground for comedy. What is most useful is the critical examination of promising new technologies and their potential implications while keeping a sober eye on the realities of the larger scale of world trends and events. It is also useful to understand something about the way new technologies tend to be adopted in an accelerated technological world.

The Gartner Hype Cycle

Studying the world of "the latest thing," particularly in computers and consumer electronics, leads to the conclusion that many types of technology are initially over-promised and can take a good deal of time and effort to become part of the mainstream of whatever applications for which they are intended. The Gartner Hype Cycle, developed by Gartner Research, a consulting firm, illustrates this quite well, and may seem somewhat familiar to those who have bought the latest gadget only to find that the reality does not quite live up to the promise [1]. While this was developed in the overheated Web economies of the 1990s, its applications with appropriate time scaling can apply to nearly any new implementation of technology as it moves from promising discovery to commonplace implementation Figure 12.1.

Stages of the Gartner Hype Cycle

Technology Trigger

The first phase of a Hype Cycle is the *technology trigger* or breakthrough, product launch, or other event that generates significant press exposure and public interest.

Peak of Inflated Expectations

In the next phase, a frenzy of publicity typically generates over-enthusiasm and unrealistic expectations. There may be some successful applications of a technology, but there are typically more failures.

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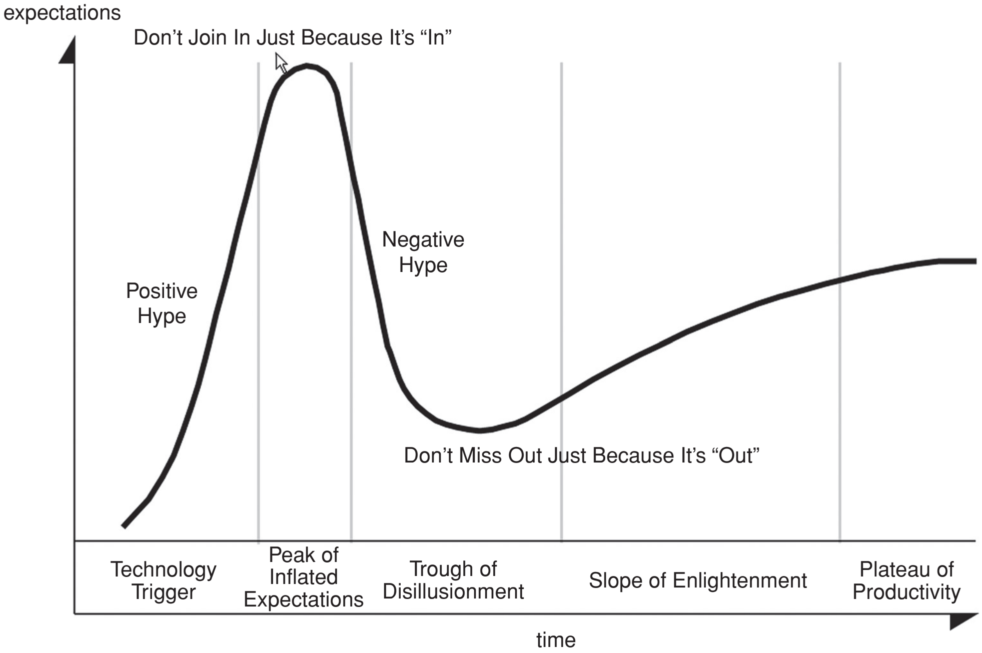

Figure 12.1. The Gartner Hype Cycle
Source: Gartner Inc. Used with Permission

Trough of Disillusionment

Technologies enter the *trough of disillusionment* because they fail to meet inflated expectations and quickly become unfashionable. Consequently, the press usually abandons the topic and the technology.

Slope of Enlightenment

Although the press may have stopped covering the technology, some businesses continue through the *slope* of enlightenment and experiment to understand the benefits and practical application of the technology.

Plateau of Productivity

A technology reaches the *plateau of productivity* as the benefits of it become widely demonstrated and accepted. The technology becomes increasingly stable and evolves in second and third generations. The final level of expectation of the plateau varies according to whether the technology is broadly applicable or benefits only a niche market.

Change and Chaos

Chaos theory is used to describe some types of systems whose values evolve with time. The chaotic aspect comes from the fact that with many of these systems, the exact position or state at a specific time cannot be predicted because minute, often unnoticed changes at the beginning can cause systems to diverge over time. Similarly, minute inputs into physical, social, and economic systems can cause them to deviate from a predicted path. Robert Lorentz, a meteorologist who studied predictive models (and who is responsible for the concept of the *butterfly effect**), found that weather models cannot predict weather accurately more than about a week in advance because of the enormous complexity of the systems and the unknown effects of small changes in initial conditions, as well as the rounding errors inherent in extensive computational modeling systems.

Although history is similarly prone to repeating itself in general terms, the specifics are nearly impossible to predict. Lorentz found that complex systems tended to center around general sets of values (termed "Lorentz Attractors") as their values varied. Thus, although the weather could not be predicted in exact terms, it could be generally said that for most non-polar locations on Earth, the temperature would range between −50°C and +55°C, and rainfall would vary from none at all to something less than about 25 meters per year with most local conditions more closely bounded. Considering that the packaging and food processing industries are *laterally integrated*, drawing on and affecting nearly every aspect of society, the prediction of long-term directions will only yield a general set of boundaries among which the future might lie. The use of these concepts in addressing the issue of future technologies lies in the recognition that human endeavors have their own "attractor" metaphors; increased personal wealth, protection of health and safety, personal convenience, and the ability to enjoy one's life, among others. Although the specifics of these concepts vary among individuals and societies, they can point to ideals around which social systems will seek to evolve.

Coupling this concept with the idea of the Gartner hype cycle can provide some insight into the impetus driving the development and implementation of new technologies, and can give an idea of why some technologies are driven quickly through the cycle (or skip it all together) whereas others flounder or fail (or wait for a change in conditions to reappear for evaluation). Beyond this, it is useful to consider some of the broad-scale changes that may occur to influence the nature of food processing and packaging.

Economic Changes

As the industrial base of manufacturing shifts from a nationalistic to an international base, with the current powerhouses of manufacturing, China and India, offering a mix of low labor costs and improving technical infrastructure, the nature of packaging and processing of foods will change as well, although for the United States, the focus of food imports may be closer in Mexico and Central and South America. In 2005, the United States crossed the threshold of importing more food (by dollar value) than it produced internally [2]. This statistic is skewed by the nature of food imports, which tend to be of higher value to justify transportation costs. Nonetheless, the landscape of food manufacturing and packaging has inexorably shifted to an international model, following everything from electronics to automobiles.

With this change, comes a change in many of the factors that make up the food processing and packaging systems. The first of these is economics; because of the likely continuation of high energy costs, and therefore the relatively unfavorable economics of transporting low-value products long distances, it is unlikely that daily commodities such as milk will be processed and imported overseas except for specific, high-value consumer products. For other products that are intrinsically higher in value, such as confections and meat products, imported products are already flowing into the marketplace in increasing volumes, and this trend is likely to continue. The far-reaching consequences of this globalization have yet to be fully determined,

Table 12.1. Food Demand Increase in China in the Period 1999–2009

Product	Increase (%)
Milk	700
Olive Oil	600
Vegetable Oil (non-olive)	200
Poultry	60
Beef	30
Wheat	25

but problems with contaminated or counterfeited products, the spread of new parasites and pathogens, and the shifting infrastructure of supply and demand will all create new challenges with which both packaging and food processing will have to cope.

The locus of the world economy will continue to shift, with an increased presence of developing countries in Asia and perhaps Africa – currently, capital-rich governments such as Kuwait and China are purchasing agricultural land from more fertile countries such as Cambodia and Congo. The long-term effects of this are unknown, but may result in significant changes in the way that multinational agribusiness interests interact with foreign competition.

This change will likely be accompanied by an irreversible increased demand for higher-quality foods, with leaps in production and prices, but also the expanded markets and broad range of infrastructure that may result in a diversity of technologies available for food processing and packaging. An extraordinary example of this is the increase in demand for certain foods by China in the period between 1999 and 2009 [3].

These increased demands will drive a concomitant demand for agricultural supplies, from water to fertilizer, and in competition with crops diverted to heavily subsidized (and therefore financially lucrative) fuels applications. This can only drive production and prices upward, perhaps providing capital for better production and packaging methods, or perhaps driving costs to minimum and requiring shortcuts that would be unacceptable today.

The world of packaging will continue to shift as well in response to economic changes and the diminished safety and environmental requirements for some types of manufacturing. Plastic film and bag imports have shifted to offshore facilities because of the high density (and therefore value) of the final product. Importing empty containers such as cans or bottles does not offer the same incentives as exporting whole manufacturing facilities to produce them locally because of the relatively high shipping costs to transport empty containers – a problem that has long motivated container manufacturers to locate operations close to food producers because it is more efficient to do the converting close to the filling operation.

The complex nature of these systems makes them extremely unpredictable. A shift in labor costs that can make processing in one part of the world more attractive can be canceled in an instant by a fluctuation in transportation costs or the availability of discretionary income to consumers in another part of the globe.

Information Technologies

The nature of information technology is changing so quickly that it may be impossible to track the specifics in a textbook, but several trends are likely to be pervasive over long periods as specific technologies appear and are refined.

Moore's Law was coined by journalist Carver Mead after an observation by Gordon E. Moore, co-founder of the Intel Corporation, that the number of transistors in a minimum-cost circuit doubles approximately every 24 months [4]. The practical implication of this is that computing power for a particular type of device (usually built for a specific market segment and price range) will double every two years, although this figure has been taken to be 18 months by the popular press.

There are several variations of this that may affect technologies in general and several specific applications in the packaging and food processing industry segments in the foreseeable future. The first of these is the divergence of Moore's Law into applications other than the central processing units of computer, and the second is the exponential growth of information sharing and connectivity between devices, and the unintended consequences of this growth.

The Divergence of Moore's Law

The popular take on Moore's law is that computing power doubles every two years, whereas the original observation was that the number of transistors (and by extraction, elementary electronic switching or storage devices contained in a circuit) doubles. This seemingly subtle difference has broader implications in that as processing power and speed grow, so do capacities of peripheral devices such those used for memory, imaging, and communication, all of which require similar elementary components.

Because packaging and food processing are very-high-volume, very-low-cost applications, as noted elsewhere in this book, the plummeting prices for all aspects of circuitry bring truly smart packaging closer to a broad scale of implementation. Similarly, the dropping cost of computational ability and peripheral capacities means that the cost of creating "smart" factories – those capable of self-optimization and flexible manufacturing – become closer to reality for smaller and smaller operations. Additionally, the ease of creating a flexible production operation – one that produces a range of products from a single installed base of equipment – increases markedly. The consequences of this can range from lower production costs to an increase in the number of devices that consumers can truly buy "made to order."

Connectivity

More and more machines are talking to one another at an increasing rate and with increasing sophistication. At this point in time, mobile phones are now sophisticated, networked computers in their own right and can link to any number of other devices. This has led to profound social changes as people in developed countries can connect more conveniently, but has also resulted in profound sociological changes as simple handheld phones become access points to both acquire and disseminate news, financial information, and transactions for people in developing countries and enable them make the leap directly from isolation to global conversation and trade [5].

As with many human problems, the lack of a common language (protocol) for information interchange becomes problematic from time to time, but the trend is clear and communications standards such as the previously mentioned IEC-61131-3 are adapted to cope with this. With an increase in connectivity, problems similar to the globalization of the food supply begin to appear. The most obvious of these are computer viruses and various bits of malware that can exploit the monoculture of the most common operating systems and can (and do) corrupt devices and whole networks with the result of a whole infrastructure based on their prevention being created.

Nonetheless, with decreasing device costs and an increase in the utilization of communication devices, the connectivity of packaging is going to become more and more likely. The most obvious examples of this are RFID devices that are being increasingly incorporated into products, packaging, and even luggage tags at airports. As the cost of producing these devices and the amount of memory available in each device increase, the amount of data transmitted (and, with the addition of simple sensors, collected) will grow enormously. Additionally, links using QR codes can directly link the consumer from packaged good to web and media experiences.

A simple change from IPv4 addressing (four clusters of three numbers, separated by periods that you might see as an Internet address) to IPv6 (six clusters) would raise the number of potential Internet addresses from 2^{32} to 2^{128}, effectively allowing each individual package and product to have its own Internet address for the foreseeable future, although there is a cost in translation time associated with this [6]. This change, similar to the change from simple three- or four-digit telephone numbers to the US standard seven digits (plus area code, if necessary) may offer a great deal more connection density and diversity among devices, objects, environments, and people.

The larger problem – one of a "common language" – may be more troublesome. Communication protocols are relatively standardized within a particular strata of devices (mobile phones, for example), but across product types this may be more difficult. Getting all types of RFID tags to "talk" to all types of cell phones may be more difficult because of different frequencies and different protocols. This tower of Babel may be a limiting factor in the intercommunication of devices and products, though this may not be a bad thing (imagine getting a computer virus in your mobile phone from a tube of toothpaste). The effects of biological engineering, sensor development, massive interconnection, and locative technologies are unlikely to be predictable but will be massively important in the science and engineering as well as economics and marketing of food and packaging products.

On a larger scale, global communication, computation ability, and accessibility can drive information technologies into unheard-of scales and the utilization of cheap, distributed systems that inevitably influence the nature of commerce, markets, and the way economies work. Certainly, the low-cost and high-speed nature of these will play directly into the economic niche within which processed foods and packaging work. Several very early changes such as the implementation of the Rural Free Delivery mail system in the United States and the use of UPC bar coding to speed checkout and inventorying practices have already been discussed in this book.

Engineering Biological Systems

The effects of recombinant DNA and related technologies has already produced a groundswell of promises but has fallen into the secondary phase of the Gartner cycle, one of slow growth and hard work. These have produced interesting and profitable projects such as the production of insulin and the incorporation of herbicide resistance into crops, which have already been marketed. Nonetheless, the potential for new organisms and biologically linked technologies is enormous. Bioplastics, aggressive biosterilants to accentuate or replace current preservation technologies, and other manipulations to provide not only new technologies and materials but entirely unheard-of types of foods and even manipulate the human digestive system may be forthcoming. More interesting is the downward spiral of cost and complexity for these kinds of development processes, mimicking the development of capable, low-cost electronics components that helped spur the Silicon Valley boom in computer design.

Thus, “garage biology” is underway as amateur developers begin to explore under the same set of circumstances that led to explosive developments in electronics several decades ago, with the substantial difference that we are not fundamentally electronic in nature and therefore not susceptible to being infected by a bad or malicious project (electrocution hazards notwithstanding) beyond a burned finger or a blown fuse.

Materials Sciences

Many materials development efforts have a very difficult time with the hype cycle; composite materials have taken years to find widespread implementation in aerospace manufacturing applications for instance, although this has been the result of manufacturing difficulties rather than a fundamental flaw in the materials themselves.

The lucrative market for new packaging materials, as well as the promise of the widespread benefits offered by potential changes, keeps both academic and industrial researchers actively pursuing new materials, surface treatments, and additives. Some of the possibilities for packaging materials to take a more proactive role both in preservation and perhaps even in processing steps (slow, intrinsic processing steps while in storage and transit replacing fast, energy-intensive ones in factories) offer some tantalizing possibilities.

Resource Scarcity

Given the unlikely probability of population growth reaching a plateau under anything but catastrophic circumstances, the Earth’s resources will be ever more hard-pressed, and we will have to move ever farther out on our technological limb to cope with these problems. With recycling growing in profitability, landfills may become the mine sites of the future as past waste is reclaimed and refined in preference to seeking dwindling supplies of difficult-to-obtain materials. The alternative is to pursue politically untenable manipulation of resource-rich countries, which has substantial historical precedent, and inevitable unpleasant consequences.

Changes in the Nature of Change

It has been postulated by genetic biochemists that humans, as a species, have uniquely evolved to be the one species that can directly manipulate its own genetic evolution rather than having it be a matter of chance [7]. Whether this is for better or worse cannot be predicted, but it is one of the certainties of the changeable nature of change itself. We do not know if, in a century, we will be dealing with the same humans among who we are currently living. A simple metabolic change – the ability to host intestinal flora capable of directly digesting cellulose, for instance – could have staggering global implications. In more mundane aspects of technological change, the intrinsic nature of science and engineering is to provide ever-changing tools and paradigms for design and analysis, guaranteeing changes in the way change occurs.

For example, the development of communications capabilities that enable a broadly interconnected population will allow many more people to consider creative solutions to a particular problem, at a cost of increased “noise” and the necessity of understanding group dynamics. Cheap computational analysis can lead to automated engineering and development, many of which are already in use, that can create and even analyze different designs using genetic, adaptive, or other evolutionary and optimization algorithms to provide startlingly unexpected results. All of this may be coupled to broadly distributed information and geolocation databases to provide unforeseen future technologies and benefits, as well as the inevitable problems and inequities. The future is certainly going to occur, but a utopia based solely on complete and static technical solutions to ever-changing social problems is as unlikely as past science fiction movies' flying cars.

Endnote

(*) The butterfly effect, popularized by Lorentz, states generally that the minute effect of a butterfly flapping its wings in China might result in an eventual hurricane in the United States, and refers to the enormous, compounded effects over time of subtle changes in starting conditions.

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