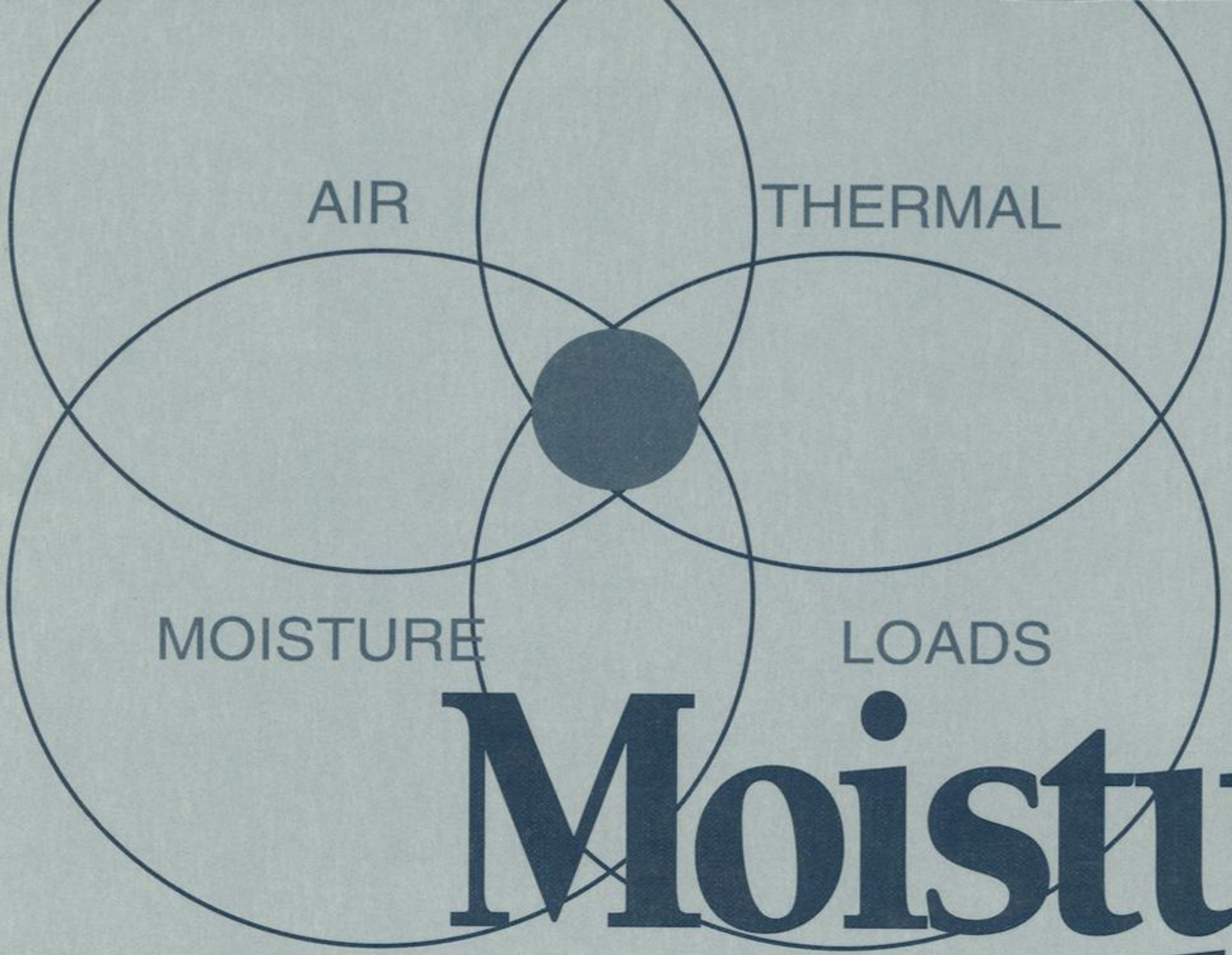

Moisture Control in Buildings

HEINZ R. TRECHSEL, EDITOR

ASTM

Moisture Control in Buildings

Heinz R. Trechsel, Editor

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NOTE: This manual does not purport to address (all of) the safety problems associated with its use. It is the responsibility of the user of this manual to establish appropriate safety and health practices and determine the applicability of regulatory limitations prior to use.

Printed in Ann Arbor, MI
February 1994

Dedication

Wayne P. Ellis
1915–1993

Former Chairman of the Board of ASTM, Standards Consultant, First Chairman of the Board of the Building Environment and Thermal Envelope Council

As ALL THOSE WHO were close to Wayne Ellis know, his foremost interest in his later years was terminology, but the issue of moisture control in buildings was also one of his concerns.

It was Wayne who, in the mid-1970s, encouraged the formation of a joint Committee C16/E06 ad hock task force on moisture control, who helped expand that task force to include members of ASHRAE and other groups, and who agreed to the establishment of that task force on a more permanent basis as the Research Coordinating Committee on Moisture within the Building Environment and Thermal Envelope Council under the auspices of the National Institute of Building Sciences.

It was also Wayne who encouraged the Editor to undertake the development of this manual. He provided his valuable advice all along the tortuous route from conception to final approval of the manuscript. His own chapter, "Applicable Guidelines, Standards, and Codes," will unfortunately remain the last of his many contributions to ASTM publications.

With these thoughts in mind, the authors and I dedicate this manual to our friend, contributor, and mentor, Wayne P. Ellis.

Heinz Trechsel
Editor

Acknowledgments

I WISH TO THANK THE AUTHORS for their contributions. Unlike the preparation of technical papers for symposia, conferences, and workshops, the preparation of a chapter within the framework of a manual is more difficult and more time consuming. I apologize to the authors for imposing strict and sometimes unreasonable deadlines, but they were necessary to keep the material timely.

A major role in the preparation and publication of any ASTM publication falls to the reviewers. Their names are listed below in alphabetical order. Their contribution is vital to a good and technically solid manual. Many thanks to all of them.

One reviewer undertook the enormous task of reading each and every chapter to help achieve a measure of overall completeness and uniformity in quality. It is my pleasure to thank Dr. Ervin Bales of the New Jersey Institute of Technology for this great help. During the development of the book proposal, Paul Reece Achenbach, former director of the Building Environment Division at the National Institute for Standards and Technology, and Wayne P. Ellis, Past President of ASTM, acted as sounding boards for various ideas relating to the manual. Their valuable counsel and consistent encouragement is gratefully acknowledged.

This manual required a myriad of tasks, from preparing author agreements to tracking down addresses of potential reviewers, preparing final drawings, book design, and editing. All these tasks fell to the staff of the ASTM Publication and Marketing Division. As always, they performed splendidly, and without their help not even the book proposal would have seen the light of day. My very best thanks to Kathleen A. Dernoga and Monica Siperko of Acquisition and Review, to David Jones, the copyeditor, of Books and Journals, and to Jonathan Bruno of Design Works, Bryn Mawr, PA, who helped illustrate the manual.

Last, but not least, my thanks go to my wife Gisela for her understanding, support, and encouragement during the four years from initial outline to final publication.

Heinz Trechsel
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Preface

WELL-DEFINED AND soundly constructed buildings have many virtues, among them the ability to serve their intended purpose, to provide a pleasant and esthetic environment, and to become an essential and beautiful backdrop for human life. Furthermore, buildings must be structurally sound and resist loads, such as their own weight, the weight of occupants and contents, wind, and seismic loads. They must keep out rain and other elements; they must provide a healthy indoor environment with regard to heating and cooling and in terms of indoor air pollutants; and they must maintain their functions over an extended service life.

All these functions are directly affected by moisture. Uncontrolled moisture will reduce the structural soundness of buildings through dry rot in wood and corrosion in steel. Moisture affects the health of occupants directly and through the potential for breeding harmful organisms. Moisture can reduce the service life through premature degradation of components. In short, uncontrolled moisture will negate the most vital and important qualities of buildings. On the other hand, moisture reduces the drying out and shrinking of wood products and furniture, and, up to a point, will alleviate upper respiratory discomfort. Thus, moisture is both a necessary constituency of our environment and a potential liability. The issue, then, is not to eliminate moisture from our buildings, but to control it both within the building interior as well as within building components and materials.

According to ASTM Practices for Increasing Durability of Building Constructions Against Water-Induced Damage (E 241), "except for structural errors, about 90 percent of all building construction problems are associated with water in some way." It is therefore understandable that much information on moisture in buildings is available, and that many books and technical papers have been written over the last 50 years on the subject of moisture and moisture control in buildings. A complete library of books, reports, technical papers and monograms, standards, and data relating to moisture control in buildings would include several thousand titles, and the serious researcher concerned with this field may quite regularly peruse several hundred.

Several good reference documents include sections on moisture control in buildings. A short bibliography of useful reference publications is provided at the end of this manual. In addition, many technical publications and conference proceedings by various organizations such as ASTM, ASHRAE, and BETEC are available and contain valuable research papers on moisture control in buildings. Also, much information on moisture in buildings is scattered throughout the literature as technical reports prepared by research organizations such as the National Institute for Standards and Technology, the Forest Products Laboratory, Oak Ridge National Laboratory, and Princeton University. However, much of that literature is difficult to obtain and access. Many such texts are referenced in the various chapters of this manual. All these publications are valuable and are highly recommended to those interested in the subject of moisture control in buildings in general or in any particular aspect of it.

However, there has been to date no publication which provides a comprehensive overview of the various issues and data related to moisture control in buildings. It is the intent of this manual to provide such an overview, to bring together in one volume the most important data and applicable state of the art relating to moisture problems in buildings, their diagnosis, prevention, and rehabilitation, and to synthesize the existing information and technology as a basis for indicating good design practice. It is the hope of the authors and the editor that this volume will serve as a desk-top reference manual for use by those who design, construct, sell, maintain, and own buildings and homes. The chapters on standards and codes, contract documents, and legal aspects of moisture control should aid in understanding the various mechanisms available for effective implementation of moisture control strategies.

Given the critical nature of moisture control in buildings, it is not surprising that early literature treated moisture as a separate, serious, distinct, and most important potential problem in building construction. However, since about 1974, the need for energy conservation has moved into a commanding position as the major concern in building performance, crowding out moisture as a primary concern. In addition, some energy conservation measures, such as the reduction of infiltration and ventilation, were applied unthinkingly and with little regard to the overall performance of buildings, sometimes causing moisture problems as side effects. As a result, concerns for moisture were relegated to a position of unfortunate, and possibly even apparently necessary, side effects of energy conservation measures. Because of this, those who promoted energy conservation were expected to solve moisture problems as well.

Of course, well-designed and installed energy conservation measures, be it in new or existing buildings, do not "cause" moisture problems, although inept application of some energy conservation measures can increase the propensity for moisture problems in already marginal structures. And, similarly, most moisture problems in buildings have causes other than energy efficiency. What both energy inefficiency and moisture problems have in common are poor design and a lack of understanding of how buildings and their equipment perform under the varied conditions of climate and occupancy. Great strides have been made in the development of technology to increase energy efficiency, to the point that energy-efficient building design has evolved into an interdisciplinary science. Moisture control in buildings has also made great strides over the last few years. ASTM has held several symposia and conferences and has published proceedings. Other organizations have done likewise, and the number of moisture-related technical contributions to national building technology conferences has increased significantly. For example, the second ASHRAE Conferences on Thermal Performance of Exterior Envelopes of Buildings in 1982 included seven papers on moisture control; the fifth similar conference in 1993 contained 17 papers on moisture. However, even today, moisture resistance is not, as a matter of code requirements, routinely designed into buildings as is structural integrity or temperature control because moisture, in the past, was not considered related to health and safety despite the long-recognized fact that moisture can lead to deterioration and eventual failure of the structure and the more recent recognition of detrimental health effects.

Accordingly, moisture control is not currently recognized as a separate and essential part of building technology. Even in such prestigious publications as the *ASHRAE Handbook on Fundamentals* and the *Architectural Graphics Standard*, moisture control is not treated as a separate subject; rather, parts are scattered over several chapters.

One objective of this manual is to help establish moisture control in buildings as a separate and major branch of building technology and building sciences. As such, moisture control must draw from many established sciences and technologies: the physics of heat and moisture transfer, material sciences, biology and health sciences, computer simulations, and others. For most of these, this manual will provide a basis of knowledge and data needed to prevent, investigate, and solve the most common moisture problems. Beyond the information and data provided in this manual, the referenced sources should provide the missing data and information for those who wish to study the issues more deeply.

From the beginning of the development of the book proposal and periodically thereafter, the question was raised as to who the intended audience was. We believe the manual will be useful to all those involved in designing and maintaining moisture-resistant buildings and in solving and repairing moisture problems in existing buildings: architects, owners, maintenance personnel, investors, researchers, and those who have to settle disputes resulting from moisture damage. For those who are experts within a particular area or chapter of the manual, the material covering such expertise may not be of great value as they, being experts, will have readily available specialized handbooks and other technical literature. Thus, the physicist will learn little from Chapter 1 on the fundamentals of moisture transport, condensation, and evaporation, and the mechanical engineer may find Chapter 2 on modeling heat, air, and moisture transport through building materials on components too general and basic for his needs. However, all experts and lay persons will benefit from the chapters outside their area of expertise.

This publication did not rely on a call for papers to solicit contributors. Rather, a book outline was prepared by the editor with input from many experts and was reviewed and approved by the ASTM Committee on Publications. Chapter authors were then selected based on expertise in their field. It was my task as editor to assure that the individual chapters conformed in a general way to the original outline and to reduce the number of conflicts and repetitions.

Were moisture control in buildings a mature science, this manual would contain no or only minor and infrequent conflicts or inconsistencies between the findings of one researcher or practitioner and others. But moisture control is not a mature science and therefore some of the foremost experts, researchers, and practitioners disagree on major issues. Where such disagreements have occurred, they were retained. So that each chapter might stand on its own, we also did not eliminate repetitions. Finally, although each chapter has undergone a rigorous peer review by three qualified reviewers, the manual is not a consensus document in the sense that ASTM uses the term, and the recommendations given in individual chapters are not necessarily those of ASTM or of the sponsoring committees, Committee E06 on Performance of Buildings and C16 on Thermal Insulation.

It is the hope of the authors and the editor that this manual will identify some of the knowledge gaps, will lead to more research for developing a more complete understanding of all aspects of moisture control in buildings, and will help to establish moisture control as a recognized, interdisciplinary engineering discipline much like that of energy conservation.

Heinz R. Trechsel
Editor

Introduction

THIS MANUAL strives to provide the major needed information and data to design and maintain moisture-resistant buildings and to investigate and correct moisture problems in existing buildings. It contains individual chapters devoted to the primary disciplines and mechanisms that promote and resist moisture-induced damage. To be responsive to the perceived need, it was essential to include in the manual many disciplines, types of investigators, theoreticians, and practitioners. Because these individuals do not currently agree in all aspects with one another, there are some conflicts and inconsistencies between the individual chapters.

As mentioned in the Preface, the main concern of building design is the development of structures for human habitation that are safe, provide a healthy and pleasant environment, and maintain these functions over a long service life. Since moisture affects all three, concerns for effective moisture control must be an integral part of the design process. This manual attempts to bring together in one volume the current state of the art relating to moisture control in buildings (good design practices), diagnosis and prevention of moisture-originated damage, and guidelines for rehabilitation of the structures. The manual addresses residential, commercial, and institutional buildings in all North American climatic zones. In all jurisdictions, design professionals are required to follow accepted standards of practice, but for many issues on moisture, accepted standards and practices are few or missing altogether and others are outdated by the development of new materials, new combinations of old materials into new systems, and new insights into the behavior of materials and structures.

The publication of this manual responds not only to the increasing awareness of the long-known potential structural and maintenance problems resulting from inadequate moisture control, but also to the more recently recognized and potentially even more serious health hazards of rot, mold, and other organisms which flourish in buildings with excessive moisture, or in localized areas with a conducive combination of moisture and temperature. The manual also recognizes the various interactions of materials, construction, equipment, and habitation, and the balance between the indoor environment, the building envelope, and the outdoor environment with its constantly changing temperature, humidity, and radiation.

The manual consists of four parts. Part 1, "Fundamentals," provides fundamental information and data relating to moisture control and the effects of moisture on buildings. Part 2, "Applications," discusses the application of related technologies to prevent or solve moisture problems in buildings. Part 3, "Construction Principles and Recommendations," gives guidelines and recommendations for designing and constructing new buildings and for increasing the moisture resistance of existing buildings. Part 4, "Implementation," provides insights into the various mechanisms for implementing moisture control strategies.

In Part 1, "Fundamentals," the theoretical basis of moisture control and applicable data is provided. Chapter 1 discusses the fundamentals of moisture transfer, condensation, and evaporation, and the appendix to the chapter is directed toward those with little or no knowledge of moisture transport mechanisms; the main body of Chapter 1 will be more useful to those with a good general understanding of the physical phenomena involved. Closely related to the first chapter is Chapter 2, which discusses the state of the art in computer programs for modeling the mechanisms discussed in Chapter 1. Chapters 3, 4, and 5 provide needed information and data on moisture-related properties of building materials and how their performance is affected by moisture. These chapters discuss building materials in general (Chapter 3), thermal insulations (Chapter 4), wood and wood products (Chapter 5). The last three chapters in Part 1 discuss: molds and other organisms in buildings and related health effects (Chapter 6); considerations of climate (Chapter 7), which includes needed tabular data for the United States, Canada, and other countries required for identifying climate zones and for use in calculations discussed in Chapters 1 and 11; and Moisture Sources (Chapter 8), which describes in both quantitative and qualitative form the major possible sources of moisture in buildings.

Part 2, "Applications," discusses the technologies that affect the moisture balance in buildings and the techniques used to determine the adequacy of materials, components, systems, and structures. Chapter 9 discusses the effect of ventilation and ventilation strategies both in cold and in warm and humid climates. Chapter 10 is devoted to issues of heating and cooling equipment and how they can be used to control moisture in buildings. In Chapter 11, several design tools for determining potential moisture effects on building components are discussed and their use demonstrated. Chapters 12 and 13 discuss the myriad of tests and measurement methods that can be used to determine material or component properties both in the field and in the laboratory (Chapter 12) and the techniques and methods used by investigators of moisture problems, including examples to demonstrate the use of test and evaluation methods (Chapter 13). An appendix to Chapter 13 also discusses statistical issues relating to the number of tests to perform and the degree of confidence a certain number of tests provides. The last chapter in Part 2, Chapter 14, provides a valuable compilation and discussion of many case studies conducted in this country and in Canada for determining the effect of moisture on constructions of actual buildings and to test various proposed standards designed to increase energy efficiency and moisture resistance. This chapter is useful in understanding the effect of climate on different building systems, components, and materials. The chapter will also be particularly helpful to those planning their own large-scale field studies. Because of a lack of major field studies and data on commercial and high-rise buildings, the chapter discusses only residential constructions.

Part 3, "Construction Principles and Recommendations," provides eight authors' recommendations for the design and construction of new moisture-resistant buildings and for upgrading existing buildings for greater moisture resistance or tolerance. The authors were carefully selected to provide a broad spectrum of the current state of the art, approaches, and solutions. Because of this, and because moisture control in buildings is still an immature science, still largely an art, the authors of these chapters do not necessarily agree with one another. Also, the guidelines are not ASTM recommendations, but present the authors' own understanding of the subject. Chapter 15 discusses the general concepts of moisture-resistant buildings. The chapter provides the traditional, generally accepted principles which apply to all buildings. Chapter 16 is devoted to roofing. Although it is recognized that roofing is the most important building component with regard to moisture control in buildings, roofing is discussed only in this chapter as it is recognized that roofing technology is well advanced and has its own broad and generally accessible literature. Chapter 17 discusses new residential construction. Chapters 18, 19, and 20 discuss new commercial and high-rise buildings (Chapter 18); existing residential buildings (Chapter 19), and existing commercial and high-rise buildings (Chapter 20). Because manufactured homes and historic buildings have unique moisture-related concerns, Chapters 21 and 22 were included to discuss these special building types.

Part 4 discusses implementation mechanisms. This section is organized along a simple concept: First, the building should be designed, built, and repaired according to contract documents which contain the principles outlined in the earlier sections and chapters. Second, codes and standards provide a firm basis for selecting products, systems, and construction features, and third, when all else fails, there are arbitration and court proceedings to resolve conflicts. The first three chapters of Part 4 follow these three phases. Chapter 23 explains the role of contract documents—specifications and drawings—in implementing moisture control strategies and provides guidelines for those not familiar with architectural design and production. Chapter 24 provides a useful compilation of standards and codes relevant to moisture control in buildings. Chapter 25 discusses legal aspects, illustrated by a real life case study. It was suggested above that moisture control in buildings is not currently treated as a separate design discipline and that it is the hope of the editor and the authors that this manual will contribute to the establishment of such a discipline. The last chapter of Part 4, Chapter 26, suggests, as a start towards such a discipline, a methodology for the design of moisture-resistant buildings modeled after the well-established methods used for structural design and analysis.

It is the policy of ASTM to require SI (metric) measurements in all its publications. Accordingly, all chapters use SI units in the text, and most chapters also provide common units in the text. Most tabular data are provided in only one measurement system. As a convenience to the reader, a metric conversion table is printed at the back of this book.

ASTM, the editor, and the individual chapter authors request comments on the usefulness, technical content, format, and any other issues related to the manual in its current form. We will strive to respond to all comments and to incorporate useful suggestions in any upcoming editions.

Heinz R. Trechsel
Editor

Part 1: Fundamentals

MNL18-EB/Feb. 1994

1

Fundamentals of Transport and Storage of Moisture in Building Materials and Components

by Marinkal K. Kumaran,[1] *Gintautas P. Mitalas,*[1] *and Mark T. Bomberg*[1]

NOMENCLATURE

a_m	Moisture diffusivity, m^2/s
a_{mT}	Thermal moisture diffusivity, $m^2/(K \cdot s)$
c	Concentration, kg/m^3
J	Flux or density of flow, quantity/$(m^2 \cdot s)$
k	General transport coefficient
P	Air pressure, Pa
p	Partial pressure, Pa
p_v	Saturation vapor pressure, Pa
T	Temperature, K or °C
V	Volume, m^3
grad ϕ	General driving potential
λ	Thermal conductivity, $W/(m \cdot K)$
μ	Vapor permeability, $kg/(m \cdot Pa \cdot s)$
ρ	Density, kg/m^3

Subscripts

B	General entity transported
m	Moisture
Q	Heat
v	Vapor
X, Y, Z	Cartesian coordinates
0	Dry material

INTRODUCTION

WATER, WHICH IS ABUNDANT on our planet, constantly undergoes various physico-chemical processes and interacts with all living and nonliving organisms. As much as water is essential for all life forms, it can also cause deterioration and dissipation of many natural and man-made materials. Buildings constructed to last many decades consist of a large number of such materials. Hence, building researchers, designers, and practitioners have always been interested in the role of moisture in buildings, such as the degradation of the thermal performance of buildings.

Among questions one would like to answer to define the role of moisture in the built environment, the following three are crucial:

1. How can the transport of moisture through building materials and components be predicted?
2. How can the harmful accumulation of moisture in building materials and components be prevented?
3. How does moisture transport affect the energy efficiency of buildings?

To answer these and similar questions, one should be equipped with a detailed knowledge of the basic physics of moisture transport and storage, two fundamental phenomena that are interrelated in a rather complex way. Some of this knowledge has been provided by soil scientists [*1*,*2*]. Building materials can be treated as porous bodies, similar to soil, and the theory developed for describing soil water movement can be adapted for building applications [*3*]. However, an additional transport process, viz. air transport, not often considered by soil physicists, constantly interacts with heat and moisture transport processes in buildings and makes the physics of moisture transport in buildings more complex.

Over the past two decades various groups of building researchers have significantly improved analytical and experimental methods to determine the hygrothermal behavior of building materials and components as influenced by simultaneous heat, air, and moisture transport [*4*]. There are numerous technical publications in this area in the literature as listed in recent reviews [*5–7*]. Later chapters in this handbook deal with various aspects of hygrothermal behavior of building materials and components individually. This chapter is intended to summarize our present knowledge of moisture transport and storage in relation to building materials and components.

THE THERMODYNAMIC STATES OF MOISTURE

Water, like any other pure substance, can exist in three states: solid (ice), liquid (water), and gas (vapor). These three states of moisture may exist in buildings. In addition, the various building materials can capture water molecules from the surrounding air and localize them on their surfaces. Moisture so localized is said to be in an adsorbed state.

In the absence of other material, the equilibrium between solid, liquid, and vapor is well defined. At any given temperature there is a well-defined maximum vapor pressure that moisture can establish; this is called the saturation vapor pressure. There is only one temperature and saturation vapor

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[1] Senior research officer, Building Performance Laboratory, Institute for Research in Construction, National Research Council Canada, Ottawa K1A 0R6.

pressure at which all three states can coexist. This is referred to as the triple point of water. The triple point temperature is 273.16 K, and the corresponding saturation vapor pressure is 611 Pa. At any other temperature, T, the following two vapor pressure equations give the saturation pressure, p_v, fairly accurately

$$p_v \text{ (Pa)} = \exp(28.542 - 5869.9/T - 2882/T^{1.5}) \text{ for } 250\text{ K} < T < 273.16\text{ K} \quad (1)$$

and

$$p_v \text{ (Pa)} = \exp(22.565 - 2377.1/T - 33\,623/T^{1.5}) \text{ for } 273.16\text{ K} < T < 330\text{ K} \quad (2)$$

The unique relation between saturation vapor pressure and temperature is the basis, as explained in the appendix to this chapter, for various psychrometric calculations in building applications.

But within the structure of a porous building material the above uniqueness between saturation vapor pressure and temperature does not exist. If a porous body is homogeneous and isotropic, it may have its own unique relation for the dependence of temperature and maximum vapor pressure. Such relations are virtually unknown because most building materials are nonhomogeneous and anisotropic. But in practice another property, considered to be representative of each porous building material, called sorption isotherm is indirectly used to supplement such relations.

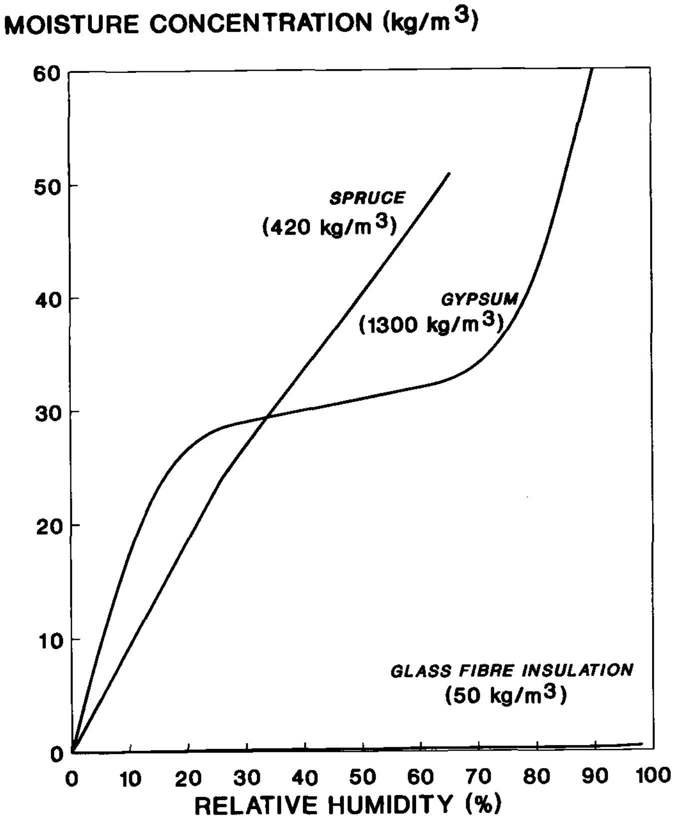

FIG. 1—Examples for sorption isotherms of common building materials. The quantities in brackets indicate approximate densities of the materials.

SORPTION, A MECHANISM FOR STORAGE OF MOISTURE

As mentioned above, solid surfaces in contact with water vapor have the tendency to capture and localize water molecules on them. This phenomenon is called adsorption. The maximum amount of moisture adsorbed by a given amount of solid depends on the temperature, the partial pressure of water vapor, and the surface area. Furthermore, each material has its own characteristic affinity towards water. This affinity is commonly referred to as hygroscopicity.

Let us consider the response of a homogeneous fibrous material to water vapor at a fixed temperature. If the surrounding air is perfectly dry, the amount of water adsorbed is zero. But as the vapor pressure is progressively increased the whole surface area of the fibers participates in providing a surface for water molecules to be adsorbed, first in the form of a monomolecular layer and then in multimolecular layers. This continues until the surface layers at various locations grow large enough to form droplets of water or frost particles. From the absolute dry state to this point of droplet or particle formation, the material is said to be in its hygroscopic range. In this range the maximum amount of adsorbed moisture is restricted by the hygroscopicity of the material. Once the vapor pressure is above this hygroscopic range, larger amounts of moisture begin to deposit in the pores until the structure is filled with condensed moisture. The maximum amount of moisture that can be accommodated by a material is limited only by its porosity. In principle this behavior seems well-defined, but in practice each specimen of building material has its own individual response to water vapor.

The relation between the amount of moisture adsorbed and the vapor pressure of moisture at a given temperature is called the *adsorption isotherm.* Naturally this relation is temperature dependent, but it is generally believed that if the adsorption isotherm is expressed in terms of relative humidity of the surrounding air, all the isotherms for a given material tend to merge into a single relation. This merged relation is called the *sorption isotherm.* Even though no unique sorption isotherm can be obtained for any building material, researchers have determined representative sorption isotherms for a variety of materials [*8*]. For example, let us consider three common building materials, viz. spruce, gypsum board, and glass fiber insulation. Figure 1 shows three representative sorption isotherms for the materials. If the pores of these materials are eventually filled with water, the volumetric water content in these materials can be as high as 800, 400, and 970 kg/m^3, respectively.

HYSTERESIS

The reverse of adsorption, namely desorption, presents further complexity. If a porous building material is saturated with water and allowed to dry in air at different relative humidities, it does not retrace the sorption isotherm. Usually, it retains more moisture during desorption than it can adsorb at any given relative humidity. This phenomenon, referred to as hysteresis, is illustrated in Fig. 2 with reference to gypsum board. Further examples may be found in Ref *8*.

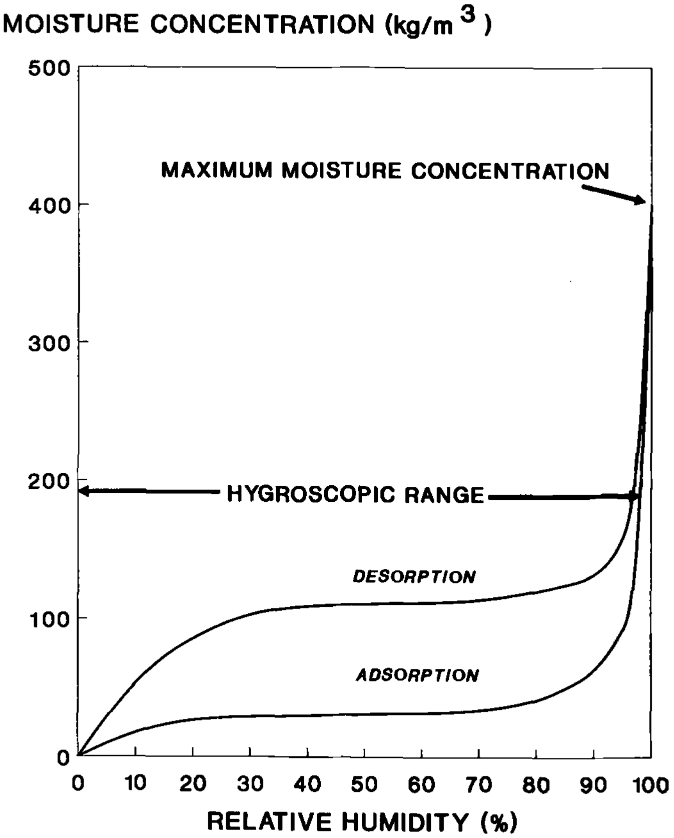

FIG. 2—Hysteresis exhibited by gypsum board.

PHASE CHANGES

As stated earlier, moisture may be present in the three normal states as well as in the adsorbed state. Subject to changes in temperature and vapor pressure, it is possible for this moisture to undergo change of state, or phase transition, as shown in Fig. 3. The phase changes affect two properties of moisture: its mobility and its energy content. Both these properties, as explained later, influence the hygrothermal behavior of building materials and components.

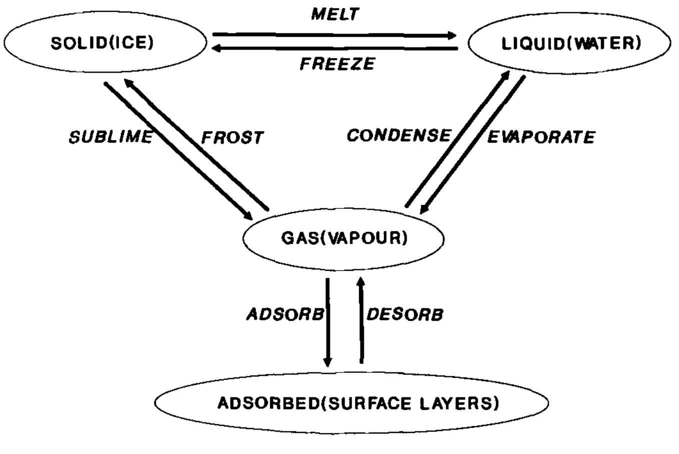

FIG. 3—Various processes undergone by moisture that involve phase changes.

TRANSPORT OF MOISTURE

Moisture can be transported from one location to another through a porous body in all the four states. To describe moisture transport theoretically one should consider:

1. Vapor transport.
2. Liquid transport.
3. Solid transport.
4. Adsorbate transport.

In vapor and liquid, water molecules are more mobile than in the latter two, and the first two processes may significantly dominate the other two in most cases. Thus building researchers have concentrated on vapor transport and liquid transport.

Any transport process is brought about by a driving force or a potential. The most well-known examples are heat transport due to a temperature gradient across two locations (Fourier's law) and electron transport due to a voltage difference (Ohm's law). Moisture transport is no exception to this general rule; however, to date it has not been possible to identify an experimentally realizable single potential that causes moisture transport. For practical reasons, the driving potential for moisture transport has been considered the result of a set of experimentally realizable driving potentials. This has resulted in the postulation of a variety of moisture transport processes as summarized in Table 1.

MOISTURE TRANSPORT EQUATIONS

Transport equations usually take the form

$$J_B = -k \cdot \text{grad}\, \phi_B \tag{3}$$

where J_B denotes a rate at which the entity B is transported, grad ϕ_B is the driving potential, and k is a quantity, called a transport coefficient, characteristic of the medium through which the transport occurs. Conventionally, J_B is expressed as the magnitude of B transported across a plane of unit area normal to the direction of transport in unit time. Hence it is also called a flux or flux density of B. Any such flux may be three dimensional, and in the Cartesian coordinate J_B can have three components, viz. J_{BX}, J_{BY}, and J_{BZ}. However, each component can be represented by an equation similar to Eq 3 as

$$J_{BX} = -k_X \cdot (d/dX)\phi_{BX} \tag{4}$$

TABLE 1—Moisture transport processes in building materials and components.

Transport Process	Participating State	Potential (Difference)
Gas diffusion	Vapor	Vapor pressure
Liquid diffusion	Liquid	Concentration
Surface diffusion	Adsorbate	Concentration
Thermal diffusion	Vapor and liquid	Temperature
Capillary flow	Liquid	Suction pressure
Convective flow	Vapor	Air pressure
Gravitational flow	Liquid	Height
Poiseuille flow	Liquid	Liquid pressure

In Eq 4 the transport coefficient k_X describes the transport in the direction X, and there will be similar coefficients k_Y and k_Z in the Y and Z directions. If the medium is truly isotropic

$$k_X = k_Y = k_Z \qquad (5)$$

But, as stated earlier, building materials in general are anisotropic and nonhomogeneous and the transport coefficients in Eqs 4 and 5 may show spatial variability.

Ideally, the coefficient k in Eq 3 should be independent of the quantity ϕ. This may be achieved if there is a rigorous theoretical method that can prescribe the ϕ that corresponds to a given flux. The thermodynamics of transport processes [*9,10*] is one such theoretical method that may be used to select ϕ's for heat and mass fluxes. The merit of this method was demonstrated [*11,12*] with reference to heat transport through dry glass fiber insulation. This has not yet been appropriately applied to many moisture transport processes. The traditional approach is to choose the correct driving potential based on experimental knowledge. For example, heat flux, J_Q, through dry insulations can be expressed as

$$J_Q = -\lambda \cdot \text{grad}\, T \qquad (6)$$

where λ becomes the thermal conductivity of the dry insulation and ϕ is the temperature, T. It is well known that for the range of temperature in which buildings operate, λ is practically linearly dependent on temperature. For wider ranges of temperature, this dependence may even be cubic because of the dominating radiative heat transport.

For each of the moisture transport processes listed in Table 1 it is possible to write equations similar to Eqs 3 and 4. But, unfortunately, most of the transport coefficients so postulated are rather complex functions of the corresponding ϕ's. Experimental determination of the functional dependence of moisture transport coefficients on the ϕ's is often very challenging. Let us now review some of the experimental techniques used to determine moisture transport properties of building materials.

VAPOR TRANSPORT

As given in Table 1, the driving potential for vapor transport is a difference in vapor pressure, p. Then, according to Eq 3, the vapor flux, J_v, is given by

$$J_v = -\mu \cdot \text{grad}\, p \qquad (7)$$

The transport coefficient μ in Eq 7 is called the water vapor permeability of the medium through which the vapor is transported. As stated earlier, μ is not a constant, but depends on p [*13*]. Experimental methods developed for the determination of μ usually give an average value for the coefficient in a range of p.

The standard means for the determination of μ is schematically shown in Fig. 4. A specimen of known area and thickness separates two spaces differing in relative humidity (RH). Then the rate of vapor transport across the specimen at a steady state is determined gravimetrically. From these data an average value for μ of the specimen for the range of relative humidity defined by the two spaces can be calculated. ASTM Test Methods for Water Vapor Transmission of Materials (E 96) prescribes two specific cases of this procedure. If the relative humidity in one of the spaces is 0% RH and the other less than 100% RH, the test method is called the desiccant method (dry cup method); if one of the spaces is maintained at 100% RH and the other greater than 0% RH, it is called the water method (wet cup method).

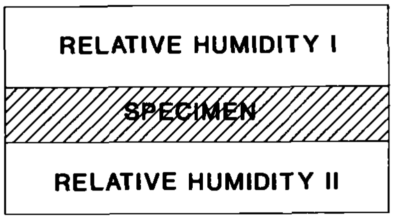

FIG. 4—Schematic drawing of an experiment for the determination of water vapor permeability.

In the dry cup method it is common to maintain the relative humidity of the second space at 50% RH. For most of the materials this range of 0 to 50% RH is well within the hygroscopic range, and the experiments can result in well-defined values for μ for the specimens. Some representative values for μ for common building materials, as determined at the Institute for Research in Construction, are given in Table 2.

In the wet cup method, however, part of the specimens is always between the hygroscopic range and the saturation range. Even though a steady state can be realized experimentally, it may not be appropriate to interpret the experimental data only in terms of a vapor transport. The data are to be interpreted in conjunction with the sorption-desorption isotherms and liquid moisture transport. This is especially true in the case of strongly hygroscopic materials such as wood and wood products. There are a number of discrepancies and unresolved issues in the area of water vapor transport measurements. Some are addressed in Ref *14*.

A difference in temperature, T, can also act as a driving potential for vapor transport. This part of vapor flux, $J_{v,T}$ can be written as

$$J_{v,T} = -\mu_T \cdot \text{grad}\, T \qquad (8)$$

In Eq 8 μ_T can be called a thermal vapor permeability. Traditionally, building physicists have disregarded this quantity assuming that this part of the vapor flux is negligible in comparison with J_v in Eq 7. Hence there are no well-developed experimental techniques accepted for the determination of μ_T. By an indirect method, for glass fiber insulation it is esti-

TABLE 2—Water vapor permeability, μ, of some building materials determined using the dry cup method.

Building material	μ, kg/(Pa·s·m)
Glass fiber (low density)	1.3E-10
Glass fiber (medium density)	1.3E-10
Glass fiber (high density)	1.1E-10
Cellulose fiber	8.3E-11
Fiberboard sheathing	1.9E-11
Gypsum board	1.7E-11
Polystyrene (expanded)[1]	2.6E-12
Polystyrene (extruded)[2]	1.7E-12
Pine	5.6E-13
Waferboard	4.2E-13
Plywood	2.9E-13

[1] Average density 24 kg/m^3.

[2] Average density 29 kg/m^3.

mated [15] that this quantity is approximately 10^{-8} kg/(m·K·s).

LIQUID TRANSPORT

From an experimental point of view, liquid transport is not as defined as vapor transport; it is very difficult to separate processes such as liquid diffusion, capillary flow, and surface flow. Hence, all are represented by one transport equation

$$J_l = -\mu_l \cdot \text{grad } c \tag{9}$$

where J_l is the total "condensed phase" moisture flux [kg/(m^2·s)] and c is the concentration of moisture (kg/m^3). Here the condensed phase is the sum of the liquid and the adsorbed phases. The transport coefficient μ_l may be called a liquid diffusivity (m^2/s) of the medium. This transport coefficient is usually not used by researchers directly for various reasons. It is impossible to stop the vapor transport component or to make it negligibly small during experiments. As moisture concentration varies from zero to the full saturation level (maximum moisture content) of the material, the value of μ_l changes at times by several orders of magnitude. In vapor transport an experiment can be organized to make use of Eq 7 directly to arrive at an average value for vapor permeability. But a similar approach is not possible in the case of liquid transport. This problem is handled in an indirect way as described below.

An isothermal moisture transport process through a specimen involving the liquid phase is selected. The effect of gravity is kept to a negligible level. If possible, the experiment is allowed to continue until the specimen under investigation attains a steady state moisture distribution. At this stage, the total moisture entering the specimen equals the total moisture leaving the specimen. By an appropriate technique, such as the gamma-ray method [16], the steady state distribution of moisture and the moisture transport rate are measured. The total moisture transport is then assumed to be expressed by the relation

$$J_m = -(a_{m\rho 0}) \cdot \text{grad } u \tag{10}$$

where J_m is the total moisture flux [kg/(m^2·s)], $(a_{m\rho 0})$ is the total moisture permeability [kg/(m·s)], and u, called the moisture content, is defined as

$$u = (\text{mass of moisture/mass of the dry specimen})$$

and ρ_0 is the density of the medium, i.e. the dry specimen. For any given value of u, all the quantities in Eq 10 except a_m are known from the experimental data, and the value of a_m as a function of u can then be calculated.

Instead of waiting for the steady state, if measurements are made on transient moisture distribution in the specimen at different intervals from the start of the process, the value of a_m as a function of u can be determined using another method. The transport equation is converted into a moisture conservation equation (see the section on modelling) as

$$(du/dt) = \text{divergent } (a_m \cdot \text{grad } u) \tag{11}$$

where t is time. If it can be assumed that the experiment represents a one-dimensional moisture transport process, Eq 11 takes the form

$$\frac{du}{dt} = \frac{d}{dx}\left\{a_m \frac{du}{dx}\right\} \tag{12}$$

or, since $c = \rho_0 \cdot u$

$$\frac{dc}{dt} = \frac{d}{dx}\left\{a_m \frac{dc}{dx}\right\} \tag{13}$$

where c is the total concentration of moisture.

The experiment generates a number of values of c as a function of x and t. According to the assumptions made, all the values of c should conform to Eq 13. Then suitable analytical techniques can be used to optimize the functional dependence of a_m on c and calculate the value of a_m as a function of c. The quantity a_m as used in Eqs 10, 11, and 13 has the status of a transport coefficient, but it has the dimensions of (length^2/time) and hence it is commonly called total moisture diffusivity of the specimen or material, i.e., analogous to thermal diffusivity.

Though both the steady state and transient methods for the determination of total moisture diffusivity appear to be experimentally feasible, a review of the existing data on building materials tells a different story; there are very few sets of data available, and the discrepancies between existing data are unjustifiable. Evidently a lot of effort still has to go into this aspect of research on moisture in buildings. It appears that the steady state method, though more direct in terms of calculations, presents more experimental difficulties. Transient methods are much easier to set up, though the analysis of the data is more tedious. One such transient method [17,18] that has a lot of potential is presented below.

A rectangular (30-cm-high, 5-cm-wide and 2 to 5-cm-thick) specimen is cut from the building material and dried. All six surfaces of the specimen are coated with a thin layer (0.2 mm) of an epoxy resin impermeable to moisture. When the resin is set, fresh surfaces of the specimen at both ends are exposed by slicing the epoxy resin. The specimen is then clamped vertically with one of the open surfaces just touching water in a container, maintained at a constant level. The other open surface remains in contact with the ambient, maintained at constant temperature and relative humidity. The experimental setup is shown schematically in Fig. 5.

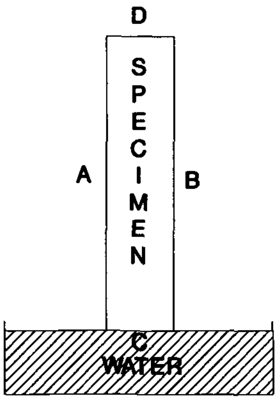

FIG. 5—Schematic drawing of the moisture intake process; all four longitudinal surfaces such as *A* and *B* are coated with water vapor resistant epoxy resin, and the surface *C* is in contact with water while the surface *D* is open to the surrounding air.

The time that the specimen touches water is recorded as the start of the experiment. Then, at selected intervals, the moisture distribution in the specimen is determined in situ using the gamma ray method. Figure 6 shows experimental data so obtained on one specimen cut from a sample of spruce. Water was allowed to enter and transport in the longitudinal direction of the specimen. Analysis of the experimental data in terms of Eq 13 using an optimization technique [19] yielded the values for a_m as shown in Fig. 7. This experiment covered the entire range of moisture content that spruce can attain. Numerical values for the total moisture diffusivity for the specimen are listed in Table 3.

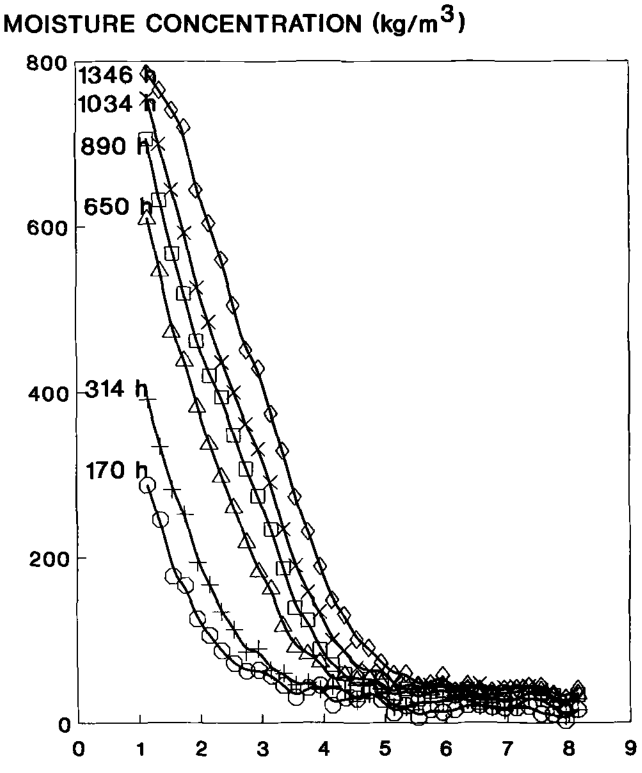

FIG. 6—Transient moisture distribution in the longitudinal direction of a specimen of spruce.

Introduction of the concept of the moisture content gradient acting as the driving potential for moisture transport has indeed provided a way for experimentalists to explore the details of moisture transport properties, but it has also created challenges which researchers have yet to overcome. These challenges will be explained in the section on modeling.

The transport equation (10) is true only for isothermal processes. For nonisothermal processes a term that corresponds to a thermal gradient also has to be considered. Then

$$J_m = -(a_m \cdot \rho_0) \cdot \text{grad } u - (a_{mT} \cdot \rho_0) \cdot \text{grad } T \qquad (14)$$

where a_{mT} is another moisture transport property which may be called thermal moisture diffusivity. Though researchers have been using this property for three or four decades, it is doubtful whether this property for any building material is known reliably or better than ±100%. Like a_m, a_{mT} is also an empirical quantity and can be a complex function of both u and T.

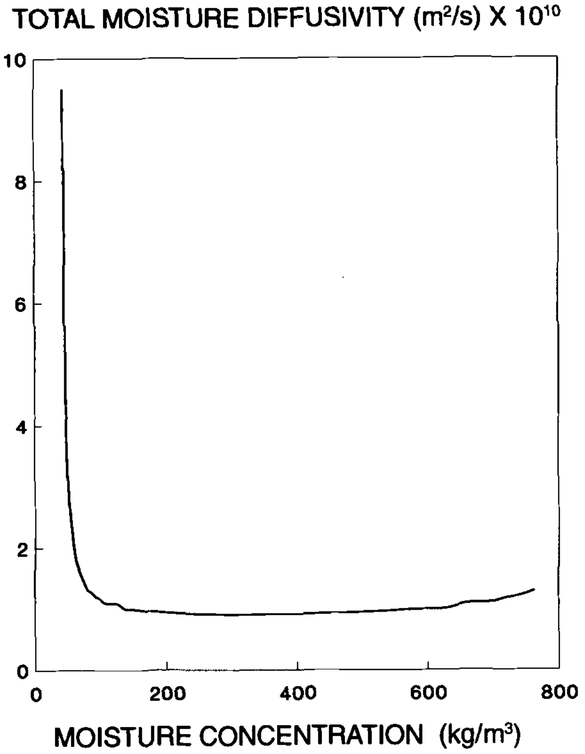

FIG. 7—Moisture diffusivity of spruce (density ≈ 400 kg/m³) at 20°C.

A steady state experiment, as shown schematically in Fig. 8,

TABLE 3—Total moisture diffusivity, a_m, for spruce in the longitudinal direction.

Moisture Concentration, kg/m³	$a_m \times 10^9$, m²/s
10	6.8
20	4.4
30	2.9
40	2.0
50	1.4
60	1.1
70	0.81
80	0.63
90	0.51
100	0.42
140	0.24
200	0.17
280	0.17
360	0.18
440	0.18
520	0.15
600	0.14
670	0.21
710	0.36
720	0.44
730	0.55
740	0.70
750	0.92
760	1.3
770	1.8
780	2.6

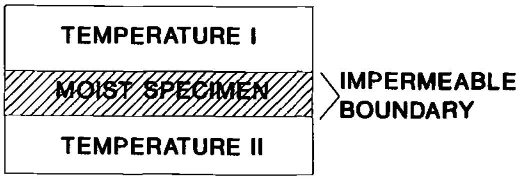

FIG. 8—Schematic drawing of an experiment for the determination of thermal moisture diffusivity of building materials.

can be used to derive information on a_{mT}. A moist specimen is enclosed between impermeable isothermal boundaries to establish a constant thermal gradient across it. The specimen is then allowed to attain a steady state moisture distribution. The temperature and moisture distributions in the specimen are then determined. At the steady state there is no net moisture transport anywhere within the system, i.e., J_m in Eq 14 is zero. If a_m for the specimen has been determined in an isothermal experiment, Eq 14 can be used directly to estimate a_{mT} as a function of T and u. There are a few examples in the literature [*19,20*] in which this method was partially applied to building materials—partial, because the dependence of a_m and a_{mT} on temperature was neglected during the data analysis and only average values over a temperature range presented. Table 4 lists a set of values for a wood fiber board specimen at an average temperature of 20°C determined using the steady state method [*20*].

Also, the optimization technique mentioned earlier can be extended to derive information on a_{mT}. In an isothermal experiment a_m is first determined. Then the specimen is subjected to a simultaneous heat and moisture transport process such that gradients of moisture content and temperature coexist and the transient temperature and moisture distributions are measured at selected intervals. A moisture conservation equation similar to Eq 13 is written to include a_{mT} and temperature gradient. Assuming that the experimental data on temperature and moisture distributions conform to the extended conservation equation and knowing a_m as a function of c from the isothermal experiment, the values of a_{mT} can be optimized. Though this is feasible, the authors are unable to present even one good example where this was successfully applied. This is an aspect where increased research activities should be directed.

TABLE 4—Thermal moisture diffusivity, a_{mT}, of a specimen of wood fiber board (density 270 kg/m^3) at a mean temperature of 20°C obtained from a steady state experiment [*20*].

Moisture Concentration, kg/m^3	$a_{mT} \times 10^{10}$, m^2/(s·K)
27	0.18
54	0.38
81	0.39
108	0.39
135	0.42
162	0.62
189	0.82
216	1.11
243	1.42
270	1.65
297	1.85
324	2.06
351	2.26
378	1.65
405	0.64
432	0.39
459	0.14

STORAGE OF MOISTURE AND ENERGY CHANGES

As moisture is transported through a finite volume in a medium, the amount of moisture retained by the volume is altered during any transient stage of the transport process. The basic causes for this are:

1. A change in local temperature.
2. A change in local vapor pressure.

Changes in temperature and vapor pressure in pores change the amount of moisture in the vapor phase needed to fill the pores, as governed by the equation of state (pressure-volume-temperature relations) for water vapor. These are often very small changes. Changes in vapor pressure in the hygroscopic region of the sorption isotherm alter the amount of moisture localized on the surface of the solid as governed by the sorption-desorption isotherm. Changes in vapor pressure outside the hygroscopic range alter the amount of condensed moisture as governed by the saturation vapor pressure–temperature relation as well as by the sorption-desorption isotherm. These changes involve one or more of the phase transitions shown in Fig. 3 which are often associated with appreciable changes in the energy content of the moisture retained. Hence they are strongly correlated, not only to the amount of moisture transported into and out of the finite volume but also to the energy changes associated with the transport processes.

MODELING OF HEAT, MOISTURE, AND AIR TRANSPORT

The preceding sections briefly reviewed some of the most important aspects of moisture transport. Moisture transport processes in buildings are strongly interrelated to heat and air transport processes. So, in any calculation method the three transport processes should be considered simultaneously. However, depending upon the situation under consideration, the model used for a set of calculations may be as simple as the Glaser [*21*] method commonly used by practitioners or as complex as a two-dimensional conduction-convection model presented in the next chapter.

Model calculations extensively depend on the knowledge of various transport properties of building materials and components. These transport properties are to be determined through experiments; there are no theoretical methods to calculate the properties. Hence model calculations are substantially empirical in nature. There are, however, a limited number of axioms that are quite useful. The generality of transport equations such as given in Eq 3 is one such axiom. Yet another set of axioms include the conservation equations.

When a transport process through a medium is modelled, the medium is treated as an ensemble of many finite volume elements. These volume elements are called control volumes. The axiom of conservation of any entity B within a control volume V, at any given instant, can be stated as [22]

Rate of storage of B in V = Rate of B entering V through its bounding surfaces + Rate of generation of B in V

The first step in modelling is then to write mathematical expressions for the three terms in the conservation equations. In order to model simultaneous heat, moisture, and air transport, one has to write conservation equations in three categories:

1. Conservation of energy (heat transport).
2. Conservation of mass (moisture and air transport).
3. Conservation of momentum (air and vapor transport).

The exactness of these equations depends on exactly how the two terms on the right hand side of the conservation equation can be written to represent real physical phenomena. As indicated earlier, this depends predominantly on empirical knowledge.

The media for the transport processes, viz. the building envelope, is considered stagnant and hence the term on the left hand side of the conservation equation is simply $(dB/dt)_V$. The first term on the right hand side, though it can be generalized as div $J_{B'}$ (the divergence of the flow of B into the control volume V), is complex due to the complexity of $J_{B'}$; $J_{B'}$ should include all the components of the flow of B. For example, for the conservation of water vapor, $J_{B'}$ may take the form

$$J_{B'} = -\mu \operatorname{grad} p - \mu_T \operatorname{grad} T - \mu_P \operatorname{grad} P \qquad (15)$$

The first two terms on the right hand side of Eq 15 have been explained earlier. The third term represents the vapor transported due to a difference in air pressure P. As explained earlier, the transport coefficients, μ, μ_T, and μ_P themselves may be functions of p, T, and P.

The rate of generation term in the conservation equation, though easy to realize physically, is rather difficult to write correctly. This term essentially represents the mass and energy generated (or destroyed) due to all the phase transitions within the control volume. The energy associated with phase transition can be very significant and can be a dominating component in the conservation equation. So errors in the amounts of various phases in the mass conservation equation can cause significant errors in the energy conservation equation. This is the challenge, referred to earlier, that the researchers face by adopting gradient of moisture content as a potential for the total moisture transport. The rate of generation of moisture considered as one entity, without differentiating the phases, simplifies the mass conservation equation by reducing the last term to zero. But the last term in the corresponding energy conservation equation should contain the components of vapor, liquid, or solid and adsorbed phases separately to calculate the latent energy contribution correctly. Two different approaches are currently used by researchers to solve this dilemma. Luikov and Mikhailov [23] introduced a quantity called the "phase transfer criteria" to partition between liquid and vapor phases, but it is unknown whether an acceptable experimental technique is available to determine this quantity. At times an arbitrary number between 0 and 1 is chosen for calculations. The second approach is to arbitrarily divide the curves similar to that in Fig. 7 into two parts as shown in Fig. 9. Such divisions are meant to split the total moisture transport into vapor transport and liquid transport components. These components are then used to calculate latent heat effects. This is only a hypothesis and needs to be confirmed by research.

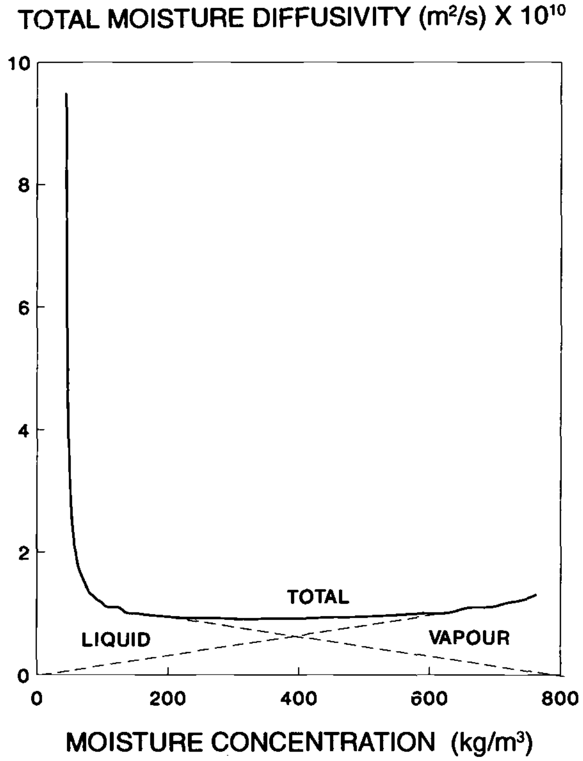

FIG. 9—The moisture diffusivity of spruce shown in Fig. 7 is arbitrarily split into vapor and liquid diffusivities.

Once the conservation equations are written, the next stage in modeling is to develop mathematical techniques to calculate the values for temperature, moisture content, vapor pressure, and air pressure in all the control volumes chosen to represent the media at any instance. In so doing, various flow components also will be calculated. A method called volume averaging technique [24] is used to interpret the quantities in conservation equations and make them experimentally realizable. The second order differential equations that result from the conservation equations are solved by numerical procedures such as finite difference method or finite element method. A number of standard text books, such as Ref 25, present details on these procedures.

MODELS AND MATERIAL PROPERTIES

However detailed the conservation equations may be and however sophisticated the mathematical techniques may be, the results from model calculations depend on the reliability of the material properties used in calculations. In addition to the moisture transport properties and the sorption isotherm introduced earlier, the following material properties are basic requirements for model calculations:

1. Thermal conductivity.
2. Heat capacity.
3. Air permeability.

Standard test methods are available for the determination of the above properties for dry materials. But in model calculations the properties of the dry materials alone are not enough. During the transport process, the moisture retained by each control volume changes. So at each instant, the stored moisture alters the properties and one should be able to calculate the above properties to correspond to the way in which they are used in the conservation equations. It is also desirable to develop experimental methods for the determination of the effect of moisture on the above three properties of the medium. The influence of moisture on heat transport through building materials has been extensively investigated and some of the findings are reported in Chapters 3 and 5.

Model developments and experiments for the determination of transport and other material properties should be performed parallel. Also, large-scale measurements with envelope components and systems should be undertaken to check the results from model calculations. Unfortunately, the duration of experiments can often be quite long and require sophisticated experimental techniques. This has traditionally discouraged researchers from conducting sufficient experimental investigations. Only a well-coordinated international effort can alter the situation and generate the much-needed data on material properties for model calculations and data on components and systems to verify model calculations.

From the above discussions it may appear that hygrothermal calculations are always complex, but this need not be the case. As stated earlier, depending on the information that one seeks, the complexities of the calculations vary. Some examples which can be performed with an electronic calculator are given below.

Example 1. Surface Condensation on Windows; Psychrometric Calculations

Problem: The room side surface temperature of a window during winter is known to be as low as 2°C. If the room temperature is to be maintained at 20°C, what is the upper limit of relative humidity that can be maintained in the room without surface condensation on the window? If it is necessary to maintain the relative humidity in the room at 50%, what is the lowest temperature that the window surface can be allowed to attain without causing condensation?

Solution: This is a straightforward, psychrometric calculation. If condensation occurs on the surface of the window at 2°C, the vapor pressure in that vicinity will be the saturation vapor pressure according to the vapor pressure equations (1 and 2) given at the beginning of this chapter, viz. 705.7 Pa. Therefore, condensation will occur if the vapor pressure in the room is at or above 705.7 Pa. At the room temperature of 20°C, the saturation vapor pressure, according to the vapor pressure equation, is 2339.4 Pa. Therefore, if the relative humidity of the room air is at or above (705.7/2339.4) × 100 = 30.17%, condensation occurs on the window surface.

If the relative humidity in the room is 50%, the vapor pressure is (2339.4 × 50/100) = 1169.7 Pa. This vapor pressure corresponds to the saturation vapor pressure at 9.27°C, according to the vapor pressure equation. (It is also said that the "dew point temperature" of the air is 9.27°C.) Therefore, if the window surface temperature reaches 9.27°C or falls below that, surface condensation is to be expected.

Example 2. Plane of Condensation in a Wall; Vapor Pressure-Saturation Vapor Pressure Method

Problem: The cross section of a wall (from inside to out) is 1.5-cm-thick gypsum, 15-cm-thick medium density glass fiber, and 1-cm-thick wafer board. If the average outside temperature is −10°C (263.15 K), the average outside vapor pressure 100 Pa, the average inside temperature 20°C (293.15 K), and the average indoor humidity 40%, is there a condensation plane within the wall?

Solution: In the vapor pressure–saturation vapor pressure method, this is treated as a steady state situation. Then, knowing the thermal conductivities and water vapor permeabilities, the temperature and vapor pressure distributions across the wall assembly are calculated for the given boundary conditions. If at any plane the vapor pressure coincides with or exceeds the saturation vapor pressure at the temperature of the plane, condensation may occur within the wall. The first plain from inside to outside, where this may happen, is referred to as the condensation plane.

Material Properties

	Thermal Conductivity, W/m·K)	Water Vapor Permeability, kg/m·Pa·s
gypsum	0.17	1.7E-11
insulation	0.036	1.3E-10
wafer board	0.055	4.2E-13

The calculated temperature and vapor pressure distributions, at steady state, are shown in Fig. 10. The figure also shows the saturation vapor pressure at various planes in the wall which correspond to the temperature calculated from the vapor pressure equations. It is seen that at approximately 0.075 m from the inside surface there is a condensation plane in the wall assembly for the boundary conditions considered. So anywhere beyond that, towards the outside surface, condensation may occur.

The information derived from this calculation is not quantitative. But there is no harm in using the information to derive some design guidelines. For example, if the gypsum is provided with a vapor retarder (such as paint on the surface or a polyethylene film at the interface with the insulation) to reduce the permeability to 1.7E-14 kg/(m·Pa·s) the calculation shows, as shown in Fig. 11, that there is no condensation plane in the wall assembly.

The steady state calculations cannot tell anything about the amount of moisture that may accumulate at various locations. Only a model that takes the conservation equations into consideration will tell that actual moisture accumulation starts at the interface between the wafer board and the insu-

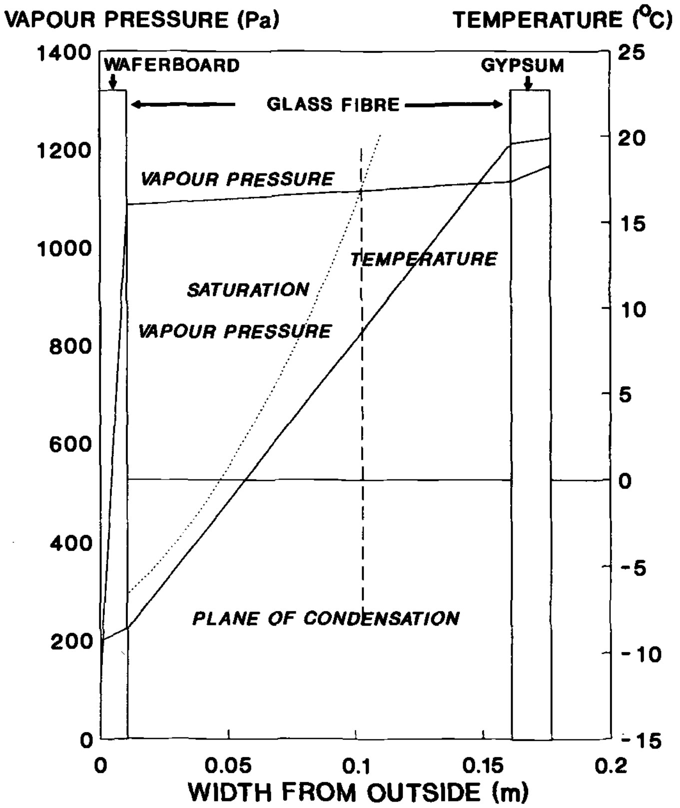

FIG. 10—Calculated results from vapor pressure–saturation vapor pressure method applied to Problem 2.

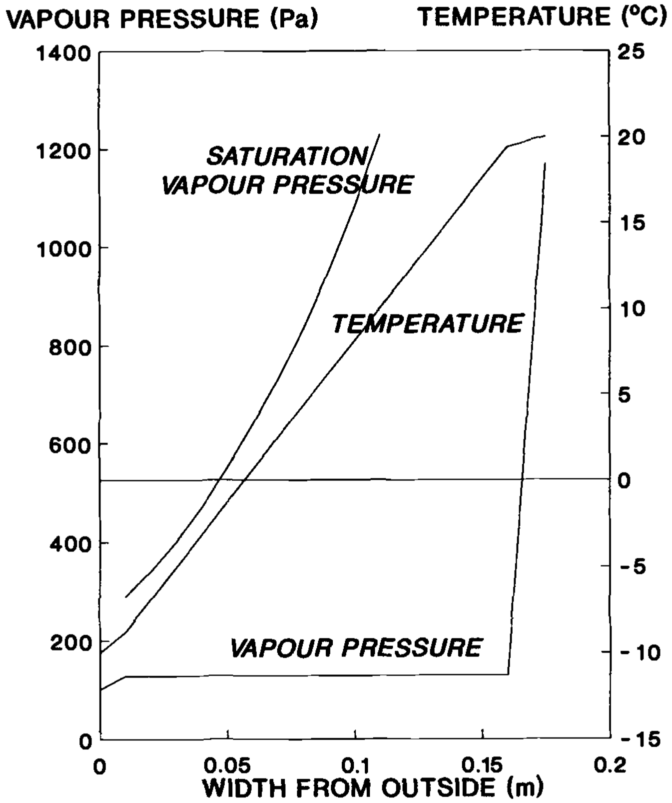

FIG. 11—Calculation shows that as the water vapor permeability of the gypsum is reduced to 1.7E-14 kg/(m·Pa·s), the condensation plane in the assembly disappears.

lation and that the amount of condensed moisture at the condensation plane calculated above is negligible for several hundred hours.

CONCLUDING REMARKS

The current knowledge on hygrothermal behavior of building materials and components is predominantly empirical. In a number of specific cases this empirical knowledge is very useful for calculations and predictions. Building design guidelines may be developed based on such predictions. But, in general, the current knowledge is not adequate to calculate and predict hygrothermal behavior. The missing aspects are:

1. A rigorous theoretical method that can identify the correct, but experimentally realizable, potentials for moisture transport.
2. The experimental methods that will lead to the determination of various transport coefficients.

Even if the current knowledge is believed to be adequate, there is a shortage of reliable experimental procedures for the determination of various transport properties postulated. Due to the very nature of moisture transport, it can not be expected that any such property for building materials may be determined in a short period such as a week or two; the experiments are rather slow and may last for many days or several months. But there is no short cut. These experiments are to be designed and performed. Only a well-coordinated international effort can achieve this and produce the much-needed data on material properties. An international effort has been launched under the umbrella of the International Energy Agency in this direction. A new annex entitled, "Heat, Air and Moisture Transport in New and Retro-Fitted Insulated Envelope Part" has been initiated in 1991 to collect and document the existing information within four years and to coordinate future research in this area. The countries involved are Belgium, Canada, Denmark, Finland, France, Germany, the Netherlands, Italy, Sweden, Switzerland, the United Kingdom, and the United States of America.

APPENDIX

Psychrometric Calculations

Psychrometric calculations deal with physical properties of moist air and analyze its hygrothermal behavior. Hence these calculations find many applications in building physics. A fundamental gas law called the "ideal gas law" and a unique relation between saturation vapor pressure and temperature form the basis of all such calculations. This appendix is intended to be a brief introduction to the basics of psychrometric calculations. A detailed account of these calculations can be found in Chapter 6 of the *ASHRAE Handbook of Fundamentals*.

Ideal Gas Law

The ideal gas law in its most general form can be written as

$$pV = nRT \qquad \text{(A1)}$$

where

p = pressure of the gas, Pa,
V = volume occupied by an amount of substance, n, of the gas (mol), and
T = absolute or thermodynamic temperature, K.

The quantity R is called a universal gas constant and is given the value 8.31441 J/(mol·K).

For any given gas of molar mass M (kg/mol), Eq A1 can be written also as

$$pV = w(R/M)T \qquad \text{(A2)}$$

where w = the mass of the gas in volume V. The molar mass of the gas being a constant, the quantity (R/M) is a constant for the gas under consideration. For example, the molar mass of water is 0.018016 kg/mol and the gas constant (R/M) for water vapor, denoted as R_w, then becomes

$$R_w = \frac{8.31441\ \text{J/(mol·K)}}{0.018016\ \text{kg/mol}} = 461.5\ \text{J/(kg·K)} \qquad \text{(A3)}$$

Similarly, the molar mass of air is 0.028965 kg/mol and its gas constant, denoted as R_a, is

$$R_a = \frac{8.31441\ \text{J/(mol·K)}}{0.028965\ \text{kg/mol}} = 287.06\ \text{J/(kg·K)} \qquad \text{(A4)}$$

Saturation Vapor Pressure

On the thermodynamic temperature scale, water under standard atmospheric pressure (1 atm = 101.325 kPa) freezes at 273.15 K. This temperature is also denoted as 0°C. At all temperatures below this, water is not expected to be in the liquid state. Whether in liquid or in solid state, it is always possible to establish an equilibrium between the condensed (solid or liquid) state and a vapor state. However, at each temperature there is an upper limit to the magnitude of the pressure exerted by water vapor. This upper limit is referred to as the saturation vapor pressure. The *ASHRAE Handbook of Fundamentals* quotes mathematical equations that relate saturation vapor pressure and a wide range of temperature. For practical building applications (a temperature range of −50 to +50°C), the following equation is appropriate.

$$p_s = \exp\,(A + B/T + C/T^{1.5}) \qquad \text{(A5)}$$

where

p_s = saturation vapor pressure, Pa, and
T = thermodynamic temperature, K.

For temperatures below 273.16 K

A = 28.542
B = −5869.9 K, and
C = −2882 $\text{K}^{1.5}$

and for temperatures above 273.16 K

A = 22.565
B = −2377.1 K, and
C = −33 623 $\text{K}^{1.5}$.

Properties of Moist Air

Moist air contains water vapor. In all psychrometric calculations it is treated as a mixture of dry air and water vapor. For example, the pressure of moist air is treated as the sum of the pressure of water vapor and that of dry air. The pressure of water vapor in such a mixture is referred to as the partial pressure, p_v, of water vapor.

The temperature of moist air is an important physical quantity in all psychrometric calculations. Once a temperature is attributed to a sample of moist air, it means that the water vapor as well as the dry air have the same temperature. This temperature then puts a limit to the maximum possible partial pressure for water vapor—it cannot exceed the saturation vapor pressure (Eq A5) at that temperature. If the partial pressure is equal to the saturation pressure, the sample of moist air is called saturated air. At all other partial pressures it is unsaturated air. Whether the air is saturated or unsaturated, in psychrometric calculations it is assumed that water vapor follows the ideal gas law (Eq A1). Thus the partial pressure and temperature define the state of water vapor in a sample of moist air. If the total pressure of moist air is also known, the state of the moist air is completely defined. But for practical building applications two other defined physical quantities are usually used to describe the state of a sample of moist air. These are:

1. Relative humidity.
2. Humidity ratio.

Relative Humidity

The relative humidity, RH, of a sample of moist air at a temperature T is defined as

$$\text{RH} = \frac{\text{partial pressure of water vapor}}{\text{saturation pressure at } T} \times 100 \qquad \text{(A6)}$$

From Eq A6 it can be seen that RH is expressed as a percentage and the highest value for RH is 100%. This is the state of saturated air at which the partial pressure of water vapor is equal to the saturation vapor pressure.

Humidity Ratio

The humidity ratio, W, of a sample of moist air is defined as

$$W = \frac{\text{mass of water vapor}}{\text{mass of dry air}} \qquad \text{(A7)}$$

The following numerical example illustrates the relation between various physical quantities introduced so far and the application of ideal gas law and the saturation vapor pressure equation in psychrometric calculations.

Example 1:

At 20°C, the relative humidity of a sample of moist air is 43% and its pressure is 101.02 kPa. What is its humidity ratio?

Solution:

Thermodynamic temperature of the sample = (20 + 273.15) K = 293.15 K. From Eq A5, the saturation vapor pressure at 293.15 K = 2338.6 Pa.

$$\text{RH} = 43\ \% = \frac{\text{partial pressure of water vapor}}{2338.6\ \text{Pa}} \times 100$$

then, partial pressure of water vapor = 1005.6 Pa, partial pressure of water vapor + partial pressure of dry air = 101 020 Pa; then partial pressure of dry air = 100 014.4 Pa.

Let us consider a fixed volume of the moist air, say 1 m^3. (It can be any volume.) From Eqs A2 and A3, the mass of water vapor in 1 m^3 = 0.007433 kg. From Eqs A2 and A4, the mass of dry air in 1 m^3 = 1.1885 kg (for any other volume the masses vary proportionally). Then, the humidity ratio for the sample of moist air = 0.006254. This means that for each kg of dry air, the sample carries 0.006254 kg of water vapor.

Heating of Moist Air

The air in buildings undergoes heating and cooling for various reasons; hence, psychrometric calculations find the number of applications to quantify the changes. When a sample of moist air is heated, one major change occurs: the relative humidity of the sample decreases. The explanation is simple. According to the ideal gas law, the change in partial pressure of water vapor is directly proportional to the change in temperature. But, according to the vapor pressure equation, the change in saturation pressure is exponential. That means for the same increase in temperature the increase in saturation pressure will be much larger than the change in partial pressure and thus heating moist air results in a decrease in relative humidity. However, the ability of the air to accommodate water vapor increases with temperature; in other words, the humidity ratio of saturated air increases exponentially with temperature. The following numerical example illustrates this behavior of moist air.

Example 2:

A sample of moist air at 0°C with a partial water vapor pressure of 500 Pa is heated to 20°C at constant volume. Compare the initial and final relative humidity of the sample. Also compare the maximum amount of water vapor that can be accommodated by air at the two temperatures.

Solution:

For a given amount of gas, the ideal gas law relates any two states as

$$\frac{p_1 V_1}{T_1} = \frac{p_2 V_2}{T_2}$$

where the subscript 1 refers to State 1 and 2 to State 2.

So, for the process of heating at constant volume

$$\frac{p_1}{T_1} = \frac{p_2}{T_2}$$

In the example given above, p_1 = 500 Pa, T_1 = 273.15 K, and T_2 = 293.15 K. Hence, p_2 = 536.6 Pa. The saturation vapor pressure at 0°C is 611 Pa and that at 20°C is 2338.6 Pa. Hence the initial RH is 82%, while the final, that of the heated sample, is only 23%. This is a substantial decrease in RH.

Now consider two samples of 1 m^3 of saturated air, one at 0°C and the other at 20°C. From ideal gas law calculations it can be shown that the 0°C sample contains only 0.00485 kg of water vapor, while the 20°C sample contains 0.0173 kg. This indicates a substantial increase in the capacity of air to accommodate water vapor at the higher temperature.

Cooling of Moist Air and Condensation

In principle, the cooling of moist air reverses the effect of heating: the relative humidity increases and the capacity of air to accommodate water vapor decreases. However, as stated earlier, the relative humidity cannot exceed 100%. Hence, as the cooling continues, at some temperature the RH reaches 100%. If it is cooled further, the capacity of air to accommodate water vapor will be less than what is available. The moist air has then to discard the excess of moisture. This is when condensation occurs. The temperature at which this happens is called the dew point temperature. If the dew point temperature is above 0°C, the condensed moisture appears as liquid water; if below 0°C, frost results. The following example illustrates this behavior of moist air.

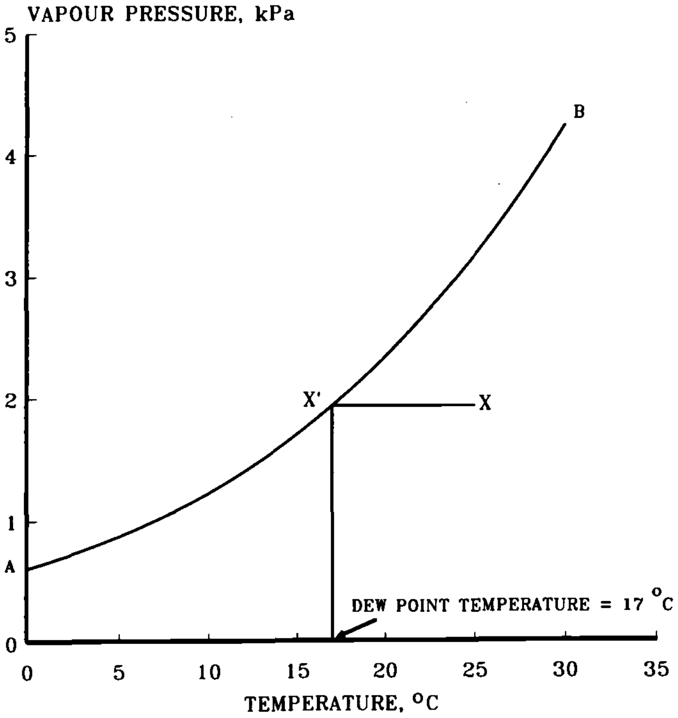

FIG. A1—Condensation of moist air during cooling.

Example 3:

The air in a room is maintained at 25°C and at 61.2% RH. What is the lowest temperature that any surface in the room can be held without initiating condensation?

Solution:

The solution to this example is shown graphically in Fig. A1. The curve *AB* is the saturation curve according to Eq A5. The point *X* marks the state of the moist air in the room. At 25°C, 61.2% RH means that the partial pressure of water vapor is 1937.8 Pa because the saturation pressure at this temperature is 3168.8 Pa. As the air is cooled the temperature and (approximately) the state of the air follows the line *XX'*. At *X'* the state coincides with that of saturated air. The temperature then corresponds to 17°C. So, if any surface in the room is below 17°C condensation occurs on the surface.

PSYCHROMETRIC CHART

All the psychrometric calculations presented so far can be performed easily using a practical tool called the psychro-

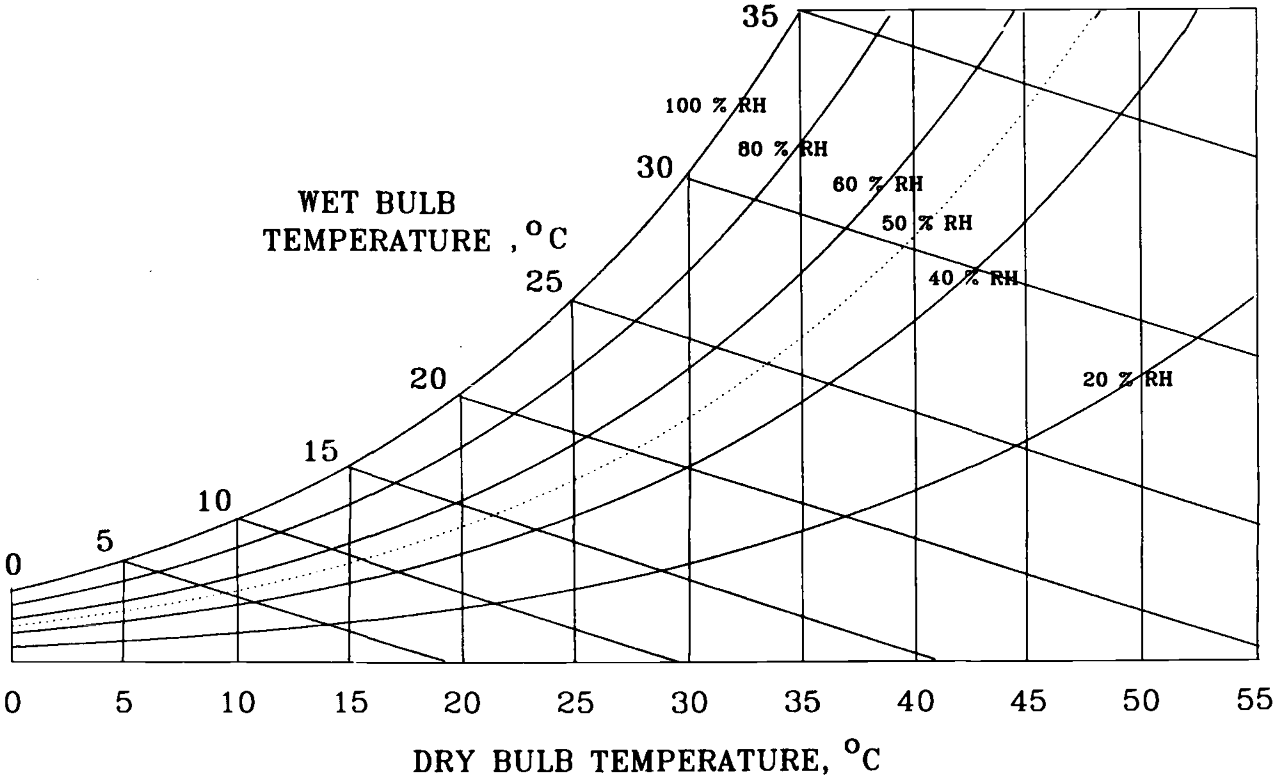

FIG. A2—A simple psychrometric chart.

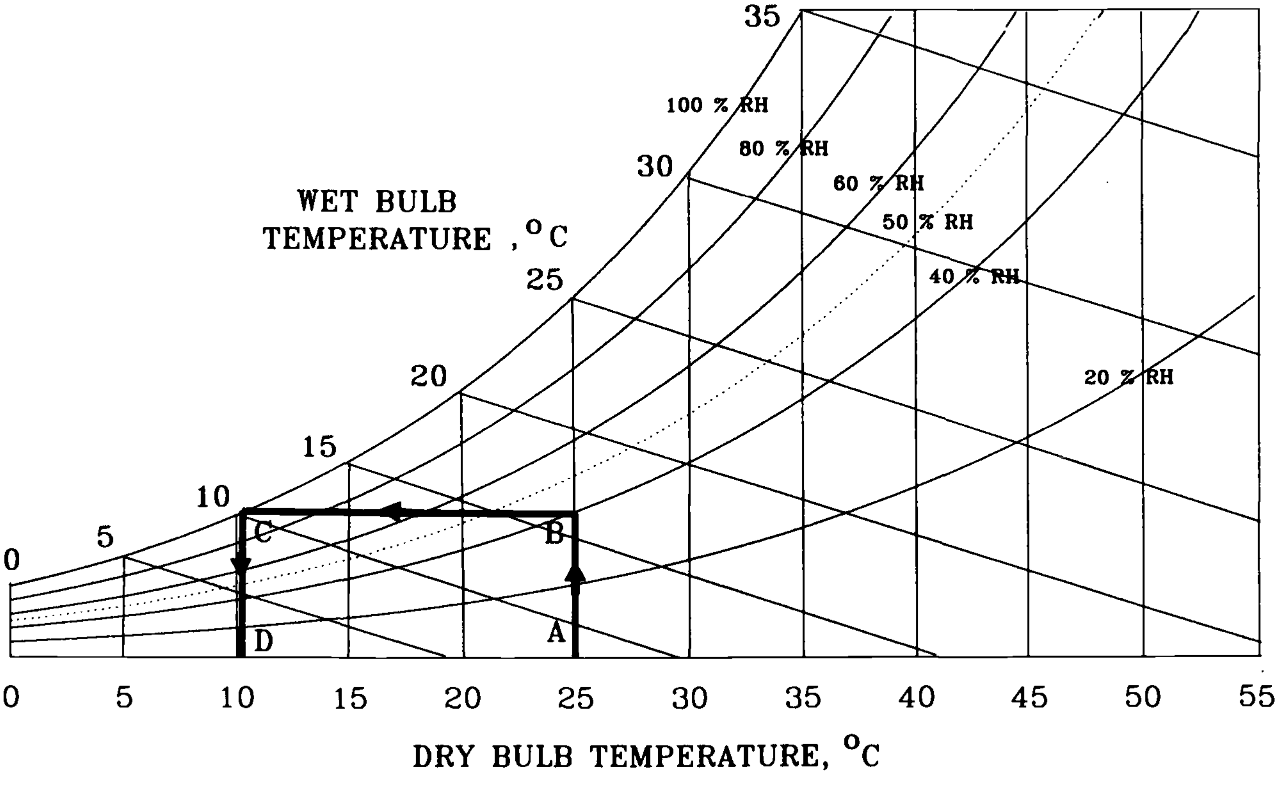

FIG. A3—Calculation of dew point temperature.

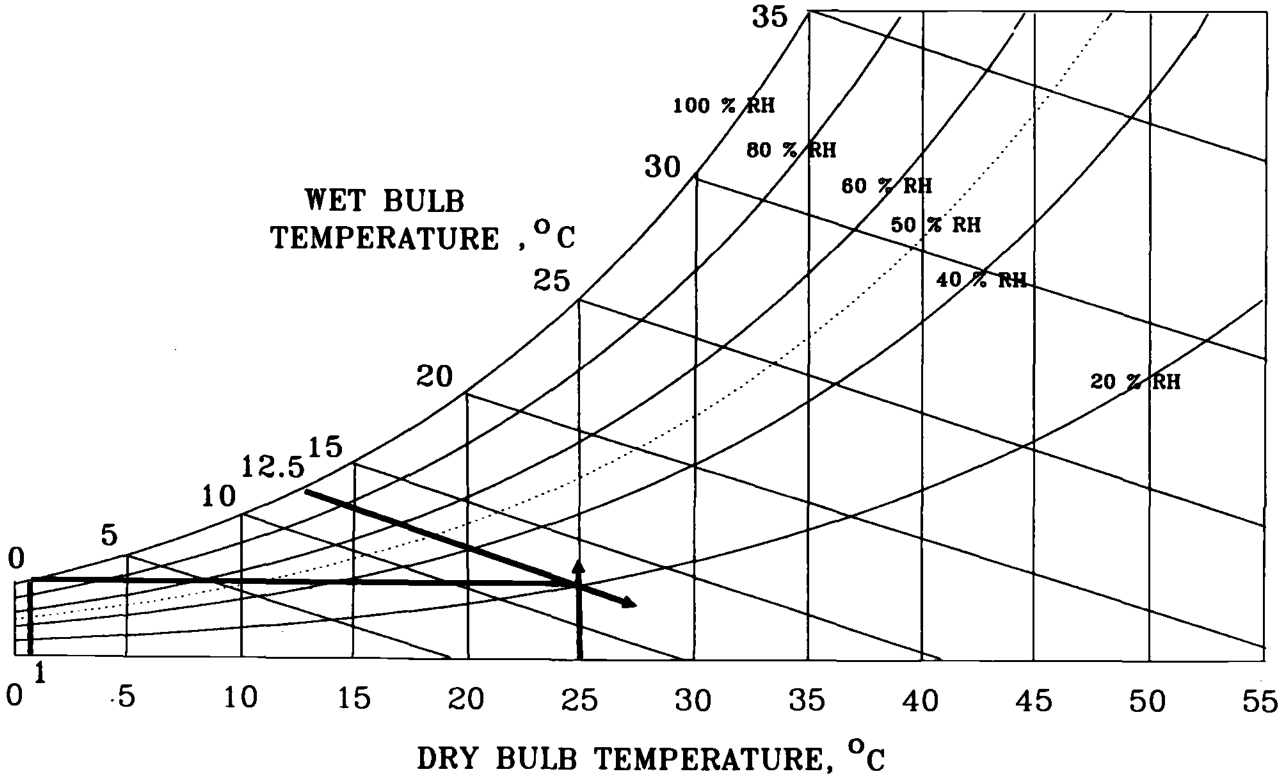

FIG. A4—Calculation of relative humidity and dew point temperature from psychrometric measurements.

metric chart, a simple form that is illustrated in Fig. A2. Such a chart graphically approximates the properties of moist air. A psychrometric chart is basically generated from Fig. A1 by including several relative humidity curves between 0 and 100%. However, it often contains information on humidity ratio, specific volume of dry air, specific enthalpy of saturated water vapor, etc. and all these are interrelated through wet and dry bulb temperatures. Many useful calculations in building applications can be performed readily with a psychrometric chart. Two examples of such calculations are given below.

Example 4. The Dew Point Temperature of a Sample of Moist Air

At 25°C, the relative humidity of a sample of moist air is 40%. What is the dew point temperature of the sample?

Solution:

The calculation is shown in Fig. A3. First of all, select Point A, which corresponds to 25°C on the dry bulb temperature axis. Now move the point vertically upwards until it falls on the 40% relative humidity curve at *B*. Next move the point horizontally until it falls on the saturation vapor pressure curve at *C*. Finally, move the point to fall on the dry bulb temperature axis at *D*. The temperature at *D*, ≈10.5°C, corresponds to the dew point temperature of the sample of moist air.

Example 5. Psychrometer and Humidity Measurement

A psychrometer shows that the wet bulb and dry bulb temperatures for a sample of moist air are, respectively, 12.5 and 25°C. What is the relative humidity of the air and what is its dew point temperature?

Solution:

This calculation can be performed using the psychrometric chart as shown in Fig. A4. On the chart a diagonal axis shows the wet bulb temperature and the horizontal axis gives the dry bulb temperature. Locate the point at which the diagonal 12.5°C wet bulb temperature line and the vertical 25°C dry bulb temperature line intersect. Then find the relative humidity curve that passes through the point of intersection. In this example the 20% relative humidity curve passes through the point of intersection. Hence the relative humidity of the air, according to the readings from the psychrometer, is 20%. Then, using the procedure described in Example 4, the psychrometric chart shows that the dew point temperature for the sample of moist air at 25°C and 20% relative humidity is 1°C.

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Modeling Heat, Air, and Moisture Transport through Building Materials and Components

2

by Tuomo Ojanen,[1] *Reijo Kohonen,*[1] *and Marinkal K. Kumaran*[2]

BUILDINGS COMPRISE A SIGNIFICANT PORTION of the assets of any nation. Hence, the structural integrity, durability, and performance of buildings play a vital role in the nation's economy. But buildings fail, and a major cause of failure are the thermal and moisture loads incorrectly accounted for during building design and construction. Building components and structures were developed through traditions and generations of experience, but far too often new building materials and construction practices are introduced without thorough analyses of their hygrothermal behavior. These analyses can be done through laboratory and field experiments and through calculations. While laboratory and field experiments are often too selective and rather slow, calculation methods can accommodate a variety of changing boundary conditions and result in much faster analysis. With rapid advances in computer technology and a better grip on numerical methods, many computer models for hygrothermal calculations were developed during the past decade. Depending upon the complexity of the problem under consideration, such models can be based on very simple, one-dimensional steady state methods or on very complex, two- or three-dimensional, transient methods. The general philosophy of modeling was presented in Chapter 1. This chapter briefly reviews the current state of modeling capabilities and presents selected applications of a computer model to illustrate the power of modeling as a tool for developing building design guidelines.

THE STATE OF THE ART

The information presented in this section is based on a recent review [*1*] of heat, air, and moisture transport models for building applications by an International Energy Agency Annex on the subject. From ten different participating countries, 28 models were reviewed. Table 1 lists the names of the models with the organizations where they were developed or where they are in use.

The 28 models are arranged in seven groups in Table 1 according to dimensionality. Yet another classification, as nine types, was achieved in terms of the complexities of the models. These nine types are as follows:

Type 1. Steady state heat conduction and vapor diffusion are modeled. The material properties are held constant. The two transport processes are linked through the dependence of saturation water vapor pressure on temperature. The models Wand, HYGRO, and BRECON2 are examples of this type.

Type 2. The main differences between this type and Type 1 are that the vapor diffusion is corrected for capillary moisture transfer and that the two transport processes are linked through the sorption isotherms of materials. The model Glasta belongs to this type.

Type 3. Transient heat conduction and vapor diffusion are modeled. Material properties are expressed as functions of moisture content. The two transport processes are linked through sorption isotherms and latent heat effects. The model HAMPI is an example of this type.

Type 4. Transient heat conduction, vapor diffusion, and liquid transport are modeled. Material properties are functions of moisture content and/or temperature. The processes are linked through sorption isotherms and latent heat effects. Fourteen of the 28 models reviewed belong to this type; these are MATCH, LTMB, CHEoH, TONY, V30, V320, WFTK, WUFIZ, JOKE, COND, P1220A, VADAU, FUKT74:6, and MOIST.

Type 5. Steady state or transient heat conduction and air transport are modeled. Material properties are held constant. The two transport processes are linked through heat capacity and stack effect. The models NatKon, WISH-3D, and ANHCONP belong to this type.

Type 6. Steady state heat conduction, vapor diffusion, and air transport are modeled independently (i.e., uncoupled). Material properties are held constant. However, the processes are linked through sorption isotherm/saturation water vapor pressure, latent heat, heat capacity, and stack effect. The models Konvek and EMPTEED represent this type.

Type 7. Steady state heat conduction and air transport and an uncoupled, but transient vapor diffusion are modeled. Material properties are held constant. The transport processes are linked through saturation water vapor pressure, latent heat, heat capacity, and stack effect. The model WALLDRY is an example of this type.

Type 8. Transient, coupled conductive and convective heat and vapor transports are modeled. The material prop-

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TABLE 1—Heat, air, and moisture transport models reviewed by IEA Annex XXIV.

Number	Name	Organization and Country
One-Dimensional Heat and Moisture Transport Models		
1	Wand	KU-Leuven, LB, Belgium
2	Glasta	Physibel, Belgium
3	HAMPI	University of Saskatchewan, Canada
4	MATCH	Technical University, Denmark
5	LTMB	INSA, Dep Genie Civil, France
6	V30	CSTB, France
7	WFTK	Fraunhofer Institute für Bauphysik, Germany
8	JOKE	TU-Cottbus, Germany
9	CONDO	TU-Cottbus, Germany
10	HYGRO	TNO-Bouw, afdeling, BBI, Netherlands
11	P1200A	SP, Sweden
12	FKUT74:6	Gullfiber AB, Sweden
13	BRECON2	BRE Scottish Laboratory, UK
14	MOIST	NIST, USA
Two-Dimensional Heat and Moisture Transport Models		
15	CHEoH	Institut de Mecanique des Fluides, France
16	TONY	Institut de Mecanique des Fluides, France
17	V320	CSTB, France
18	WUFIZ	Fraunhofer Institute für Bauphysik, Germany
19	VADAU	Chalmers University of Technology, Sweden
Two-Dimensional Heat and Air Transport Models		
20	NatKon	KU-Leuven, LB, Belgium
21	ANHCONP	Lund University, Sweden
Three-Dimensional Heat and Air Transport Model		
22	WISH-3D	TNO-Bouw, afdeling BBI, Netherlands
One-Dimensional Heat, Air and Moisture Transport Model		
23	WALLDRY	CMHC, Canada
Two-Dimensional Heat, Air and Moisture Transport Models		
24	EMPTEDD	TROW/CMHC, Canada
25	TCCC2d	VTT, Finland/NRC Canada
26	TRATMO2	VTT, Finland
Three-Dimensional Heat, Air and Moisture Transport Models		
27	Konvek	KU-Leuven, LB, Belgium
28	WALLFEM	CMHC, Canada/FSEC, USA

erties are functions of moisture content and/or temperature. The processes are linked through sorption isotherms, heat capacity, latent heat, and stack effect. The model TCCC2D is an example of this type.

Type 9. Transient, coupled conductive and convective heat and vapor transports as well as liquid transport are modeled. The material properties are functions of moisture content and/or temperature. The processes are linked through sorption isotherms, heat capacity, latent heat, and stack effect. The models WALLFEM and TRATMO2 are examples for this type.

The complexity of the models increases through the nine types listed above in terms of the number of transport processes and how their interactions are modeled and the functional dependence of material properties. The 28 models reviewed also differ in terms of:

1. The way in which heat exchanges in cavities and air spaces are modeled.
2. The way the surface heat, air, vapor, and liquid water flows are modeled.
3. The way in which indoor boundary conditions are assigned.
4. The way in which the outdoor boundary conditions are assigned.

Some of these models are developed to solve very specific cases while only five, viz. Konvek, WALLFEM, TCCC2D, TRATMO2, BRECON2 and MOIST, are meant to be general. The majority of the models treat cavities as conductive layers with an equivalent thermal conductivity. However, Konvec, WALLDRY, WALLFEM, ANHCONP, BRECON2, and MOIST take into account the enthalpy flow due to mass transport through the cavity. The models TCCC2D, TRATMO2, NatKon, and WISH-3D make the distinction between conduction, convection, enthalpy flow, and radiation.

A majority of the models use only a surface film coefficient for heat transfer. The models ANHCONP and BRECON2 distinguish between radiation and convection and use a surface film coefficient for vapor transfer. The models Konvec, WALLDRY, EMPTEDD, and TCCC2D use surface film coefficients for heat and vapor transfer and impose a surface air pressure, and TRATMO2 in addition uses a surface water content for liquid transfer. WALLFEM distinguishes between radiation and convection, uses a surface film coefficient for vapor transfer, and imposes a surface air pressure or air flow.

In general, wherever applicable, all models use temperature, relative humidity, or water vapor pressure, and air pressure to define indoor boundary conditions for heat, water vapor, and air transport, respectively. The more sophisticated models such as TCCC2D and TRATMO2 can use the temperature profile at the indoor boundary. The treatment of outdoor boundary conditions varies significantly from model to model. In the simplest cases only air temperature, relative humidity, and air pressure are used. Models such as MOIST and VADAU use temperature, water vapor pressure, solar gains, and clear-sky long-wave radiation. The most sophisticated models such as TCCC2D, TRATMO2, and WALLFEM have the capability to use temperature, vapor pressure, diffused and global radiation, wind velocity, wind direction, and rain to define the outdoor boundary conditions using detailed weather data.

The review undertaken by the International Energy Agency Annex rated TCCC2D as one of the most sophisticated models now available for hygrothermal analysis of building components. The authors have recently used the model to analyze many practical problems [2-5]. A brief outline of the model and its three selected applications are given below to illustrate the potential of model calculations to gather information on design guidelines.

Description of TCCC2D

TCCC2D stands for Transient Coupled Convection and Conduction in 2-Dimensions. It is a computer program developed for hygrothermal analysis of residential building walls, i.e., light-weight constructions. It solves two-dimensional heat, air, and moisture transport and conservation equations that represent hygrothermal behavior of multilayer building structures. The transport equations are based on temperature, pressure, and water vapor pressure as driving potentials. The Darcy flow equation with the Boussinesq approximation [*6*] for incompressible fluids is used for convective flows. Local thermodynamic equilibrium is assumed between stagnant and flowing phases. Allowance is made for phase changes.

The theoretical background for the equations used in TCCC2D has been explained by Kohonen [*7*]. The specific forms of the continuity (for air), momentum, energy balance, and mass balance (for moisture) equations used in the model in two dimensions (X and Y in Cartesian coordinate) are numerically solved using a finite difference method. Temperature, pressure, and vapor pressure fields are calculated at the grid points, while the flows are calculated at the midpoint of grids. The upwind discretizing method [*8*] is used in the solution of the convection terms. Moisture content of each material is coupled with vapor pressure and temperature through sorption isotherms. The interactions between temperature, pressure, and moisture fields are schematically shown in Fig. 1.

TCCC2D also contains a module on material properties. Common building materials such as plywood, wood fiberboard, chipboard, pine, gypsum board, glass fiber insulation (varying densities), expanded polystyrene (varying densities), cellular concrete, lime-sandstone, and brick are the materials currently included. Various laboratory measurements were done [*9*] on these materials to determine the following properties:

1. Sorption isotherm.
2. Vapor diffusion coefficient as a function of moisture content.
3. Total moisture diffusivity as a function of moisture content.
4. Air permeability.
5. Thermal conductivity.

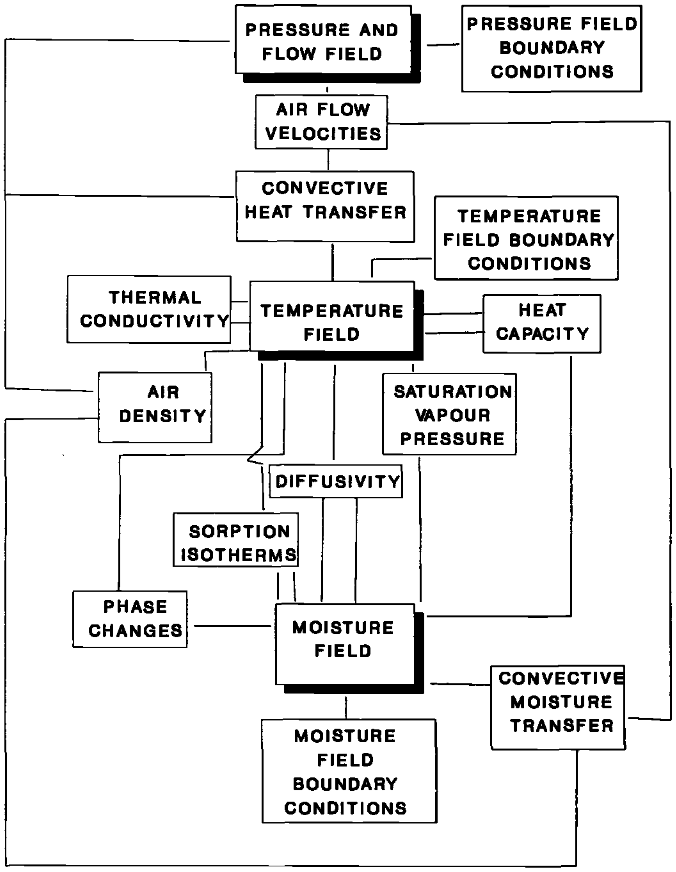

FIG. 1—The interactions between pressure, temperature, and moisture content fields in the domain of TCCC2D calculations.

Weather data can be used as the exterior boundary conditions for simulations. Thus, one may use temperature, relative humidity, solar radiation, pressure, and rain conditions based on weather data.

APPLICATION 1. MOISTURE ACCUMULATION DUE TO AIR CONVECTION

The structure consists of a 150-mm-thick layer of mineral fiber insulation bounded by a 12-mm-thick chipboard inside (room side) and a 12-mm-thick wood fiberboard outside. The height of the structure is 2.5 m. The inside cover has cracks at the top and bottom of the structure so that air inside the insulation is in contact with that in the room. The outside cover was assumed to be airtight everywhere. The room conditions were assumed to be:

1. Temperature = 20°C.
2. Water vapor pressure = 1400 Pa.

and the outside conditions:

1. Temperature = −20°C.
2. Water vapor pressure = 70 Pa.

Simulation of the above case with TCCC2D showed that the temperature difference between the room and the outside results in an airflow of 0.033 L/s·m from the room into the structure and back again into the room, i.e., a continuous convective flow as shown in Fig. 2*a*. These conditions were maintained constant throughout for 31 days in a simulation. The results from the calculation, represented by Figs. 2*b* and 2*c*, show that an appreciable amount of moisture had accumulated in the upper part of the structure even though the airflow rate was rather small. Thus, any type of continuous airflow into the structure may locally affect the hygrothermal behavior of the structure.

APPLICATION 2: EXFILTRATION OF INDOOR AIR THROUGH A WALL

The wall assembly simulated is schematically shown in Fig. 3. The room conditions are constant temperature (20°C) and constant RH (≈38%), and the out-door conditions are constant temperature (−10°C) and constant RH (≈38%). The upper and lower boundaries are impermeable and adiabatic. The total height of the wall is 1.86 m. The total thickness is 0.145 m. The gypsum board together with the vapor barrier is

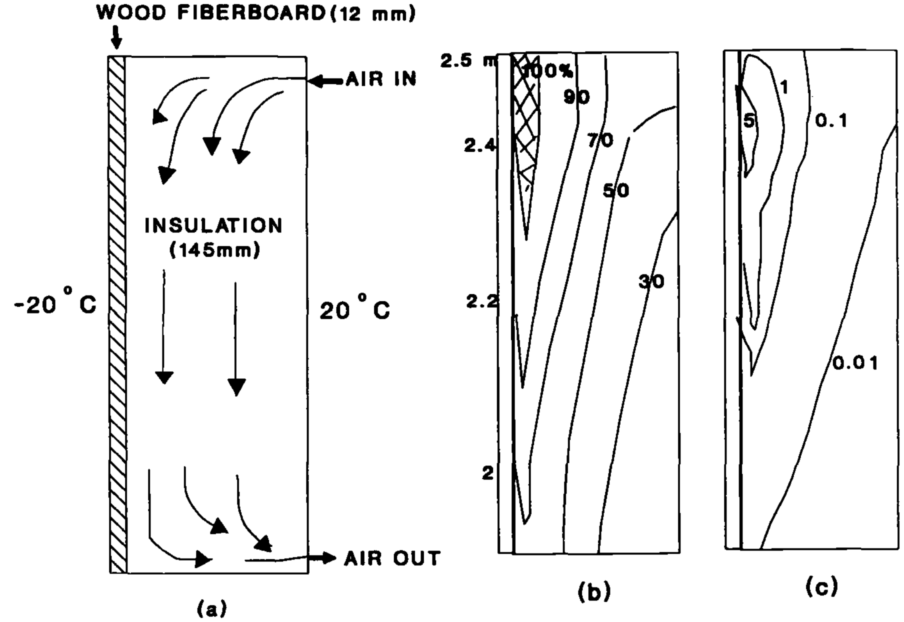

FIG. 2—(a) Schematics of the wall assembly simulated in Application 1 of TCCC2D; the airflow pattern calculated is shown by the arrows. (b) Relative humidity (%) distribution after 31 days as calculated using TCCC2D. (c) Moisture content (kg/kg of dry material) distribution after 31 days.

simulated as a surface with high resistance to water vapor transport.

Five different cases of exfiltration were simulated. Always the rate of airflow was 0.25 L/s per 1-m section of the wall. This airflow was modeled as one with a velocity of 0.01 m/s. The five different cases of air exfiltration examined are schematically shown in Fig. 4. The simulations were done for 100 h exposure.

Results

1. Figure 5 shows the distribution of moisture in the wall assembly (Case 2a in Fig. 4) after 100 h. Most of the moisture

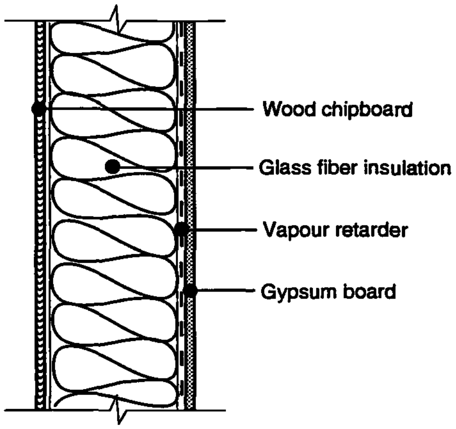

FIG. 3—Schematics of the wall assembly simulated in Applications 2 and 3 of TCCC2D.

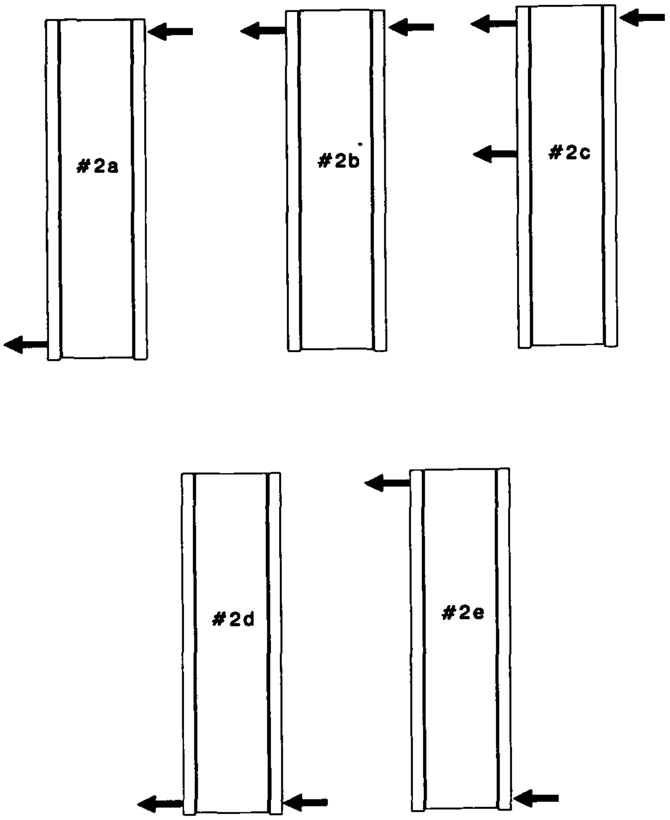

FIG. 4—The five different cases, 2a to 2e, of airflow paths simulated in Application 2 of TCCC2D; the arrows indicate the direction, point of entry, and point of exit of the flow.

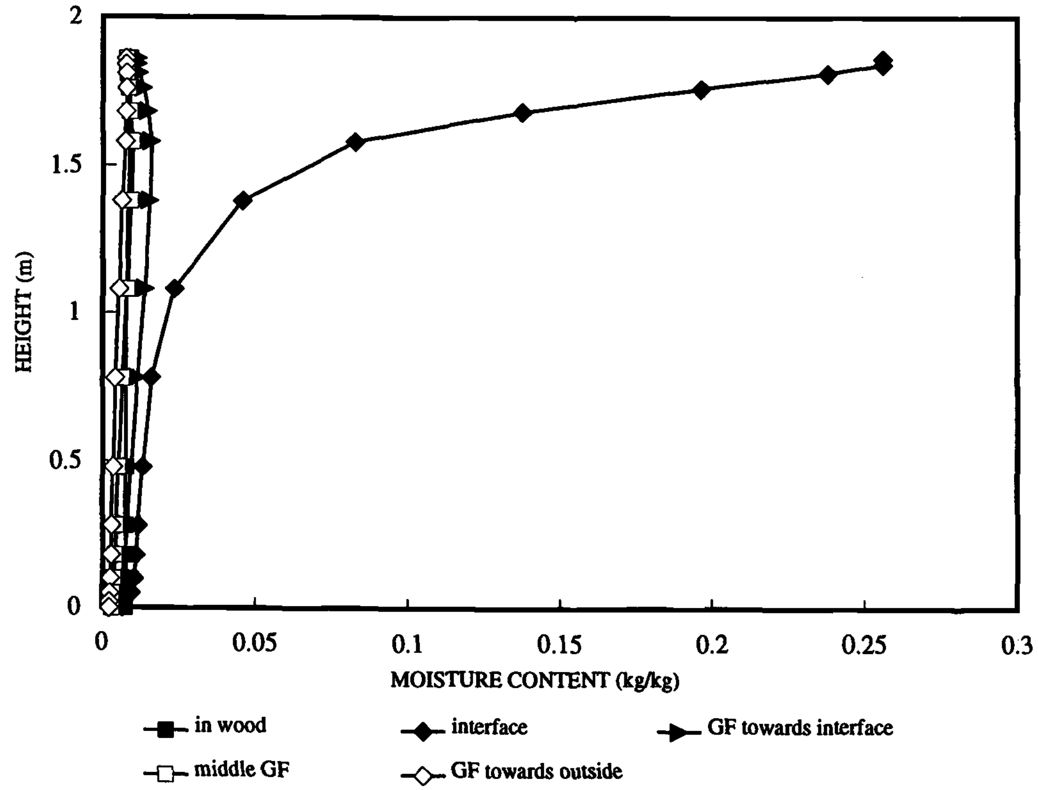

FIG. 5—The distribution of moisture in the wall (2a) at various planes after 100 h exposure; the initial moisture content was approximately 0.005 kg/kg everywhere.

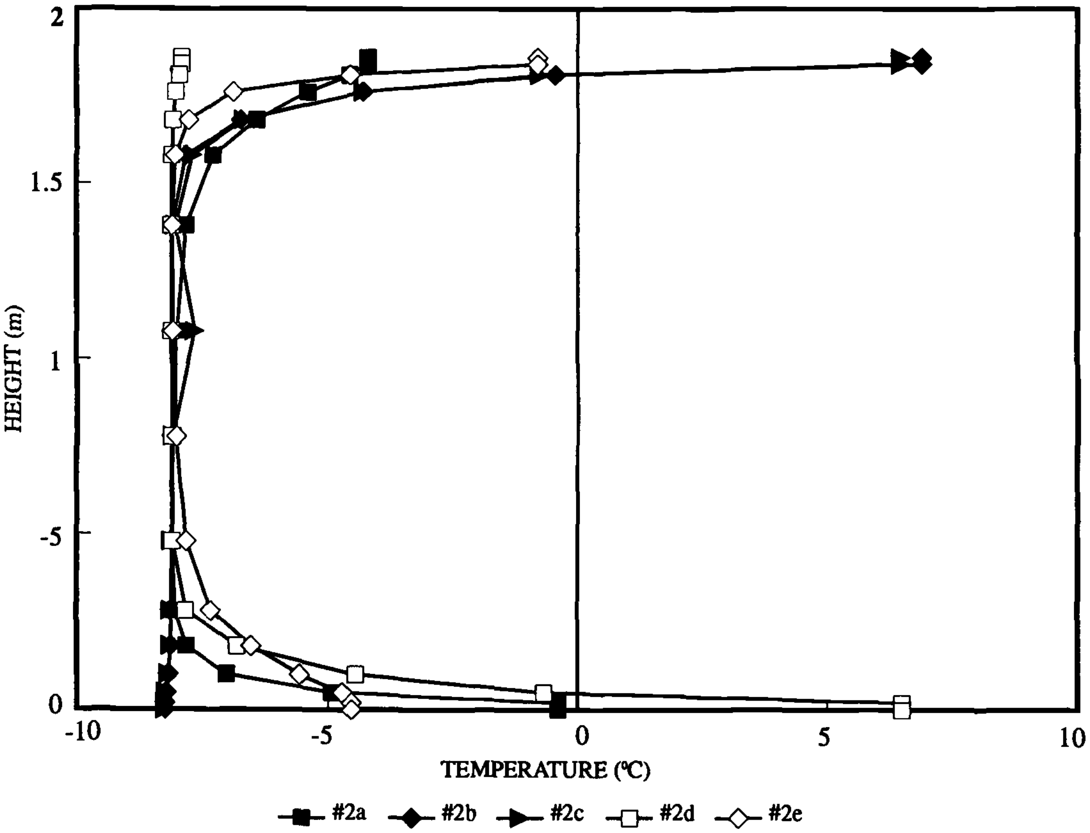

FIG. 6—The effect of the five airflow patterns (Application 2) on the distribution of temperature at the interface of exterior sheathing and the insulation.

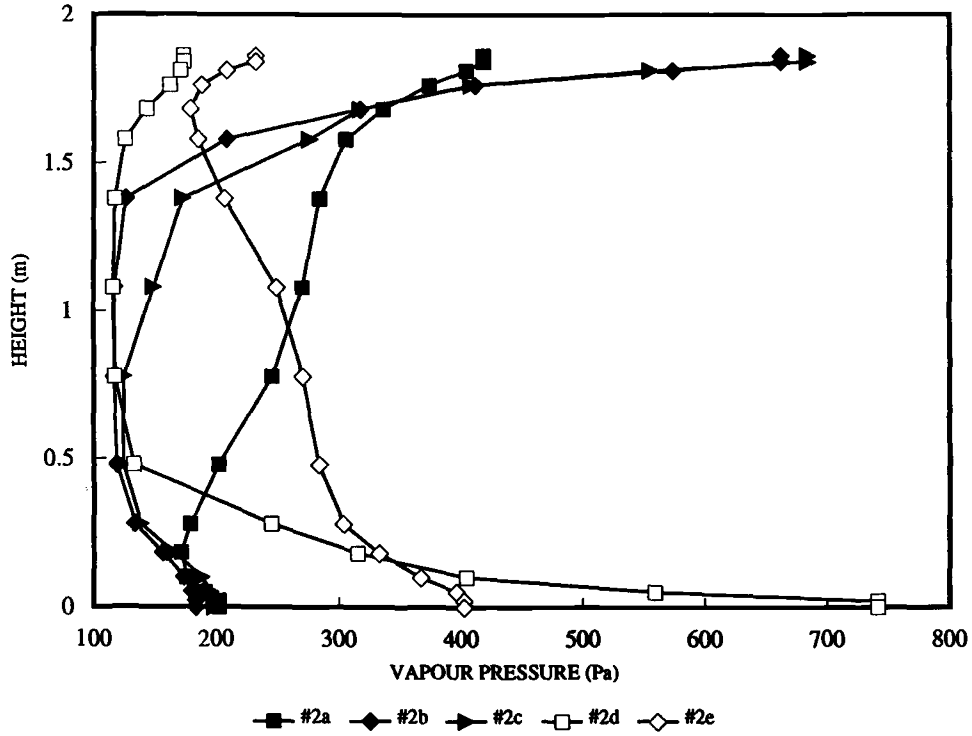

FIG. 7—The effect of the five airflow patterns (Application 2) on the distribution of vapor pressure at the interface of exterior sheathing and the insulation.

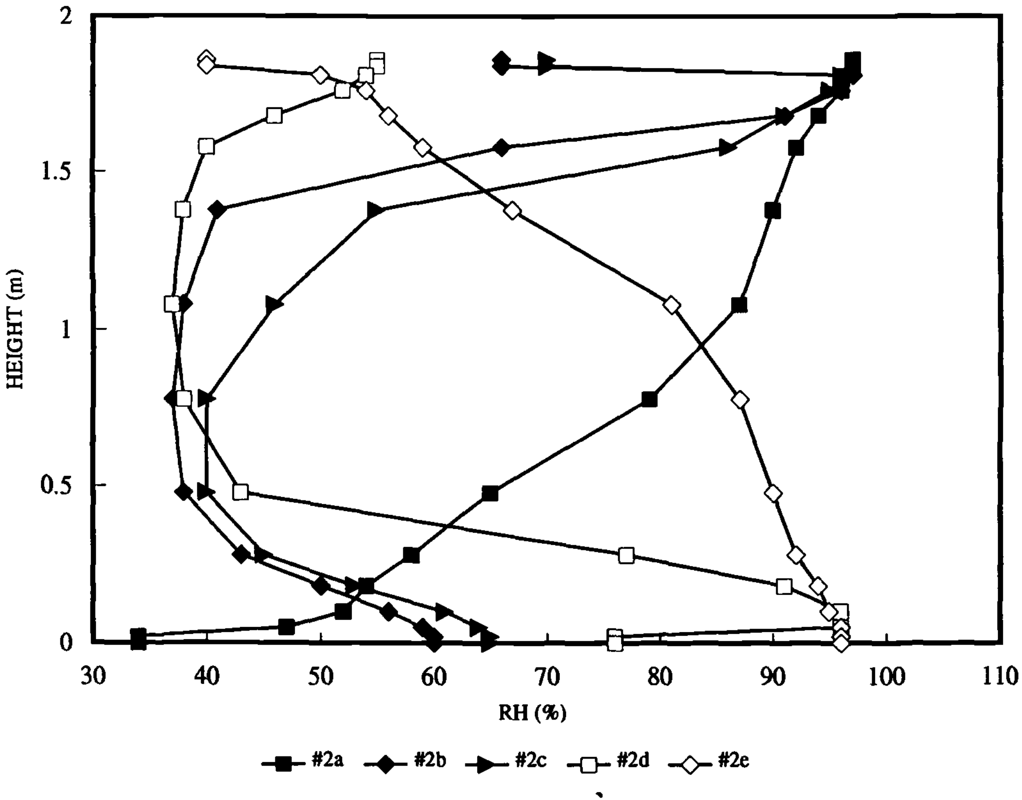

FIG. 8—The effect of the five airflow patterns (Application 2) on the distribution of relative humidity at the interface of exterior sheathing and the insulation.

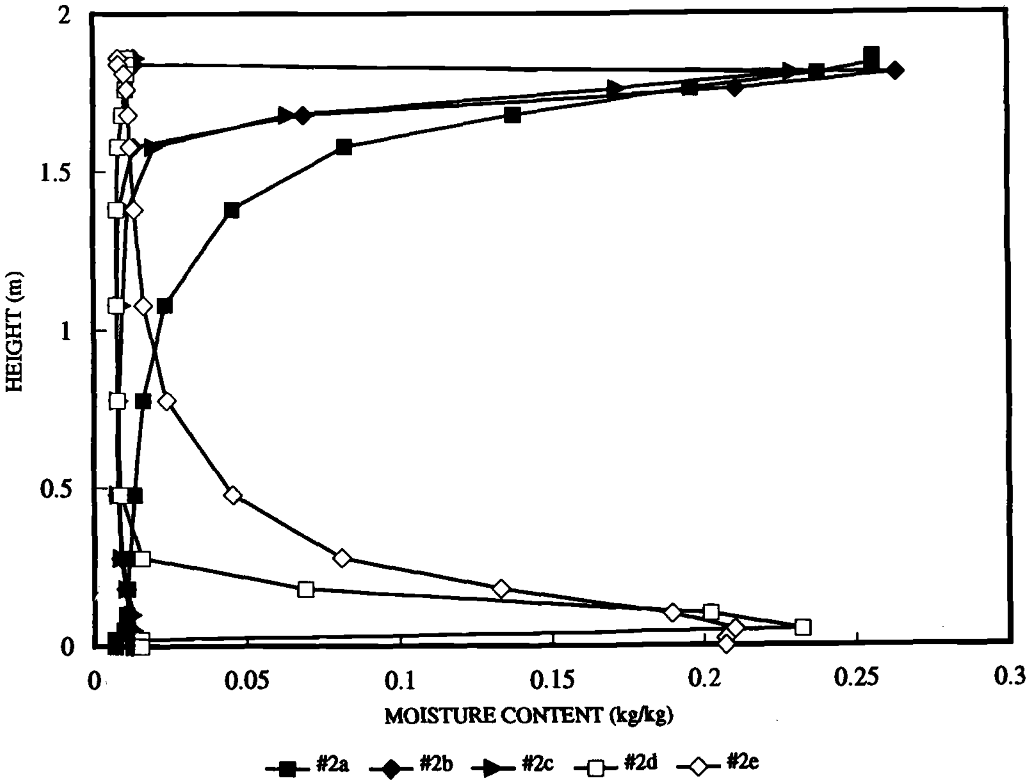

FIG. 9—The effect of the five airflow patterns (Application 2) on the distribution of moisture at the interface of exterior sheathing and the insulation.

carried by the airflow is condensed at the interface between the woodchip board and insulation. This is true with all the other four cases. The indication is that all major hygrothermal changes are occurring at the interface. Hence, further details from the calculation are listed below, referring mainly to the interface.

2. Figure 6 shows the temperature distribution after 100 h at the interface in all five cases. The temperature is always significantly higher in the vicinity of the exit path of the airflow than at other places. Also, the shorter the path between the points of entry and exit of air, the higher the temperature at the point of exit.

3. Figures 7 and 8 show the vapor pressure and RH distributions, respectively at the interface in the five cases. Always opposite to the point of entry of air, regions of 100% RH develop and condensation initiates. This is true even when the exit point is right across the point of entry and hence at a significantly higher temperature than in other cases.

4. Figure 9 shows the profile of moisture distribution in all five cases at the interface. Irrespective of the path the airflow takes, there is always higher moisture accumulation just opposite the point of entry. Obviously the airflow pattern influences the rate of moisture accumulation in the cavity. This is shown in Fig. 10. In Cases 2a and 2e, since the path of airflow within the cavity is longer, the total rate of condensation is higher. Figure 10 shows that in these cases about 70% of moisture entering the cavity is condensed while in the others only 25 to 30% is condensed.

5. Figure 11 shows the history of heat flux on the outer surface of the wall assembly. The average heat flux approaches a value of 11 to 11.5 W/m^2 in all five cases, which is significantly higher than the 6.7 W/m^2 calculated for the heat transfer alone. The condensation of moisture and the heat transported by warm air from inside account for the difference. In the cases simulated here, the contributions from the above two modes are comparable.

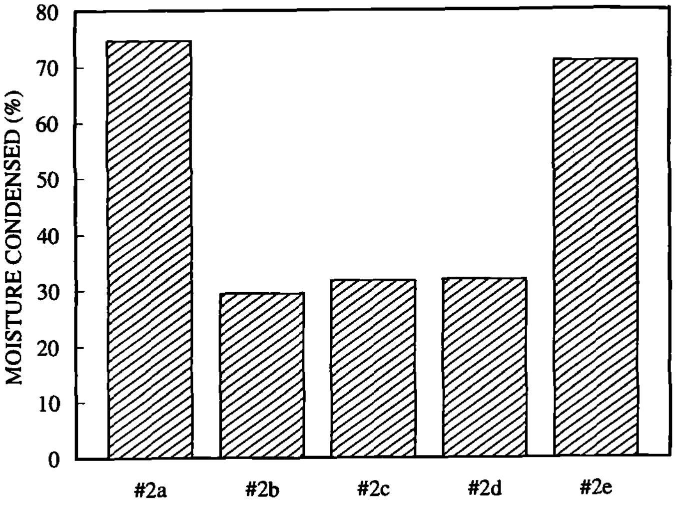

FIG. 10—The percentage of moisture condensed out of the air entering the cavity in the five cases of Application 2.

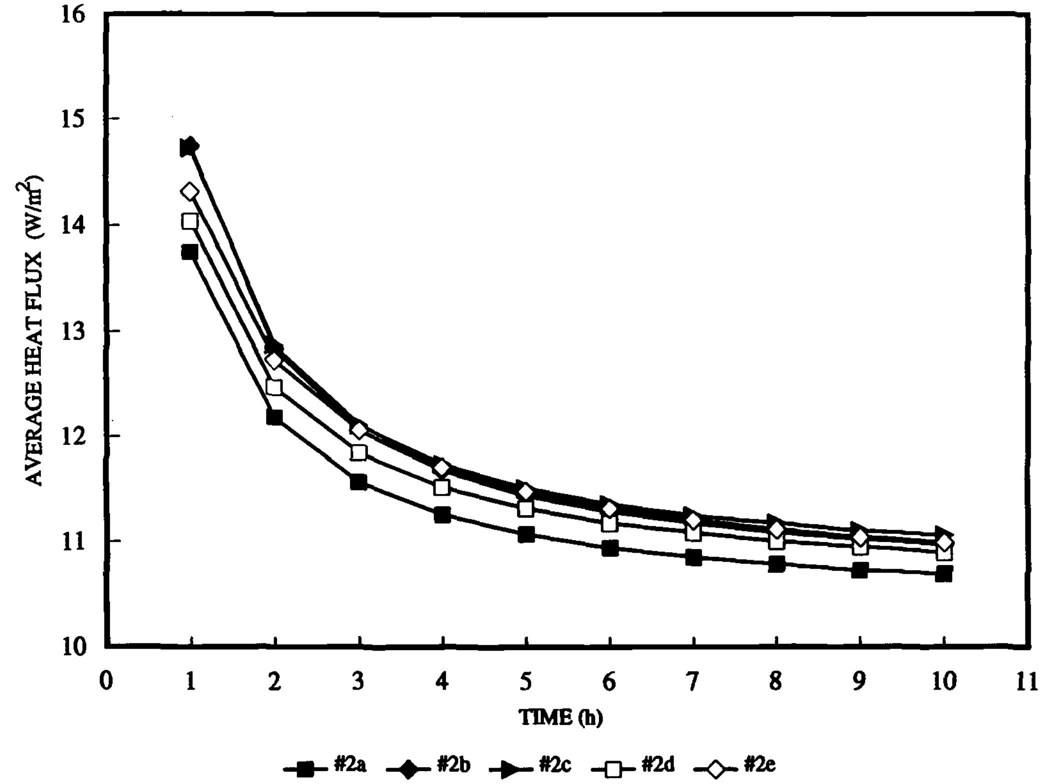

FIG. 11—The history of the average heat flux out of the exterior surface of the wall assembly in the five cases of Application 2.

APPLICATION 3: AIR EXFILTRATION AND MOISTURE ACCUMULATION IN RESIDENTIAL WALL CAVITIES

The residential wall assembly selected for the numerical analysis is similar to that shown in Fig. 3. It is a 150-mm-wide timber-frame cavity wall filled with glass fiber insulation. The interior finish is 12-mm-thick gypsum board with a Type I vapor retarder, and the exterior sheathing is 11-mm-thick wood chipboard. The height of the wall is 2 m. The objective of the analysis was to investigate numerically the effect of air exfiltration on the hygrothermal behavior of residential wall assemblies exposed to Canadian and Finnish weather conditions for one year. Calculations in Application 2 have shown that the worst-case scenario of exfiltration is when the air enters the cavity at the top of the wall assembly and leaves at the bottom, as shown in Fig. 4 (Case 2a). Hence this path of exfiltration was selected for the simulation. The exfiltration was assumed to be the result of an overpressure of 10 Pa in the building. A field investigation [*10*] showed that in a typical Canadian residential building this will correspond to an exfiltration rate of 0.98 L/(m^2·s).

The outside air temperature and relative humidity varied according to the weather data from selected locations. For this study, solar radiation to and longwave radiation from the outer surface of the wall were omitted. The simulations for a one-year exposure were done using weather data from nine Canadian and three Finnish locations listed in Table 2. From October 1 to May 1, the indoor air is maintained at 21°C and 30% RH. For the rest of the year, the indoor temperature and relative humidity are the same as the outside temperature and relative humidity. The initial moisture contents of the glass fiber and chipboard were calculated from sorption curves and corresponded to 30% RH. The simulations were started from July 3, which corresponded approximately to the

TABLE 2—Location and minimum and maximum temperatures of the weather patterns used in the simulations during the heating season. The indoor conditions are 21°C and 30% RH and the exfiltration rate is 0.98 L/(m^2·s).

		Temperature,°C	
Location	Northern Latitude	Minimum	Maximum
	CANADA		
Edmonton	53°32′	−32	+32
Fredericton	45°92′	−31	+37
Montreal	45°47′	−30.5	+32
Ottawa	45°45′	−30	+30.5
Resolute Bay	74°72′	−41.5	+16
Toronto	43°80′	−22.5	+32
Vancouver	49°25′	−12.5	+27
Windsor	42°27′	−19	+35
Winnipeg	49°90′	−39	+33
	FINLAND		
Helsinki	60°10′	−30	+28.5
Jyväskylä	62°15′	−35	+27
Sodankylä	67°20′	−40	+26

TABLE 3—Boundary conditions used in the sensitivity analysis.

Location	Airflow Rate, L/($m^2 \cdot s$)	Indoor RH, %
Sodankylä	0.98	30
	0.50	30
	0.25	30
	0.10	30
	0.98	25
	0.98	20
	0.98 (uniformly distributed)	30
Vancouver	0.98 (uniformly distributed)	30

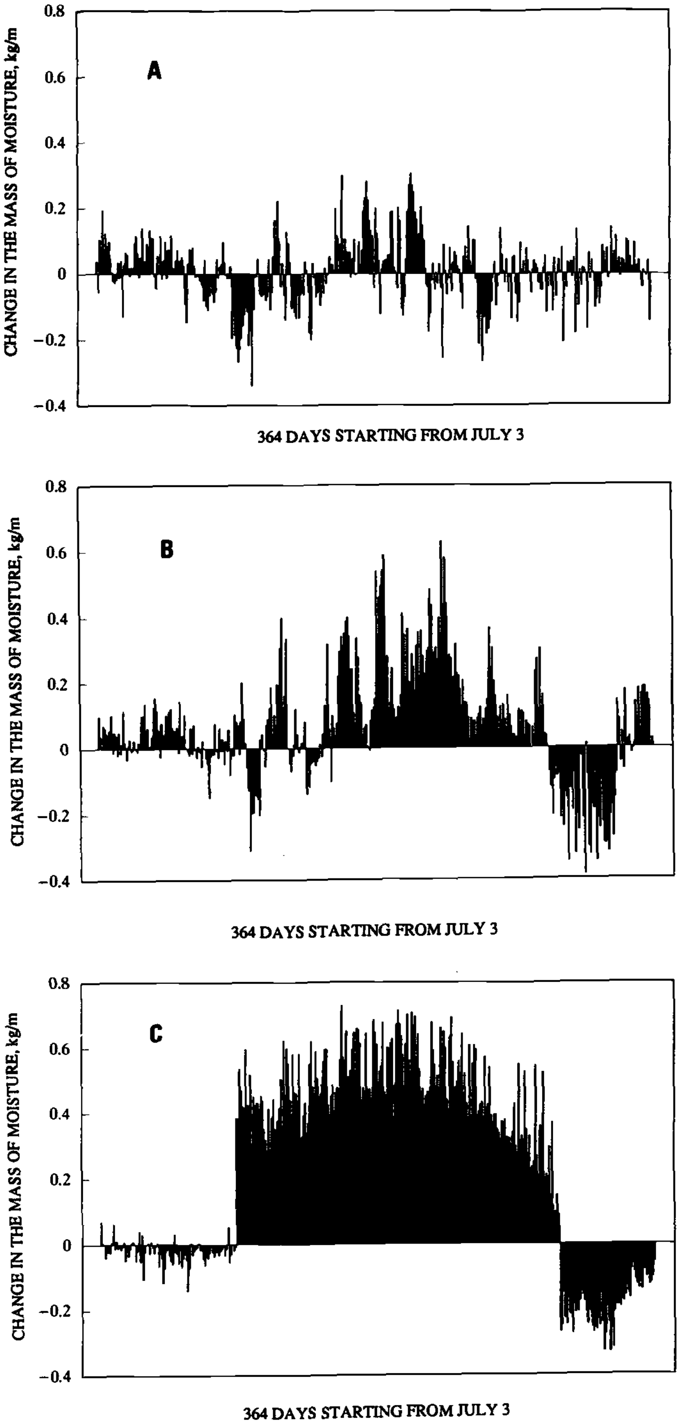

FIG. 12—The calculated daily change of total mass of moisture in the analyzed structure due to air exfiltration in (A) Vancouver, (B) Helsinki, and (C) Resolute Bay climatic conditions.

middle of the drying period. At this starting point, the equilibrium moisture content corresponded relatively well to the chosen initial conditions. This made it possible to analyze the yearly moisture accumulation from just one year's simulation. (Alternatively, one could start from January 1, but this being at the middle of the heating season, the assumed initial moisture content is unrealistic and simulations will have to be done for two successive years.) In an attempt to identify permissible levels of indoor humidity, simulations were also carried out by varying the values from 30% RH. Also, the effect of airflow rates on hygrothermal behavior was numerically analyzed. The case shown in Fig. 4 (2a) generates nonuniform airflow within the cavity and, in particular, at the interface of the insulation and the exterior sheathing. For comparison, simulations were done by uniformly distributing the flow field over the surface of the structure and the results compared with the flow pattern given by the case in Fig. 4 (2a). The boundary conditions used in these calculations are summarized in Table 3. All these additional simulations are referred to as sensitivity analysis in this application.

Simulations were done for a 52-week period starting from July 3. In the finite-difference formulation of the wall cavity, the airflow rate of 0.98 L/($m^2 \cdot s$) was expressed as 1.96 L/(s·m) (this means that the wall section in Fig. 3 is 1 m deep and the crack is arbitrarily chosen to be 2 cm wide; depending upon the finite-difference matrix used, this width can be altered to appropriately define the airflow rate of 0.98 L/($m^2 \cdot s$)). The analysis generated hourly values for pressure, temperature, water vapor pressure, and airflow velocity fields, as well as net moisture flow into or out of the structure caused by exfiltration, the moisture content distributions in the material layers, and the total moisture content of the structure. The air flowing into the structure has a partial vapor pressure of 745 Pa during the heating period. If the temperature in the structure approaches, say, 0°C, water vapor condensation is facilitated. Moisture is also accumulated in material layers due to their sorption properties. The results from the simulation are discussed below under three sections: hygrothermal behavior, thermal behavior, and sensitivity analysis.

Hygrothermal Behavior

The net convective moisture flux into the structure depends on the vapor pressure of the indoor air, which flows into the structure, and that of the outflowing air

$$g_{net} = q_{m,a}\,[\{p_v M_v/(p_a M_a)\}_{in} - \{p_v M_v/(p_a M_a)\}_{s,out}] \qquad (1)$$

where

g_{net} = net convective moisture flux, kg/($s \cdot m^2$),
$q_{m,a}$ = air mass flow rate through the structure, kg/($s \cdot m^2$),
M = molar mass,
in = inside air,
s,out = air flowing out of the structure,
a = air,
v = vapor.

In calculations, the approximation

$$g_{net} = q_{Vin}\,[\{p_v M_v/(RT)\}_{in} - \{p_v M_v/(RT)\}_{s,out}] \qquad (2)$$

where q_{Vin} is the airflow rate from the inside air into the structure [$m^3/(s \cdot m^2)$], which was used when solving for the net moisture flow. Positive values for g_{net} mean that moisture is accumulating in the structure, and negative values mean that air convection is drying out the structure.

Figure 12 shows the calculated daily net mass of moisture ($g_{net} \times 24$ h $\times$ 2.0 m) that flows into or out of the structure in Vancouver and Resolute Bay in Canada and Helsinki, Finland, during one year. The weather in Vancouver is mild, and it gave the lowest moisture accumulation in the structure. When exposed to the weather conditions of a very cold region, Resolute Bay, the hourly mass of moisture accumulation was positive for most of the year. In Helsinki weather, an appreciable amount of moisture accumulated during wintertime.

The calculated monthly net and cumulative mass of moisture accumulation in Vancouver, Helsinki, and Resolute Bay are presented in an alternative format in Fig. 13. When the last cumulative moisture value (in June) exceeds 0 kg/m, air exfiltration has caused yearly net moisture accumulation in the structure during the calculation period. Figure 13 shows that in Resolute Bay the exfiltration considered here causes large amounts of moisture to condense in the structure, which does not have time to dry out. The situation is the same in Helsinki, but the cumulative effect is much smaller than in Resolute Bay.

In the simulations, the drying of the structure through the wood chipboard by diffusion was also taken into account, and all the moisture was absorbed by the materials according to their sorption properties. Moisture was found to accumulate mostly near the interface of chipboard and thermal insulation. Vertical moisture content distributions of the chipboard and the outer part of the glass fiber layer are presented in two-week intervals throughout the year in Fig. 14 for Vancouver, in Fig. 15 for Helsinki, in Fig. 16 for Winnipeg, and in Fig. 17 for Resolute Bay weather conditions. The moisture content values of the chipboard represent the horizontal average values of the 11-mm-thick chipboard at each height. For glass fiber, the moisture contents are those of the outer node of the material layer, which in the finite-difference representation was also 11 mm thick.

At every location selected, moisture accumulated in the material layers during the heating period. According to the calculations, a good part of the moisture was accumulated at the upper part of the structure, close to the interface of the insulation and the sheathing, where the warm and humid airflow met the cold outer layers. Only in the mild climate in Vancouver did the maximum moisture content of the chipboard remain at a relatively low level, under 0.2 kg/kg. In Helsinki, the maximum value was about 0.5 kg/kg, and in Winnipeg and Resolute Bay, the total saturation value, 1.0 kg/kg (corresponding to about 700 kg/m^3 with this material), was nearly reached. As stated in the previous paragraph, in Resolute Bay yearly moisture accumulation in the structure was clearly indicated, i.e., the moisture content at the end of the simulation period had significantly increased from the initial values. The exact position of the moisture in real structures may differ from the calculated because the freezing of water and the water flow at the interface of the material layers could

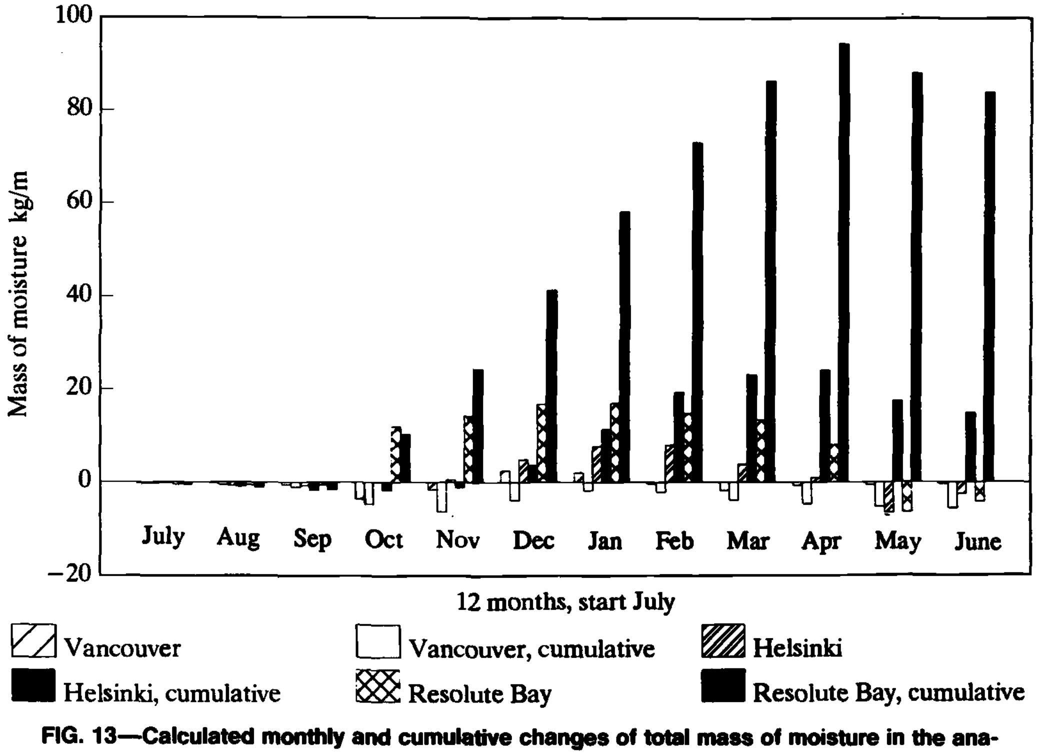

FIG. 13—Calculated monthly and cumulative changes of total mass of moisture in the analyzed structure due to air exfiltration in Vancouver, Helsinki, and Resolute Bay climatic conditions.

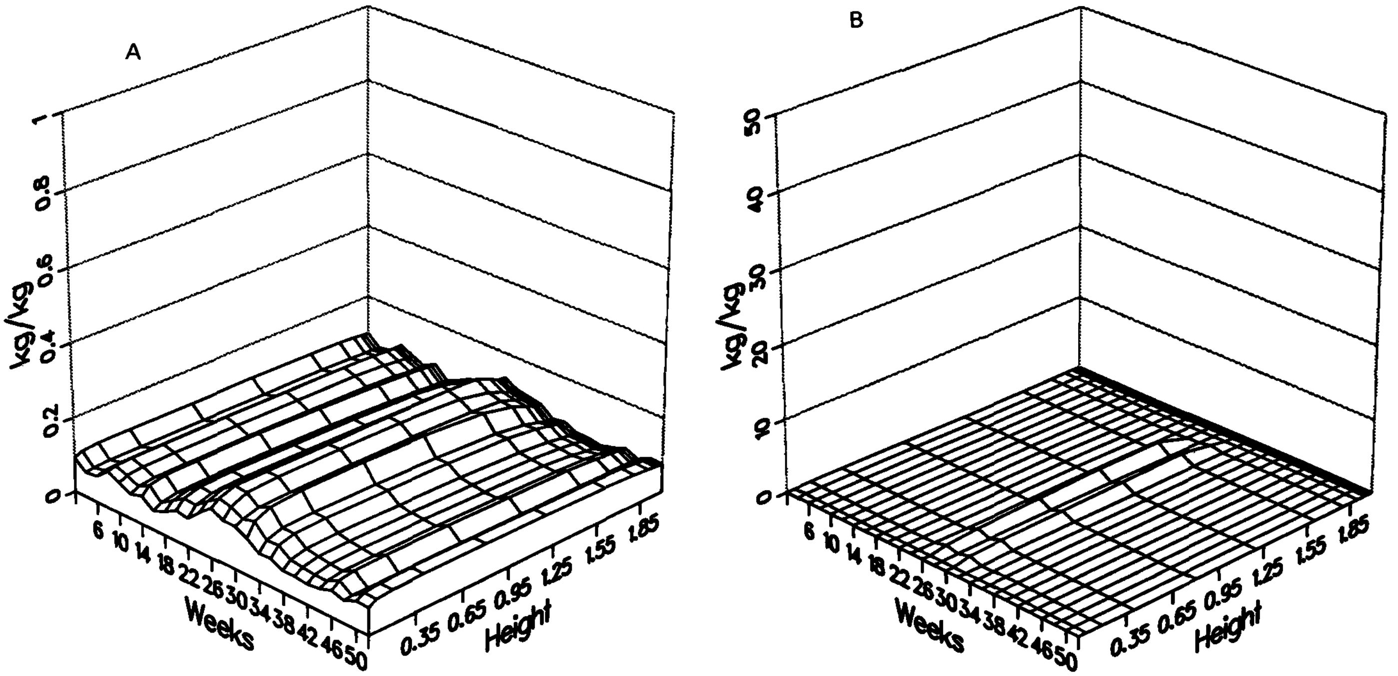

FIG. 14—Vertical moisture content distribution of (A) the chipboard and (B) the outer 11 mm of the glass fiber insulation at two-week intervals in Vancouver climatic conditions.

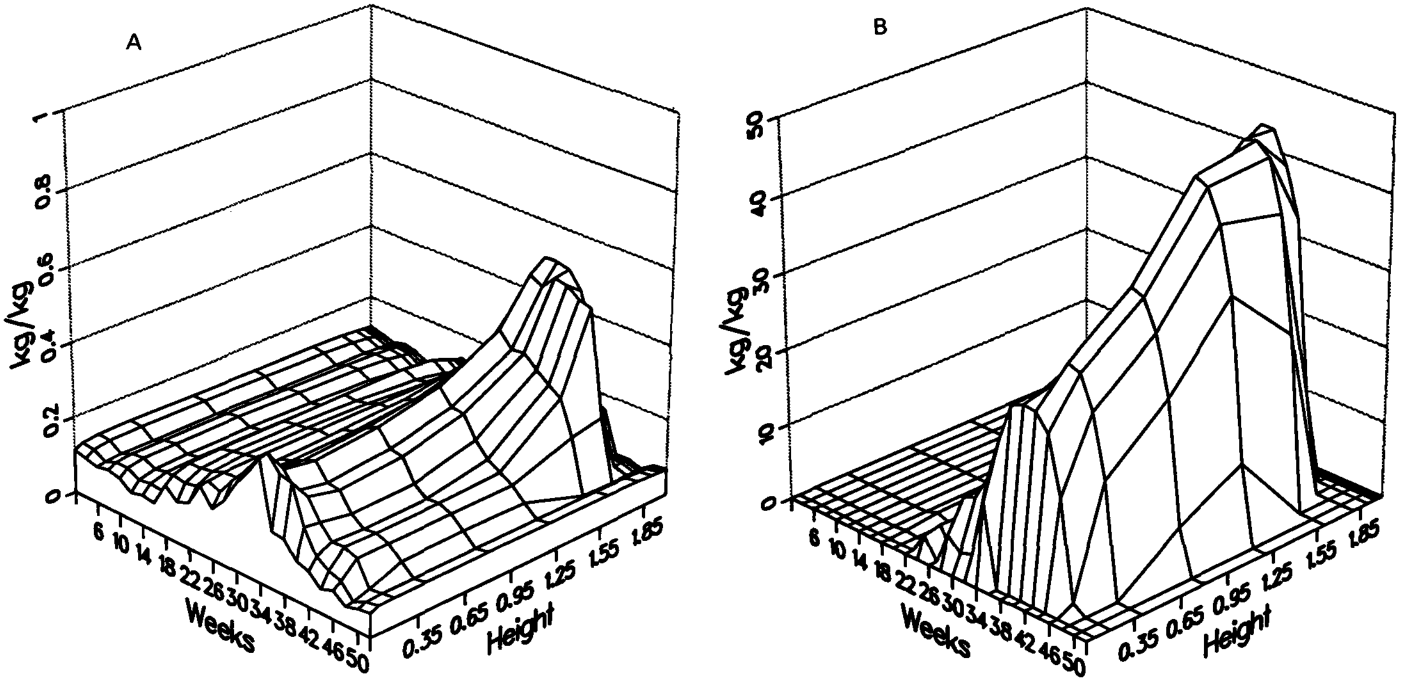

FIG. 15—Vertical moisture content distribution of (A) the chipboard and (B) the outer 11 mm of the glass fiber insulation at two-week intervals in Helsinki climatic conditions.

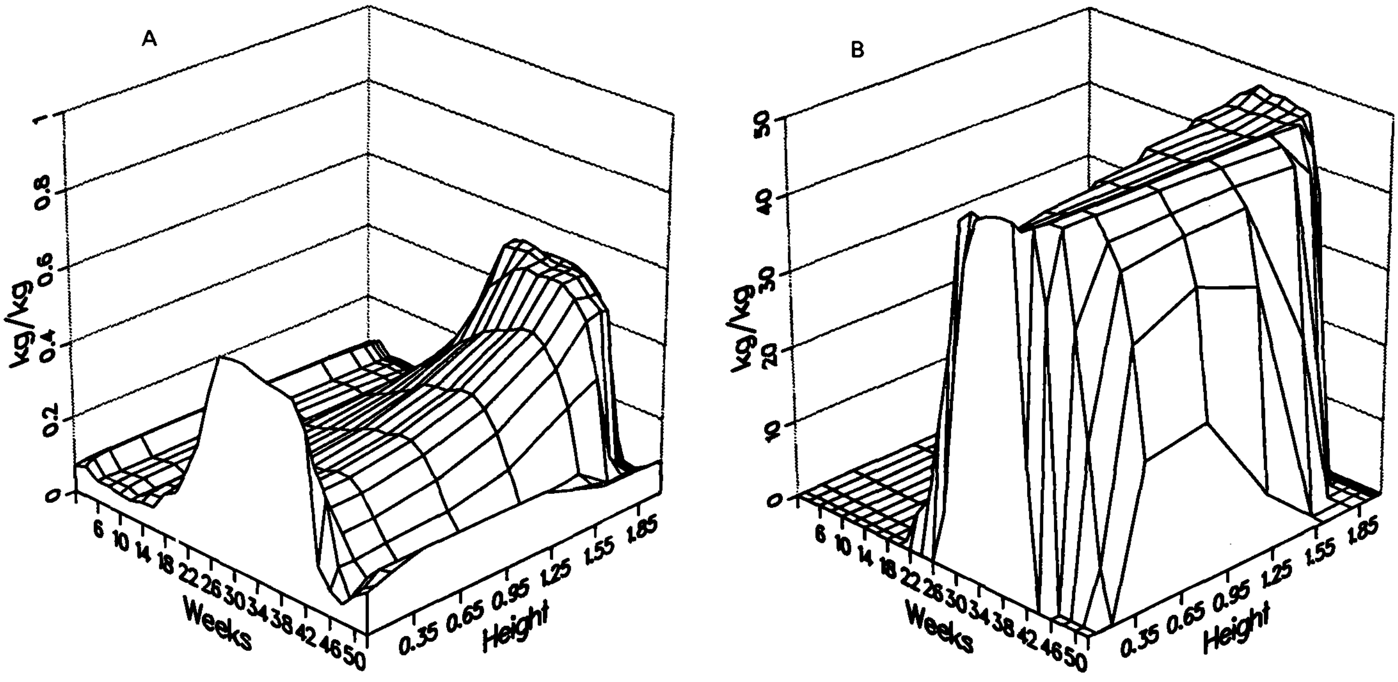

FIG. 16—Vertical moisture content distribution of (A) the chipboard and (B) the outer 11 mm of the glass fiber insulation at two-week intervals in Winnipeg climatic conditions.

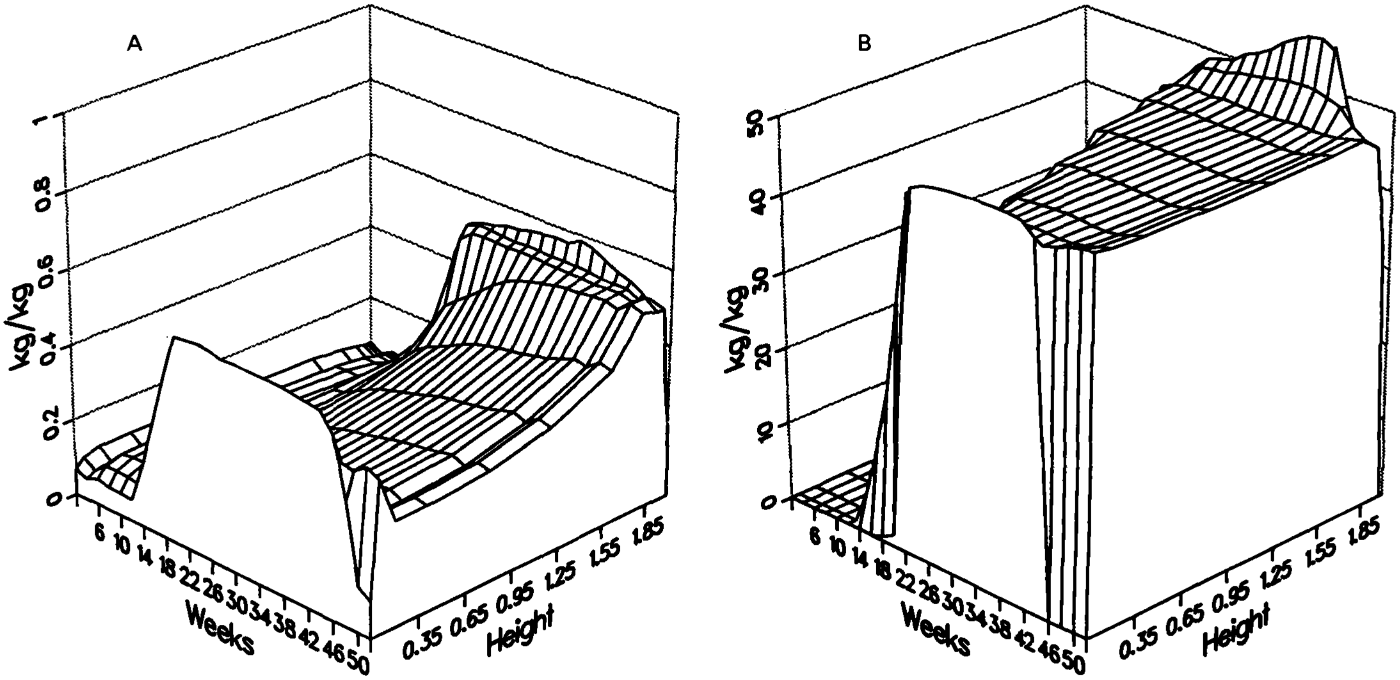

FIG. 17—Vertical moisture content distribution of (A) the chipboard and (B) the outer 11 mm of the glass fiber insulation at two-week intervals in Resolute Bay climatic conditions.

not be simulated. Even then the calculated total moisture balance of the structure is a reliable figure that can be compared between the different cases analyzed.

Figure 18 shows the total mass of moisture per surface area of structure (kg/m^2) as a function of time for all the locations. (The dimension 1 kg/m^2 corresponds to a 1-mm-thick water layer per total structural thickness.) When the maximum total mass of moisture was used as a criterion, the climate conditions analyzed could be sorted according to the increasing risks in hygrothermal behavior during exfiltration from less to more severe as listed in Table 4. The maximum moisture values are compared to the yearly mean temperature, vapor pressure, and saturation vapor pressure values in Table 4.

The locations chosen for this investigation, based on the simulation results, can be grouped into three: mild, medium, and cold. In mild climates (Vancouver and Windsor), the moisture accumulation is relatively small during the winter. In very cold climates (Resolute Bay, Sodankylä, Winnipeg), the possibility for yearly moisture accumulation exists. At the remaining locations that belong to the medium climate group, the moisture accumulation can be high during heating season, but the structures should be able to dry out during summertime.

The maximum amount of moisture is, as an approximation, inversely proportional to the yearly mean outdoor temperature. The only exception in the Canadian climate was between Vancouver and Windsor. In Windsor higher maximum moisture accumulation with higher outdoor mean temperature is shown. This can be attributed to the longer and colder winter period at Windsor than at Vancouver.

TABLE 4—The locations used in the simulation arranged in the order of increasing risk of moisture accumulation according to the simulation results. For comparison, the yearly mean values for outdoor temperature T, water vapor pressure, p_v, and saturation vapor pressure, $P_{v,sat}$ are also listed.

Location	Maximum Mass of Moisture, kg/m^2	Outdoor Climate (yearly mean)		
		T, °C	P_v, Pa	$P_{v,sat}$, Pa
Vancouver	1.0	9.13	960.4	1257.1
Windsor	3.0	9.77	996.2	1489.4
Toronto	6.5	6.90	877.0	1252.2
Helsinki	7.6	4.31	755.7	1005.0
Fredericton	8.0	5.88	813.1	1218.7
Montreal	9.1	5.73	831.0	1236.2
Jyväskylä	9.4	2.79	706.9	935.4
Ottawa	9.5	5.71	828.2	1241.6
Edmonton	11.8	1.77	600.1	956.5
Sodankylä	13.3	−0.80	565.7	770.7
Winnipeg	14.6	1.62	699.1	1052.7
Resolute Bay	28.1	−16.54	219.7	270.3

Also, the Finnish climate has shorter winters and summers than the Canadian climate but with approximately the same mean outdoor temperatures. For example, during wintertime in Ottawa, there are longer cold periods than at Helsinki. Therefore, the calculated moisture accumulation in Helsinki during the heating season was found to be smaller than that in Ottawa.

Figure 19 shows the daily mean outdoor air temperature variation at the three locations: Vancouver, Helsinki, and Resolute Bay. A correlation could be seen between the outside air temperature, the length of the cold season, and the accumulation of moisture in the structure.

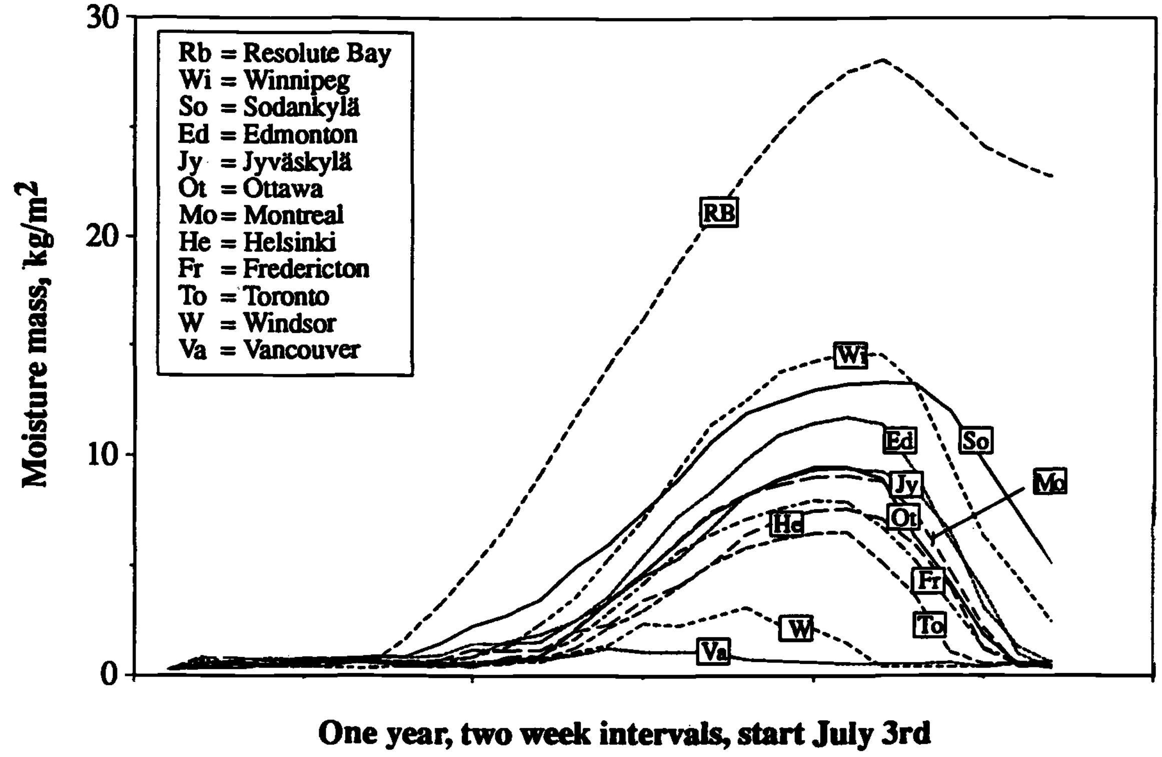

FIG. 18—Calculated total mass of moisture per surface area of structure (kg/m^2) as a function of time for all the analyzed locations.

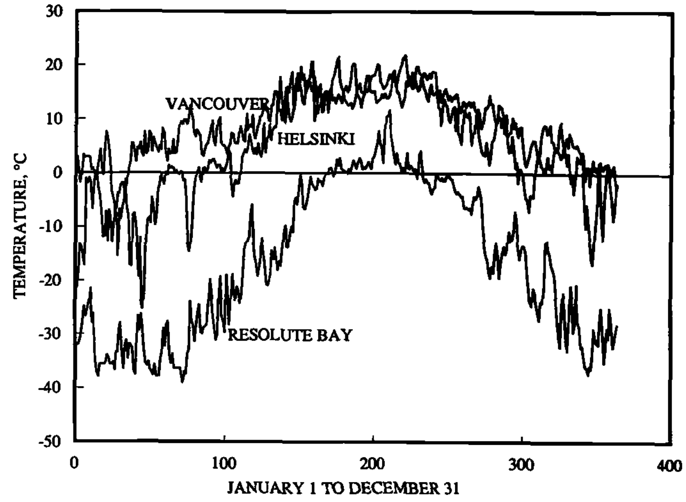

FIG. 19—Daily mean outdoor air temperature variation at Vancouver, Helsinki, and Resolute Bay during one year.

Thermal Behavior

During the heating season, exfiltrating air warms up the structure, and temperatures around the main airflow route are usually higher than those in a nonconvective case (uniformly distributed airflow). Therefore, in a case with nonuniform air exfiltration, the temperature of the out-flowing air is significantly higher than that of the outside surface of the structure during the heating season. Table 5 shows the temperatures of the out-flowing air and chipboard with different airflow rates and also with a uniformly distributed airflow when the outside air was at −9.5°C. The results are chosen from the calculations using real weather data of Sodankylä, Finland, in late February, and so they do not present a stationary case.

For example, with outside temperature at −9.5°C and with an airflow rate of 1.96 L/s·m, which is called the reference case hereafter, the minimum and maximum temperatures of the inner surface of the chipboard were −7.5°C and +0.2°C, respectively, the maximum being at the upper part of the structure. The temperature of the out-flowing air was +5.9°C. In this case, condensation conditions existed inside the structure (Sodankylä weather data, February). Almost the whole interface of the glass fiber and chipboard was at 100% RH, but the calculated vapor pressure of the air flowing out through the crack was only about 500 Pa, 54% RH. The out-flowing air was not saturated because of the nonuniform airflow through the structure, which caused the higher temperature.

TABLE 5—Calculated temperature of air flowing out of the structure ($T_{s,out}$) and the minimum (min) and maximum (max) values for the temperature (T_{cb}) of the inner surface of the chipboard; the outdoor temperature at that stage was −9.5°C.

	Temperature, °C		
Airflow Rate, L/(m^2·s)	$T_{s,out}$	$T_{cb,min}$	$T_{cb,max}$
0.98	+5.9	−7.5	+0.2
0.50	+0.3	−8.0	−2.5
0.25	−3.7	−8.5	−4.1
0.10	−6.5	−8.7	−5.2
0.98 (uniformly distributed)	−8.6	−7.3	−7.3

With an airflow rate at 1.00 L/(s·m), the out-flowing air temperature was +0.3°C with a saturation vapor pressure about 625 Pa, which is lower than that of the incoming airflow at 745 Pa, but the calculated vapor pressure of the out-flowing air was only about 405 Pa, 65% RH. Water vapor pressure of the out-flowing air depends not only on the temperature but also on the airflow rate and flow pattern through the structure and the moisture conditions of the material layers. When the exfiltrating airflow rate is decreased, the temperature of the out-flowing air also decreases. This means that with smaller airflow rates, the accumulation of moisture starts with higher outside air temperatures than in the reference case. Therefore, the amount of moisture accumulation in a structure due to air exfiltration will not show a linear correlation to the airflow rate with nonuniform airflows.

With uniformly distributed air exfiltration, the out-flowing air temperature was as low as −8.6°C (Table 5), which is relatively close to the outside air temperature. In this case, the drying effect of the out-flowing air, in terms of the saturation vapor pressure, is much lower than in the reference case. Uniformly distributed airflow will probably cause moisture accumulation to start at higher outdoor temperatures than in a nonuniform case.

Sensitivity Analysis

The weather pattern of Sodankylä was selected for the sensitivity analysis. In the reference case, with 1.96 L/(s·m) airflow rate in the beginning of July, about 45% of the maximum moisture content reached during a one-year simulation was retained by the structure. This result, as well as the local moisture content values during the heating season, indicates severe problems with the hygrothermal behavior of the structure at this location.

The exfiltrating airflow rate and the relative humidity of the inside air were changed according to Table 3. The calculation results are presented using the mass of moisture per surface area of structure as a function of time, corresponding to the results shown in Fig. 18; Fig. 20 shows the results for different airflow rates, Fig. 21 the comparison between uniformly distributed and nonuniform airflow routes, and Fig. 22 those for different inside air relative humidities.

When the airflow rate (Fig. 20) was decreased from the reference value, the drying of the structure became slower. After a one-year simulation, the total mass of moisture in the structure with 1.00 L/(s·m) airflow rate was higher than that in the reference case. With airflow rate at 0.20 L/(s·m), the yearly maximum and the end value for the mass of moisture per structural area were about 4.1 and 1.8 kg/m^2, respectively. These correspond to about 30% of those with almost ten times higher airflow rate in the Sodankylä climate.

Figure 20 results show that correlation between the air exfiltration flow rate and moisture accumulation is not linear. It is difficult to determine a limit value for a safe air exfiltration flow rate in a cold climate because risks for moisture accumulation are indicated also with very low airflow rates. In very cold climates, any kind of air exfiltration will result in moisture accumulation at some location on the interface of the insulation and the sheathing considered here. If that moisture remains at that location for some period during the heating season, the temperature field within the cavity may favor

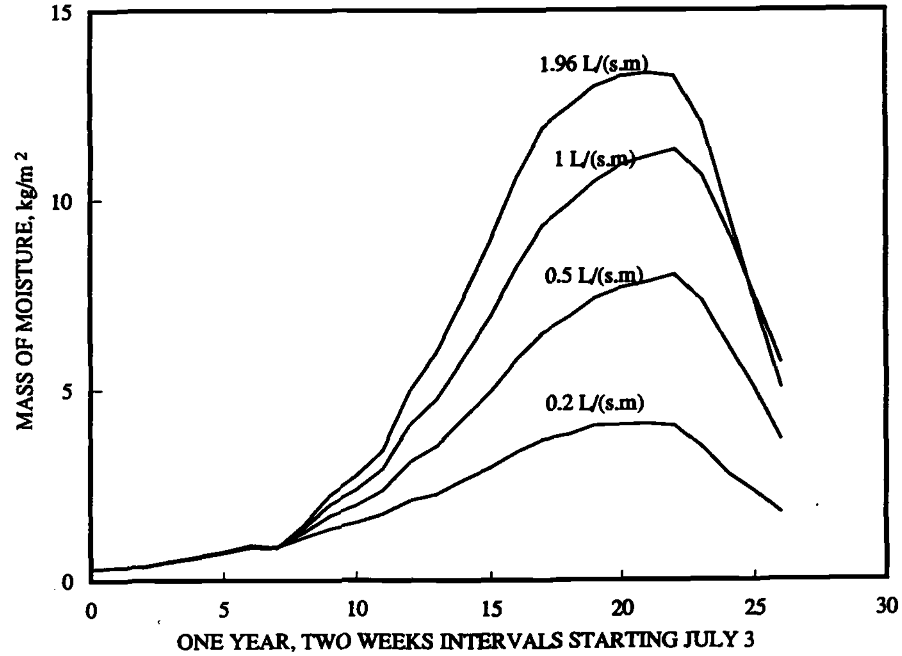

FIG. 20—The effect of exfiltration airflow rates on the total moisture absorption in the structure in climatic conditions of Sodankylä, Finland.

chemical or biological processes that degrade the performance of the component in the wall assembly.

If the airflow rate of 1.96 L/(s·m) is uniformly distributed (Fig. 21) over the surface area of the structure, moisture accumulation starts earlier than in the case with the reference airflow route.

This is due to the low temperature and higher vapor pressure value of the air flowing out of the structure (Table 5). However, the uniformly distributed moisture dries out faster than the more locally accumulated situation from the reference case. The maximum value of total moisture mass in the cold climate was about 4% smaller than in the reference case with nonuniform airflow and in the mild Vancouver climate about 45% higher, albeit still relatively small. In mild cli-

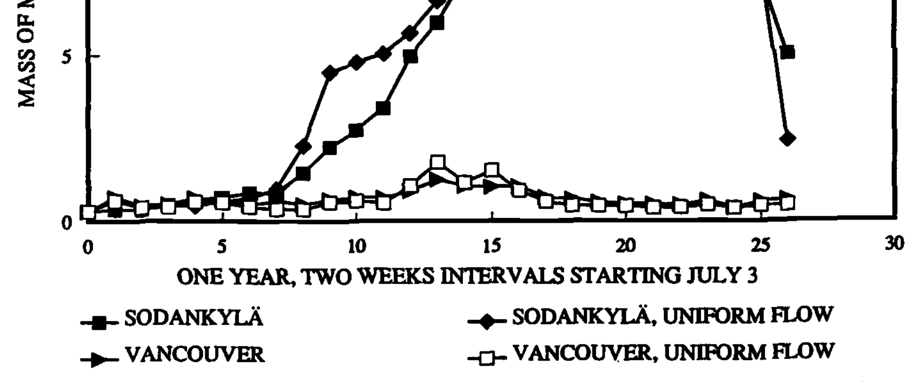

FIG. 21—Comparison of moisture accumulation between uniformly distributed and non-uniform exfiltration airflow.

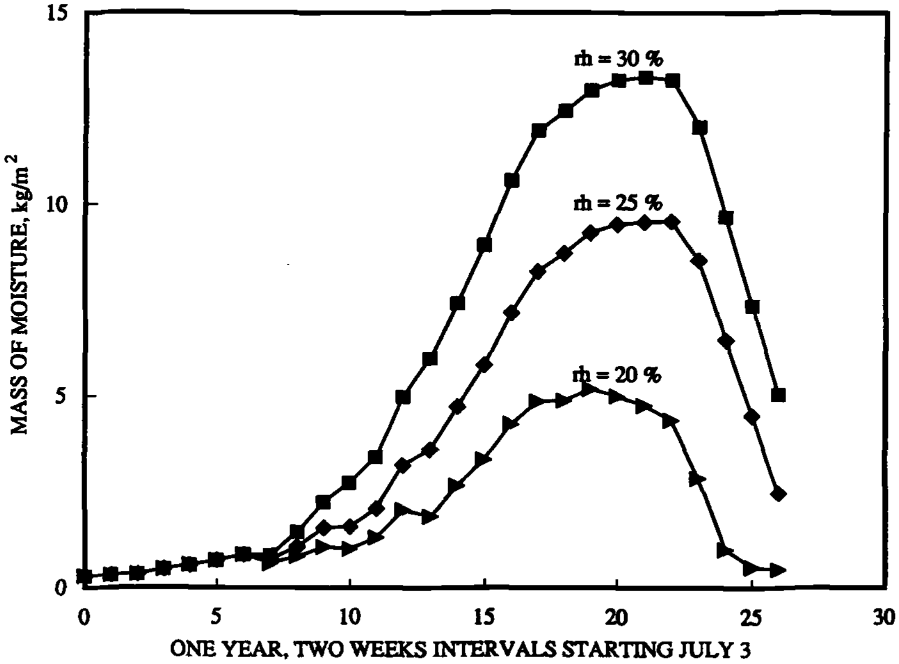

FIG. 22—The effect of inside air relative humidity (T_{in} = +21°C) on the moisture accumulation in the structure in climatic conditions of Sodankylä, Finland, with exfiltration airflow rate 1.96 L/(s·m).

mates, the uniformly distributed air exfiltration may cause higher maximum values of moisture in structures than with the reference-type flow pattern.

According to the total accumulated mass of moisture in the structure, the differences in the hygrothermal behavior of the structure between uniformly distributed air exfiltration and the reference case are small. However, a nonuniform air exfiltration will cause much higher local moisture content values when compared with the uniform airflow. Therefore a nonuniform airflow may result in deteriorated hygrothermal behavior of the structure.

The effect of inside air relative humidity on moisture accumulation (Fig. 22) was significantly stronger than that of the airflow rate. In the reference case, the partial vapor pressure of the inside air was already relatively low, 745 Pa. When this was decreased to 500 Pa, about 20% RH, the yearly cumulative effect could be avoided, but the maximum mass of moisture per structural area was still about 5 kg/m^2. On the other hand, high inside air vapor pressure values will also increase the risks of moisture accumulation in milder climatic conditions.

The numerically analyzed cases of air exfiltration presented here show the risks of moisture accumulation in residential wall cavities and the effects of airflow rate, airflow route, inside air vapor pressure, and climatic conditions on the extent of moisture accumulation. Exact criteria and acceptable limit values for the variables of air exfiltration cannot be given by simulation results only because the moisture distribution in real cases with three-dimensional heat, air, and moisture transfer differs from the numerical, two-dimensional approximation.

Moisture accumulation during air exfiltration depends on the vapor pressure of the air flowing into and out of the structure. Inside air relative humidity and temperature set the level for the convective moisture flow into the structure. When the outdoor temperature is low, say, under 0°C, the air flowing out of the structure has relatively low saturation vapor pressure. Depending on the indoor air vapor pressure, air exfiltration can bring more moisture into the structure than it can take out. Thus the main factors causing moisture accumulation during air exfiltration are the indoor and outdoor climatic conditions, especially vapor pressure and temperature. If the weather pattern has several months of cold, there may even be yearly moisture accumulation in the structure with typical indoor air vapor pressure values.

Though the amount of moisture accumulated depends on the airflow rate, from a practical point of view this is not the real issue. If the indoor and outdoor climate conditions allow moisture accumulation, any small exfiltration airflow rates may produce high local moisture content values in material layers.

With uniformly distributed air exfiltration, moisture accumulation starts earlier in the weather cycle, but it will also dry out the structure faster than in the case of a nonuniform airflow. A nonuniform airflow may cause higher local moisture accumulation and, therefore, also more risks for the hygrothermal behavior of the structure than a uniform airflow.

According to the results from the numerical analysis, a 10-Pa overpressure inside a building may cause harmful moisture accumulation within the wall and subsequent degraded hygrothermal behavior of the structure in most Canadian and Finnish locations. Though simulations show that, except in Resolute Bay, the cavity on the whole dries out in the warmer part of the annual cycle, at places such as Winnipeg severe cold weather results in the deposition of moisture at certain preferred locations. These locations may remain wet for a considerable part of the year, and the long-term hygrothermal behavior of these locations may significantly differ from that of the rest of the wall assembly. Depending on the material behavior, geographic location (outdoor conditions), and indoor vapor pressure of the building, overpressurization may have to be avoided to ensure the long-term performance of the structure.

CONCLUDING REMARKS

A review of the current activities of various research groups involved in modeling shows that, during the past ten years or so, substantial advancement has been made in this field. Researchers have a better grasp on the physics of various transport processes, increased knowledge on numerical techniques, and easier access to super computer power. It is expected that even faster advancement will be achieved by the turn of the century. The existing models will be revised and upgraded and many will be evaluated by comparing the results from model calculations with field observations.

In the meantime, the users of any existing model should be fully aware of the limitations of the model. They should know all about the assumptions that went into the model. They should confirm whether or not any of the predictions made by the model have been experimentally verified. They should confirm the reliability of the material property data used in the calculations.

It is doubtful whether the results obtained using even some of the most sophisticated computer models are always quantitative. Probably they never will be. But the power of computer model calculations to assess relative performances of various designs of a building envelope component or the relative performance of a given component at any selected geographical location and hence to develop useful design guidelines is unquestionable. Applications 2 and 3 of TCCC2D quoted in this chapter demonstrate this power of computer model calculations. Perhaps this is exactly the role of a computer model in the hands of a building practitioner—a tool that will economically, in terms of time and resources, assess the relative performances of building components.

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3

Relevant Moisture Properties of Building Construction Materials

by Ronald P. Tye[1]

BECAUSE OF ITS UNIQUE COMBINATION of physical, chemical, and thermodynamic properties, water exists in the solid, liquid, and vapor phases over the normal temperature range of human existence and comfort. Each of these forms, either separately or in combination, can adversely affect or influence the performance and behavior of materials used for buildings. This chapter discusses the effects of moisture on the properties and behavior of constructional and functional materials except for thermal insulations and wood and wood products, which are discussed in Chapters 4 and 5, respectively.

It is generally accepted that well in excess of 75% (some estimates being over 90%) of all problems with building envelopes are caused to a greater or lesser extent by moisture. The problems are many and varied, depending on type of building (e.g., residential, commercial, or functional), its design, site, inhabitants, geographical region, and materials used in its construction.

It is clear that current relevant knowledge, including that on materials properties, is insufficient. There is an obvious need for more information in order to alleviate the most pressing issues. First, there is a lack of fundamental information. The numbers and range of generic materials and manufactured building materials and their combinations are large and continue to expand with the range of applications and conditions. An examination of both "open" and specific product literature indicates, in general, that while some data are provided, much that is relevant is either not available or very limited in amount and scope.

Depending upon the material and its form, its properties can be affected by many and varied parameters. The materials themselves are often heterogeneous, displaying a range of property values. In general, moisture absorption and vapor transmission characteristics are dependent upon both temperature and humidity and buildings operate in a dynamic environment. Most data available has been generated in the laboratory using tests carried out under "static" rather than "dynamic" conditions, with the results being applicable to one temperature or one set of temperature conditions only. Furthermore, there can be significant differences in results for a particular property, especially in moisture transfer, depending upon the laboratory test method and/or individual technique used. An appropriate analysis for moisture performance has not been possible due to inadequate materials characterization, and thus results and conclusions have been qualitative at best. Field test data are very limited and generally specific to one combination of materials and/or conditions. Where more relevant testing (in situ) has been carried out, the goals have generally been to examine other performance characteristics. Moisture effects have been implied or obtained indirectly or qualitatively.

Due to the volume of testing required and the cost and time involved, it is unlikely that sufficient information will become available for all relevant properties of all materials under all conditions. However, by examining the overall matrix in conjunction with the specific problems for different applications, it should be possible to prioritize the important property(s) required for particular materials or their combinations for appropriate conditions. From this, more relevant test methods can be developed to provide the necessary information expediently and cost effectively.

The matrix of relevant parameters involved in a discussion of moisture and building materials, while not infinite, is formidable. Limited information is available on how moisture affects certain materials and their properties; however, it is not sufficient for a general discussion on quantitative effects for all materials. Absorption and permeability/permeance are the only two properties for which much information exists. Data from various published sources for both properties have been examined and rationalized where possible for inclusion in this chapter; however, it is reiterated that the indicated values should only be considered as typical of a range for a particular material type. In general, they do not include allowance for the effects of the various parameters shown or known to have influence on performance.

This chapter is thus a distillation of the available quantitative and qualitative information available. It provides guidelines and includes typical examples of many factors that must be considered in choosing and using a particular material in order to avoid the deleterious effects of excessive water in a building. In addition, it provides an indication of some of the necessary properties information required to obtain a better understanding of moisture behavior for improved material utilization.

NOMENCLATURE

In order to discuss the subject of moisture intake and transmission in building materials, various definitions and terms are required. These are:

Absorption—The process by which a porous material extracts fluid (water) from an environment. When measured,

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the results are normally reported as a percentage of the dry value by weight or volume.

Adsorption—The process by which fluid (water) molecules are concentrated on a surface(s) (of a porous material) by chemical and physical forces or both.

Capillarity—Action by which the surface of a liquid (water) in contact with a solid is raised proportional to surface wetting.

Dew-Point Temperature, D_P—The temperature at which a specific atmosphere is saturated with water vapor and cooling below which will produce condensation, °C or K. D_P is directly related to saturation water vapor pressure.

Latent Heat (h_L)—The change in enthalpy during a change of state, J/kg. For water, the heat energy required to change from ice to liquid water at constant temperature (fusion) and from a saturated liquid to a saturated vapor (vaporization) are important parameters.

Perm—See water vapor permeance.

Water Vapor Diffusion—The process by which water vapor moves through a permeable material due to a difference in vapor pressure.

Water Vapor Permeability, μ—The time rate of transmission of water vapor though unit area of a material (flat) of unit thickness induced by unit vapor pressure difference between two specific surfaces under specified temperature and humidity conditions. It is the property of a substance that permits passage of water vapor, and where it varies with psychometric conditions the spot or specific permeability defines the property at a specific condition, ng/s · m · Pa, where Pa is the vapor pressure difference.

Water Vapor Permeance, M—The time rate of water vapor transmission through unit area of a material or construction induced by unit vapor pressure difference between two parallel surfaces under specified temperature and humidity conditions. It is a performance characteristic represented by the quotient of the permeability divided by the thickness, $ng/(s \cdot m^2 \cdot Pa)$.

In many instances results of the permeance of materials are published in the "Perm" unit. This has a very specific definition of 1 grain of moisture per hour transmitted through 1 ft^2 of a 1-in.-thick material under a vapor pressure difference of 1 in. Hg. It was identified as the maximum allowable rate through a building material or system for a residential construction in ordinary climate (not exceeding 5000 heating degree days) in order to ensure there would be a very low probability of deterioration due to moisture. There is no direct S.I. equivalent unit. However, in metric units, the equivalent rate of moisture transfer is $57.2\ ng/m^2 \cdot s \cdot Pa$.

Water Vapor Pressure—The partial pressure of water vapor at a given temperature; also, the component of atmosphere pressure contributed by the presence of water vapor, Pa.

Water Vapor Resistance, R_V—The steady vapor pressure difference that induces unit time rate of vapor flow through unit area of material, or a construction that can be considered to act as a homogeneous body, for specific conditions of temperature and relative humidity at each surface. It is the reciprocal of permeance, $Pa \cdot m^2 \cdot s/ng$ or $TPa \cdot m^2 \cdot s/kg$.

Water Vapor Resistivity, r_V—The steady vapor pressure that induces unit time rate of vapor flow through unit thickness of a material, or a construction that can be considered to act as a homogeneous body, for specific temperature and relative humidity at each surface. It is the reciprocal of permeability, $(Pa \cdot m \cdot s)/ng$ or $TPa \cdot m \cdot s/kg$.

Water Vapor Retarder (Barrier)—A material or system that adequately impedes the transmission of water vapor under specified conditions. Essentially, a retarder is a material or combination of materials that restricts the transmission of water vapor. However for some applications, such as those involving cold surfaces impervious to moisture flow, any thermal insulation system used must be covered with barrier material or must be a system that is totally restrictive to moisture transmission.

Water Vapor Transmission Rate—The steady water vapor flow in unit time through unit area of a body normal to specific parallel surfaces under specific conditions of temperature and humidity at each surface, $kg/(h \cdot m^2)$.

BASIC PROBLEM STATEMENT

The effect of moisture on buildings can be seen or experienced both internally and externally in various ways. Major examples of the former include a cold (or hot) damp, uncomfortable environment, excessive heating, cooling and maintenance costs, mold growth, unsightly dark areas on the surface of walls and ceilings, and in the worst case wet and waterlogged areas. A more recent consideration has been an increase in harmful pollutants, causing an unhealthful internal environment. Some of these may be generated by results of the action of moisture over time on particular materials or material combinations. Externally one can observe physical degradation manifested by cracks and imperfections, masonry spalling, bubbling or peeling of membranes, and painted surfaces. These are supplemented with evidence of rusting and other corrosive effects due to chemical reaction and may be combined with decay and mold growth as a result of biological processes. Some of these effects may be seasonal, while some may be reversible or arrested by appropriate timely actions. However, many are irreversible, often resulting in serious or total deterioration of a material or the component in which it is situated.

The major sources of moisture accounting for these phenomena include any one or combinations of the following:

- Moisture existing in structural materials prior to use.
- Direct impingement of rain and snow on the structure.
- Leakage through cracks, voids, and other imperfections in and around the structure.
- Capillary action from the surrounding ground or other available contacting source.
- Standing water such as ponding (particularly flat roofs).
- Condensation of moisture vapor in the ambient air, especially that contributed by the building occupants.
- Melting of ice (including cyclic effects).

Furthermore, once moisture is present, it can then be transported in a material or component by one or more processes. The processes and driving forces are summarized in Table 1.

The design, construction, and operation of an efficient building depends on having sufficient numbers and types of materials and their combinations available to provide a protective function against the effects of moisture and moisture

TABLE 1—Processes of moisture transport.

Process	Moisture State	Driving Force
	DIFFUSION	
Adsorbate	Adsorbate	Concentration gradient
Gas	Vapor	Vapor pressure gradient
Liquid	Liquid	Concentration gradient
Thermal	Vapor and liquid	Temperature gradient
	FLOW	
Capillary	Liquid	Suction
Convection	Vapor	Air pressure gradient
Gravitational	Liquid	Height
Poiseuille	Liquid	Liquid pressure gradient

movement from each of these sources. These materials have to be characterized adequately in terms of their ability, either separately or in combination, to withstand or protect against these various moisture sources. For this reason, it is necessary not only to have information on their moisture pick-up and transmission properties and mechanisms but also on their relevant physical and chemical characteristics in a moist environment covering long-term use in the environmental temperature range for which the building is designed. Providing reliable information is available for these parameters, a suitable choice of material(s) can be made for a particular function within the enclosure or envelope.

However, it must be borne in mind that the correct choice and use of material is not the sole criteria for a good, healthful, low level moisture content building. The overall performance is very much dependent upon the original design, including selection of materials and use of ventilation, plus the care involved in the subsequent construction of the building when using the chosen materials. A building has to operate in a dynamic environment. Thus, architects, designers, and engineers need to become more familiar with the subject of building physics, especially moisture transport mechanisms and calculations related to specific materials or their combinations and their function. Furthermore, those involved directly with the construction must be made more aware of the sometimes disastrous effects that small "expedient" and apparently simple changes in design, construction practice, or choice of material can have on resultant performance.

It is both impractical and unnecessary for a building and its internal environment to be totally moisture free. In fact, large amounts of moisture are generated in some buildings, while for human comfort a certain amount of available moisture in the environment is necessary. The prime objective, therefore, in the design and the use of construction materials for any type of building is *moisture control*, with particular emphasis on maintaining the optimum performance of the installed thermal insulation. This is accomplished by appropriate design combined with selection and application of appropriate materials to perform necessary functions within the envelope and interior. Direct ingress from external sources must be avoided. Generated or stored internal moisture must be channelled and removed by appropriate means in unharmful ways. In this way, poor performance and degradation due to excessive amounts of moisture can be avoided while acceptable levels within the internal environment can be maintained. The role of air barriers, i.e., materials having a high permeance either separately or in conjunction with vapor retarders, is discussed in Chapter 17.

BASIC SOLUTION

In order to satisfy the preceding criteria, several basic materials principles need to be considered.

a. *Impermeable Layers*—The most obvious and dominant material criterion is that a structure should consist of "impermeable," i.e., very low permeance, components. For example, roofs and external walls, including fenestration components, must not only be fabricated with water-resistant materials but must also be able to withstand the loads imposed by forces due to wind stack effects and wind-driven rain and snow, water leaks, ice buildup, and differential expansion caused by cyclic moisture and temperature conditions. Furthermore, in cold climates, external warm moist air will migrate within the structure to colder outer surfaces (or vice versa in hot climates) and condense. Thus, it is necessary to utilize a low-permeance vapor retarder within the building envelope to ensure that moisture buildup from this source will not occur or can be kept to an absolute minimum and removed simply.

The use of such layers ensures that the structure will be a "dry" one. However, their use implies that the materials are chosen, combined, and applied correctly. The existence of any cracks, voids, and other convection paths in such layers will permit moisture migration and can, in fact, trap moisture, causing increased moisture levels within the envelope, thereby exacerbating problems. Thus, any joints using materials between contacting surfaces must involve the use of impermeable materials also.

b. *Drainage*—It is necessary for groundwater to flow away from the foundation structure. While site selection is important in this respect, the foundation should be laid on materials, e.g. gravel, sand, or other highly porous media that provide adequate means for water to be removed naturally.

c. *Capillary action*—Consideration must be given to the incorporation of a layer of gravel or other capillary-breaking material to prevent any excess groundwater from being drawn up into the structure. Furthermore, the incorporation of a damp proof course of slate, building felt, or other impermeable or very low permeance material is necessary to avoid capillary transport between masonry and wood and other porous materials, such as thermal insulation, in the structure.

d. *Directed water*—Excess water from rain and snow, e.g. ponding on flat roofs, needs to be removed or its effect minimized by choosing and correctly applying materials that can withstand the standing water. In addition, materials for window sills, drip plates, and joint sealants between components must also withstand effects of such standing water.

It should also be pointed out that the above principles are supplemented with two others which are not directly material oriented (other than materials compatibility). These are:

e. *Ventilation*—Appropriate means should be employed whereby moisture vapor, especially from major generating areas, can be removed by natural and/or forced convection of the air from lower to higher temperature environments. This is discussed in detail in Chapter 9.

f. *Raising Temperature*—By raising the temperature of an element, component, or area to reduce the temperature differential between the inner environment and outer envelope, the favorable conditions for moisture vapor movement and condensation are reduced. One solution is to increase thermal insulation levels on the building exterior, including the use of composite panels of insulation in combination with other materials which are impermeable.

MATERIALS

Because of the many and varied functions required of buildings, a broad range of materials and combinations of materials can be found both in the structure and contents. The major generic building materials (including four, classified in terms of their function rather than type, consisting of one or more of the generic types) are listed as follows:

- Asphalts and related bituminous products
- Composites, including combinations of two or more materials
- Glasses
- Gypsum products
- Masonry, including bricks, cements, concretes, grouts, mortars, and tiles
- Coatings, including cementitious and polymer based (usually considered as being applied at a thickness that does not exceed 0.75 mm)
- Mastics (where applied as a protective coating, the thickness is usually considered to exceed 0.75 mm)
- Metals
- Paints
- Papers
- Plastics, including fiber-reinforced products
- Rocks, stones, slates
- Soils (including subfoundations)
- Textiles
- Adhesives
- Membranes
- Sealants

The list is large and the spectrum involves a full range from the naturally occurring—including fabricated, modified, or treated forms—to the completely manufactured and manmade. The amounts and forms of a particular material, e.g. metal, can vary from a thin foil to a component of large cross section. In addition, a material can serve a number of functions by its use in different forms. For example, a metal or plastic can be used as a vapor retarder or membrane (thin foil), a siding (sheet), a pipe, tube, fastener, fitting, or structural member (fabricated).

The performance and effectiveness of a material when in contact with water in any of its three phases may depend significantly, especially with time, upon form and amount of material. Furthermore, this behavior may depend upon additional factors including temperature, environment, and the other materials with which it is in direct contact or association. This overall matrix of relevant factors affecting the direct and interrelated effects of moisture on materials is thus extremely imposing, especially in view of the numbers of materials and combinations and the number of manufacturers of many of the generic products. Some factors are more significant than others, but all play a role.

PROPERTIES

The direct water-related properties required of any material used in a building are as follows.

Moisture Absorption

In general, this should be as low as possible, especially for the external envelope material. Thus, either the material itself should not absorb (or adsorb) water or it should be protected with some other material(s) that does not absorb moisture.

Moisture Transmission

In general, this should be very low, especially for the liquid form. However, since moisture in some amount will always be present as vapor, its movement has to be controlled by use of low-permeance materials such that it can be removed safely and not allowed to condense and accumulate in any area, particularly where freezing can occur. For some climates and for some specific buildings, various materials having somewhat higher permeance but acting as air barriers may also be desired to assist in such control.

Moisture Storage

Some materials within the building space, e.g. coatings, gypsum products, papers, and textiles including furnishings, can absorb and store moisture. This can be released depending on conditions and subsequently transmitted within the through the envelope.

Additional material properties that will or may be affected, especially over a period of time ("aging"), by water in one or more of its three phases are:

Chemical (Including Biological)

Contacting water in an appropriate environment will or may react directly with the material (including impurities) and especially with contacting dissimilar materials, including associated thermal insulation, to form acids or alkalis, initiating chemical reactions and galvanic action which results in corrosion, efflorescence, rusting, staining, etc. Examples include the etching of window glass and the corrosion of unprotected metal frames of fenestration units, particularly in salty coastal environments; unsightly surfaces of masonry and steel exteriors; mold and mildew growth on internal walls in a warm, damp environment; emission of harmful and potentially toxic gases (e.g. formaldehyde from adhesives in furnishings and fabricated wood products); and discoloration of high-reflectance paints applied to building exteriors in hot climates. In some cases, these effects may be considered somewhat cosmetic in nature. However, in many others, reactions may take place unseen or unsuspected on internal structural components within the envelope. In such cases, the overall long-term strength and durability of the building or component can be significantly affected, often resulting in structural degradation and ultimately in building failure.

Mechanical/Physical

The various strength parameters (compression, flexure, impact, shear, tension) of materials can be adversely affected by moisture. Corrosion of metals due to chemical reaction is one specific example where structural performance is degraded. For polymeric and similar materials, absorbed moisture, especially under conditions of continuous cycling of environment and temperature, causes significant dimensional changes which degrade the mechanical performance. Fiber-reinforced plastics are now being used in increasing quantities in buildings. The presence of moisture in the fiber reinforcement, either initially in fabrication or caused by differential and anisotropic expansion with time, which produces cracks and flaws, reduces the bond strength between the fiber and matrix and thus the tensile and compressive strengths of the composite. Various polymers and related materials, especially those used as sealants and coatings, can harden and lose their mechanical strength, flexibility, and adhesive qualities due particularly to effects of UV radiation and temperature cycling. This results in the formation of cracks in the material and/or gaps between materials through which moisture may enter. Another example of aging effects on mechanical strength is that of blistering of a coated insulated roof system. For this, residual or migrated moisture in the thermal insulation under the coating vaporizes due to the energy supplied from the sun and causes bubbles. Unless the coating has or retains sufficient mechanical strength and elasticity to withstand the high gas/pressures involved, the bubbles rupture, allowing moisture to penetrate through the tear and further degrade performance.

Thermal (Including Thermomechanical)

Depending upon the density and porosity of a material, the presence of any moisture can have a significant impact on overall thermal performance. At 273 K the thermal conductivity of both liquid water and ice is high, being approximately 0.5 and 2.0 W/m·K, respectively, while the specific heat, approximately 4200 J·kg/K, is also very high, being some two to four times that of most building materials. The thermal diffusivity (the quantity thermal conductivity divided by the product of specific heat and density) can, therefore, vary considerably.

Thus moisture in a porous material has immediate direct effects insofar that it increases the thermal conductivity and the specific heat by its presence (depends directly on porosity). This in turn affects the thermal diffusivity due to a direct increase in density. In addition, if moisture condenses and accumulates in or on a material within the structure and cannot be removed, then it provides a direct conductive "thermal bridge," thus contributing further to heat losses (or gains) within the envelope. Finally, the contributions, due to the latent heats of fusion and vaporization of water, including that contained in a material, are also important parameters, particularly under cyclic conditions over significant temperature ranges that a building can experience in some climates.

In general, most of these moisture effects are more critical for highly porous insulation and wood materials, especially when used in large thicknesses. However, the effect on all materials, especially masonry types which have a large range of porosity, is important since overall performance has to be evaluated by considering the total system and all contributions.

The above discussion relates specifically to moisture and aging effects on thermal transport properties. However, there is also a need to consider its effects on relevant surface thermal optical properties, i.e. emittance, reflectance, and transmittance. Condensation of moisture droplets, especially when accompanied by dust particles or discoloration of surfaces due to chemical or other action, can degrade the appropriate property on which optimum performance is based. For example, these phenomena will increase the emittance of polished metal surfaces such as unperforated aluminum foils used as radiant barriers in attics, reduce the effectiveness of special optical coatings that are applied on or between glass surfaces of windows to provide high thermal performance, reduce the absorptance of collector surfaces of solar panels, and reduce the reflectance of special paints and coatings applied to building exteriors in hot climates.

One final thermal or thermomechanical property to be considered is thermal expansion, and one example has been described earlier. Buildings can experience large temperature excursions during a diurnal cycle. The integrity of joints between the same or different materials must be ensured as expansion and contraction take place. Ideally this can be accomplished by suitable matching of the coefficient of thermal expansion. However, this is usually impractical with building materials since coefficients of expansion can vary widely by up to an order of magnitude in extreme cases, e.g. glass and plastics. Generally in buildings, joints between materials include a thick layer of a somewhat flexible caulk, filler, or sealant compound. These have a relatively high thermal expansion combined with appropriate flexure and related strength characteristics, enabling them to deform or conform without fracture as the temperature fluctuates.

If applied correctly, these materials form a joint which initially is impermeable to moisture. However, depending on their position in the structure and the environmental conditions, they can absorb moisture with time. As a result, they can harden, swell, contract, or otherwise deform. The expansion and strength characteristics change, ultimately resulting in shear.

Thus the joint does not remain integral and a path for moisture ingress is formed.

Basically, materials can be categorized for two essential roles: (1) to minimize direct ingress of water into or within a building (barrier), and (2) to control moisture vapor movement within and through the building envelope (retarder).

WATER BARRIERS

To accomplish the first role, a material or material combination has to be virtually impermeable to water. Essentially, this is attained by ensuring that the porosity is very low (usually implying a high density and/or a substantial thickness) such that the internal material surface area is very small. As a consequence, even in direct contact with water or at high relative humidity, there is little opportunity for water to penetrate or accumulate other than directly on the external surface. A further requirement is that it should be relatively inert to the action of water or an environment that contains significant amounts of moisture.

An examination of the list of materials in the previous section indicates that there are many that can serve the barrier function within the envelope, either singly or in combination. They can be classified as serving in either a direct structural component or a protective role.

The first category includes glasses, metals, and solid plastics, including reinforced products. These are impermeable to moisture above a minimum thickness where pinholes and flaws can be eliminated in production. They are relatively inert to moisture and can also be protected where problems with moisture are known to exist. For example, special paints and enamels or surface finishes (galvanizing, anodizing) exist to protect steels from rusting and aluminum and copper from corroding.

Many people would include masonry and rocks and stones in this category, and, in general, a number of these materials can be considered impermeable to moisture as they are used in substantial thicknesses. However, both generic classifications include a very wide variety of types and forms covering a broad range of porosity. Thus, some care must be taken in deciding at what level of porosity and at what thickness a particular material may be deemed impermeable for its application. Wind-driven rain is an important consideration in the context.

Rocks and stones have been utilized as basic structural materials for buildings for many centuries. Many such structures are hundreds of years old with few obvious signs of any deleterious effects of moisture. In contrast, there are other examples where buildings fabricated, and especially decorated, with natural stone materials have undergone substantial deterioration over much shorter periods of time due to the combined effects of moisture, wind, and temperature. In the former case, the materials used were high-density low-porosity wear-resistant stones such as granites, marbles, and slates, particularly for roofs. In the latter they were the more porous sandstone types having less resistance to surface abrasion and wear and to the effects of moisture within the more open structure.

A somewhat similar situation exists in the masonry category with one particular and very important difference. Masonry materials are predominantly man-made and consist of a combination of graded aggregates of powdered and particulate earth minerals such as clay, pumice, sands, schist, cement or other binders, special additives, air, and water. The mixture is blended thoroughly into a homogeneous mix and poured into molds to provide appropriate forms such as slabs, blocks, bricks, and tiles. These are allowed to hydrate and harden, i.e. "cure" either by natural or accelerated means. In the former, e.g. concrete foundations, prefabricated building elements and some block units, the concretes cure in the open or in a controlled natural environment. Accelerated curing is accomplished either by firing to high temperatures, e.g. clay bricks and ceramic tiles, or by steam heating either at atmospheric pressure at a temperature in the range 50 to 80°C for 12 to 18 h or at high pressures (autoclaving) at 120 to 150°C for shorter periods of time, followed by storage in the open or a controlled natural environment.

The composition and curing mechanisms of concrete and cement-based materials are complex subjects, but one very important parameter is the role that moisture plays in determining the properties and subsequent moisture performance of the materials. The amount of moisture (water/cement ratio of the mix) affects many properties including mechanical strengths, shrinkage, and bonding. In addition, the amounts of moisture available during the curing process affects the drying rate, which can also affect subsequent moisture behavior.

Finally, freeze-thaw resistance of exterior concretes is controlled by use of aggregate materials having appropriate absorption and surface moisture characteristics such that critical saturation is avoided. The material can accommodate the expansion and contraction with increase and decrease of hydraulic pressures associated with freeze/thaw cycles.

In general, the quality of any concrete material is improved by adjusting the water content to a minimum acceptable level sufficient to allow mixing and working of the homogeneous paste. This is attained by keeping the water/cement ratio in the order of 0.25, often by the utilization of add-mixtures. By reducing the water content to this level, the porosity and shrinkage and crack tendency are reduced and bond strength increased. These factors will all improve resistance to moisture transfer by reducing the permeability to moisture and air, increasing direct water tightness, lowering absorption, and reducing weathering.

Essentially, the optimum design properties required for a cement-based material are based upon complete hydration of the cement. They will only be obtained providing sufficient moisture is available over the curing period to avoid drying of the concrete, thereby arresting the hydration. Thus it is essential that the moisture be available either in the original mix or from a high relative humidity (>80%) moderate temperature environment.

Mortars and grouts are two other cement-based materials that also contribute to moisture performance of masonry components. The former materials are essential for the provision of leak-free joints in the integral structure including its reinforcements. Grouts which are produced by adding water to mortar containing small amounts of lime are an essential element to reinforce masonry because of the ability to bond the masonry to steel. They are also used in empty cores of block walls to give added strength and reduced permeability.

The dominating factor for both forms and, particularly with mortar, is water retentivity. To ensure a good bond and weather-tight joints, the mortar must not lose water rapidly either to the environment or to the highly absorptive block material such that it stiffens and loses its plasticity. Both material types contain a high cement content, and in this case the tensile bond strength increases with increased water content. Thus these materials are used with the highest acceptable level of water in the mix comparable with the ability to work the paste.

A considerable number of protective covering and coating materials are available from the various categories listed in the earlier section. These range from paints, applied in thin layers (<0.01 mm), to substantial thicknesses (>3 mm) of mastics and cementitous materials. They serve two different functions depending upon the type of building, the amount of moisture generated, and the climate. They can act as a barrier by a combination of low-vapor permeability combined with low-moisture absorption and good adhesion and durability characteristics or as a breathable layer having a higher permeability value to allow passage of water vapor where applicable while retaining the other properties.

Two general classifications apply. Elastomeric materials are those that are capable of undergoing an elongation of at least 15% but retain the ability to recover to the original dimensions. Those that do not have this ability are classed as nonelastomeric, and some may be quite rigid, for example stucco and other cement-based external coverings or fire protection materials for internal components.

One of the major uses of both coating types, other than as paints, is for covering insulated roof decks and particularly for protection of spray-applied or other rigid thermal insulation. The choice is dependent on the building type, type of roof, the climate, and the compatibility of the materials. Such coatings include asphalts and bitumen products, plus a wide variety of single and double component acrylics, butyls, epoxies, hypalons, neoprenes, silicones and synthetic rubbers, urethanes, vinyls, and other polymeric materials. For applications involving harsh environments, these coatings may include some aggregate or be supplemented with a cement-based polymer cover coating. In general, these materials are applied at thicknesses of at least 0.5 mm and preferably 0.75 mm and greater to attain optimum performance over a reasonable lifetime, up to 20 years.

The overall efficiency of these materials is based on their ability to remain integral over the complete surface to which they are applied, including all joints, connections, projections, etc. While the specific low absorption and transmission properties are necessary, there are several other important parameters to consider in the selection of this type of material for a particular application. To ensure that the coating is integral, free of flaws, and not subject to cracking, the material must have a good tensile strength and modulus, good tear and hard strengths, good elongation and low-temperature flexibility, plus resistance to heat aging and accelerated weathering. Uniformity of thickness and texture are very important and are controlled by the applicator in accordance with appropriate guidelines depending upon the type. Environmental conditions of temperature, humidity, and wind velocity are important factors in application, such that the coverings will remain free of flaws initially while resisting the tendency to crack or separate from the substrate.

Thus there appears to be an adequate choice of materials available to fulfill the objective of resisting direct moisture ingress.

VAPOR RETARDERS AND AIR BARRIERS

To fulfill the second or control role, two mechanisms of moisture movement have to be considered. Since water vapor escapes from the internal environment by convection and/or diffusion, both mechanisms have to be addressed by a suitable choice of material(s) and its installation. Convection (air movement) involves passage of moisture through cracks, openings, and other imperfections. Water vapor passes through building envelope components by diffusion from areas of high vapor pressure to areas of lower vapor pressure. In practice, considerably more moisture is transported by convection than by diffusion.

Assuming that the building has been designed and constructed with appropriate barrier materials to ensure that there is minimum ingress of liquid water from external surfaces, the major objective becomes control of moisture vapor. This involves ensuring that the moisture developed within the warmer environment is dissipated so that it does not diffuse or travel by convection to the colder environment, condense, and accumulate in the exterior of the envelope, particularly in the thermal insulation. The prime means of accomplishing this is to incorporate adequate vapor retarders and an air barrier. In many cases, one correctly installed barrier can serve both functions.

In general, a retarder or barrier—whether installed on the interior side (moisture-air combination) or on the exterior side (predominantly air) of a building envelope—consists of films and sheets of different plastics and reinforced, impregnated, or otherwise treated plastics, papers, and felts. When installed on the external side, it needs to have a high enough permeance so that diffusion of moisture vapor can still take place through the envelope. However, external sealing also reduces convective currents through and within wall cavities and thus helps to maintain the overall effectiveness of the thermal insulation.

To be most effective, the barrier should be continuous. Thus all joints in the material must be lapped and sealed. Great care is necessary to ensure that there is continuity of all joints at walls, floors, ceilings, frames of penetration units, and all penetrations for utility services. A continuous barrier installed on the external side does reduce problems associated with maintaining continuity of a barrier installed on the interior side. Materials for external air barriers need to have higher strength in order to withstand damage in handling during construction. Thus, they are usually thicker than similar forms for internal installation.

The first criterion for any vapor retarder is its resistance to water and both moisture vapor and air flow. However, it must have other favorable properties for long-term efficacy in application. These include being resistant to abrasion, corrosion, flammability and fire, mildew, puncture and tears; good adhesive, flexible impact, shear and tensile strengths; good environmental and thermal stability and be fabricated and applied easily and inexpensively. Table 2 illustrates the relative importance of some of these parameters for various building applications.

The majority of materials listed earlier, especially in combination, all resist moisture transmission to some extent and can thus be considered as vapor retarders or air barriers. However, those fulfilling the generally accepted classification of vapor retarder consist of the structure itself and three basic material groups.

(a) *Rigid*—These have some structural integrity and consist predominantly of metals, particularly aluminum and stainless steel, plastic and reinforced plastics, and laminated combinations of plastics and metal films. Normally they are fas-

TABLE 2—Necessary properties for membrane type barriers.

Type	Puncture Resistance	Abrasion Resistance	Tear Resistance	Tensile Strength	Fire Resistant	Noncorrosive	Rot Resistance	Mildew Resistance
Wall (residential)	H	L	H					
Underslab (residential and commercial)	H	H	L	M		X	X	X
Roof deck (internal)	L	M	M					
Roof deck (external)	H	H	H					
Duct insulation	M	M	M	M	X	X		
Metal building insulation	M	M	M	M	X	X		
Cold storage	H	H	H			X	X	X

NOTE: L = low; M = moderate; H = high; X = highly desirable.

tened in place using mechanical means, and all joints require sealing with an appropriate sealant. They are used close to the inside surface or outside surface depending on the building application. Providing adequate thicknesses are chosen and careful installation practices used, these systems can have an extremely high resistance to water vapor transmission and can be considered barriers.

(b) *Flexible*—These are usually non-load bearing and consist of thin sheets and foils ($< \sim 0.05$ mm) of asphalt or other coated felts and papers, metals, plastics, and laminated combinations. They are usually available in rolls, and sometimes they are attached to a thermal insulation product. Adhesive tapes or other materials are necessary for sealing joints, and careful installation is required to avoid physical damage to the product and the formation of air leakage paths.

These very thin materials and products should be homogeneous and have thickness integrity over the total surface. For example, pinholes or other small imperfections must be avoided since they can reduce the resistance to vapor transmission by significant amounts. Information contained in Chapter 20 of the *ASHRAE Handbook of Fundamentals* [*1*] illustrates the importance of such effects. A typical scrim kraft laminated foil with no imperfections can have a permeance of approximately 1 mg/s·m^2·Pa. However, with only 380 pinholes per square metre, this increases to a value of over 2 units, while for only a small number of holes larger than pinholes the permeance is increased by an order of magnitude.

The effect of materials compatibility in a composite product is shown by another example. In this a 0.008-mm-thick aluminum foil/polyethylene and adhesive/kraft paper laminate had a 75% lower permeance than a similar one fabricated with a latex adhesive due to the fact that the polyethylene was more efficient in sealing the pinholes and cracks in the thin metal foil.

Recent studies have been carried out on the contribution of radiant barrier materials to moisture accumulation in attics [*2*]. These have provided further information on the permeance of perforated metal foils and metallized plastic films involving hole area/total area ratios from 0.01 to 1%. Permeances value were determined in several different ways:

(i) calculation from simple diffusion theory
(ii) measured in the laboratory at 24°C using the ASTM Test Methods for Water Vapor Transmission of Materials (E 96 Procedure B)[2]
(iii) measured by an alternative method at 38°C and 12 or 25% RH
(iv) estimated from field observations in two houses

Although there were differences in the materials involved, reasonably good agreement in overall values was found between (i) and (iii) where permeance was a direct function of the area ratio. Similarly, reasonable agreement in overall value was seen between (iii) and (iv). However, an approximate order of magnitude difference existed between the two, the latter two techniques giving a lower permeance value of the order 1200 ng/m^2s·Pa for an area ratio of 0.4 to 0.5%.

(c) *Coatings*—These are generally applied in the field and are predominantly liquids or semi-liquids which acquire their low-permeance characteristics on drying or otherwise curing. Hot melts including thermoforming and thermofusible sheet materials are also included in this category. Their base can be bitumen, polymeric, or resinous. Depending upon their application and the design requirement, other components can include ballast or other fillers, flame retardants, pigments, plus either a volatile solvent or water. They are applied by brushing, dipping or mopping, rolling, spraying, or troweling. With the exception of paints, e.g. used as thin coats internally on gypsum wall board or externally on masonry, these products are applied externally, generally in thicknesses of at least 0.5 mm and usually in excess of 0.45 mm.

Coatings are best applied to the substrate in one or at most two uniform applications under recommended temperature, time, and environment conditions. Good workmanship is essential in order to ensure continuity, uniformity, and adequate coverage of all surfaces, including any joints and flashings, etc., around pipes and other irregularities of the envelope structure. The choice of coating is dependent on the type of substrate since it must be strong enough to resist cracking due to mechanical strain caused by movement of the underlying structure. Comparison of permeance characteristics can only be based on determinations on cured specimens above a minimum thickness.

Because of their form and application technique, these materials are not truly homogeneous. As a result, their properties are not necessarily directly thickness dependent. In general there is a minimum thickness of a particular material when tested for transmission properties in its dry and cured state above which it starts to exhibit a permeability level suitable for consideration as a vapor retarder. In addition, if this thickness is increased by a factor of 2 or 3, the resulting permeance can be reduced by factors of 20 to 50 depending on the material.

Chemical reaction is another important consideration, especially for these materials. For example, bitumen-based materials should not be used where petroleum products may be present, as in treated soils or in areas near refineries. Some

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[2] Method most widely used for building materials (discussed later).

of these coatings and some materials, included in (b), may contain salts to enhance their fire-retardant characteristics. In the presence of water, these salts may be released and cause corrosion of metals. For flexible laminated composite films, this can often result in complete disintegration of the metal layer of the retarder, especially where the original aluminum foil is very thin (<0.01 mm).

(d) The final category that can be included is the structure itself. This consists of a combination of two or more materials and systems including rigid, semi-rigid materials, composite components and curtain walls, and thermal insulation. Providing all joints are adequately sealed, such systems will have the necessary low-permeance characteristics for moisture control.

Basically for residential constructions, especially in more moderate climates, the design criterion for an adequate vapor retarder has been that the permeance should not exceed the historically recommended 57.2 ng/m^2·s·Pa (1 perm) unit. In recent years, the growing tendency has been to install retarders having lower permeance values to assist in"tightening" the building to vapor and air flow. However, for a variety of other buildings, especially cold stores or where large quantities of moisture are present during operation, very much lower limits of permeance, including total impermeability, are recommended either for the envelope itself or for components such as cold pipes and ducts within the building.

In determining a design value for the retarder/barrier, the effects of joints can be critical. As discussed in Chapter 20 of the *ASHRAE Handbook of Fundamentals*, a typical field-applied coating system having a laboratory-measured permeance of 0.6 ng/s·m^2·Pa may be found to have a field-installed value of five to ten times the value due to additional leakage at the joints. In choosing materials for use as vapor retarders, conservative allowance should be made for such effects.

In general, therefore, depending on the application, the vapor retarder can be selected from one of the above categories having appropriate low water vapor transmission characteristics and applied such that joints, cracks, and other imperfections are well sealed. For complete "impermeability," the rigid category offers the most suitable choice.

For the purpose of further discussion, it is assumed that in performing to its design, the material or system is integral with no significant holes or tears and otherwise installed correctly. The absence of holes and tears, such as can be found around joists, electrical fittings, pipes, etc., is critical. This is illustrated by another example discussed in Chapter 20 of the *ASHRAE Handbook of Fundamentals*. There it is shown that small holes of relatively small equivalent area (0.007 m^2) to a total area (100 m^2) of 60 ng/m^2·s·Pa can provide convective paths through which nearly 20 times as much moisture can flow by convection rather than by direct transmission through the retarder.

CRITERIA FOR CHOICE OF VAPOR RETARDER

In determining the vapor retarder requirement for a particular building type and application, several factors have to be considered.

(a) The critical operational parameters for an application are the dew point temperature (related directly to saturation vapor pressure) and the vapor pressure difference (proportional to relative humidity) between the moist warmer and the colder environments on either side of the retarder. These two parameters can be determined for any set of conditions for a particular building type by calculations utilizing available information on the thermodynamic properties of water at saturation, which are contained in standard psychrometric tables or charts.

In general, for the continental United States, the extremes of external operational (design) conditions for buildings can range from a winter low of −35 to −40°C and 65 to 75% RH in northern areas to a summer high of 35 to 40°C and 60 to 65% RH in the southern regions. These give rise to dew point temperatures between −42 to 28°C and corresponding water vapor pressures from 10 Pa to 3.3 kPa. Thus for any building type, the maximum range of vapor pressure differences developed across the building envelope can be calculated dependent upon the chosen internal environment design criterion (temperature and humidity).

(b) Both the magnitude and direction of the flow of water vapor are established by the design conditions and local environment. In most cases, while the former will be variable, the latter can be undirectional or reversible, e.g. cold stores, where the vapor pressure difference is always or generally higher in the external environment. In hot summer conditions the vapor retarder/barrier must be placed on the external (warmer) side of the insulation of the envelope. Alternatively, for most residential and highly occupied buildings, the cold winter conditions usually require that the vapor retarder be installed on the inside surface of insulated envelope. However, for certain building types in regions experiencing large annual variations in local climate, e.g. coolers and cold stores in northern regions and air conditioned or refrigerated structures in southern areas, both the temperature and vapor pressure of the interior can be higher or lower than those of the exterior. This factor requires special consideration for the material type and placement of any vapor retarder.

(c) The overall material performance is dependent not only on the particular permeability value but also the thickness, the area, the number of joints, the substrate to which and how conveniently it is attached, and the expected lifetime. Thus a particular design value can be obtained by using longer wider pieces of higher permeance material with fewer joints than one of low permeance that is available in smaller pieces, such that more joints are necessary. Alternatively, a thicker coating of more easily applied material may be preferable to a thinner lower permeance material that requires special application techniques to the substrate.

(d) The influence of temperature and relative humidity on the performance of the vapor retarder material. The permeance requirements can be determined in accordance with the design criteria discussed in (a). For these, the temperature can vary from approximately −40 to 40°C and the humidity over a broad range. In addition, it should be remembered that external surfaces of buildings in predominantly hot climates can experience temperatures as high as 80°C. In such cases where a material is applied on or close to the exterior, it will attain temperatures significantly higher than 40°C and may cycle over a span of up to 100°C in extreme cases.

TABLE 3—ASTM E 96—Recommended test conditions.

	Nominal Conditions		
		RH, on the Two Surfaces of Specimen	
Procedure	Temperature, °C	In Cup	Outside Cup
A	23	0	50
B	23	100	50
C	32	0	50
D	32	100	50
E	38	0	90

Data from one procedure cannot be converted to any other procedure reliably.

In general, most permeability and permeance data on buildings materials and systems for vapor retarders have been determined over very limited ranges of temperature and humidity conditions. For example, in E 96, a widely used test method, isothermal test temperatures are chosen within the approximate range 20 to 38°C and fixed pairs of relative humidities on each side of the specimen as shown in Table 3.

Little or no information from laboratory tests is available on moisture properties at any other isothermal temperature and range of humidity or for conditions involving any representative temperature gradient or cycle within the design range.

Vapor retarder materials for use under concrete slabs or as ground cover over open spaces require water vapor transmission testing before and after various exposures and other conditioning procedures, some of which include higher temperatures. However, all subsequent transmission tests are carried out at one or more of the ASTM E 96 conditions listed in Table 3. Various field tests or simulations have been carried out essentially to study overall heat transmissions characteristics of building envelope components under various climate conditions. Some of these have included effects of mass transfer and moisture buildup. However, insufficient materials characterization has been included on the components for firm conclusions to be drawn regarding possible effects of temperature or temperature cycling and humidity on the vapor and air barrier materials included in the construction.

Some attempt to estimate the effect of temperature on rubbers, polymers, and similar materials where the moisture migration mechanism is via activated diffusion has been made using the results of a few tests, and an equation based on the activation energy [*3*] is

$$\mu = \mu_0 \exp^{(-E/RT)}$$

where T is the absolute temperature, R the gas constant, E the activation energy determined from E 96 or similar permeability tests carried out at two different temperatures, and μ_0 is a constant as $T = \infty$. This technique of constructing spot permeability curves at different temperatures may be applicable as an approximation for other materials.

TEST METHODOLOGY

It can be seen that a very large number of parameters need to be evaluated in order to develop a comprehensive understanding of materials behavior in the presence of moisture. While a number of test methods are available to study the influence of some of the parameters, they are not necessarily applicable to all materials and the results are not representative of performance in building applications and conditions. Most of the generated information can thus be used only in a comparative mode.

However, for some important parameters, the accepted test method itself may not provide reliable results, while in others a standard test technique has yet to be developed. The prime example of the first category for a very important property is the permeability test and that for the second is equilibrium moisture content due to absorption and adsorption. Moisture effects on thermal performance, as discussed in Chapter 4, is a further example of the second category. The relevant factors affecting these particular test methodologies for permeability and moisture contents are discussed briefly.

Permeability

Published collected data for permeability and permeance properties show that there are very broad ranges of values for different materials. Furthermore, individual material types can vary significantly within a particular range other than for either the very dense impermeable or the low-density highly permeable types. As discussed, materials-related factors can often account for much of the variability seen. However, a major contributing factor concerns the limitations of available test methods.

Current test methods are based upon the principles of Fick's law

$$W = -\mu(dP/dX)$$

where W is the mass of vapor diffusing through unit area in unit time, p is the vapor pressure, x is the length of the flow path, and μ is a constant.

In general, these methods use some form of desiccant (dry cup) or water (wet cup) technique. In the former, a specimen is sealed over a dish containing a desiccant. The dish is then placed in a constant temperature/humidity environment, weighed periodically, and the water vapor transmission determined through the steady rate of gain in mass with time. In the latter the only difference is that water replaces the desiccant and the water vapor transmission is obtained through mass loss with time. In both, the surrounding environment is usually 50% RH such that the vapor pressure difference is nominally the same for each set of so-called "service conditions." In North America the most widely used and accepted standard test, particularly for building materials, is ASTM E 96.

There are, in addition, two other standard methods available. These are ASTM Test Method for Water Vapor Transmission Rate of Sheet Materials Using a Rapid Technique for Dynamic Measurement (E 398) and ASTM Test Method for Water Vapor Transmission of Flexible Barrier Materials Using an Infrared Detection Technique (F 372). Each involves the dynamic evaluation of water vapor transmission between a "dry cell" of low RH and a "wet cell" of high RH by means of a specific piece of equipment. In the former, the change in electrical resistance is used to measure mass gain, while the latter involves change in infrared transmission. In general, these are used on thin films and sheet materials used particularly for packaging. However, in some cases they are used for building materials, but conversion factors are necessary to relate such data to that obtained by the standard E 96 gravimetric procedures.

Water vapor transmission characteristics of a material are complex and the permeability can be a function of both length, temperature, and relative humidity. Thus, the test method provides only an average or "spot" value

$$\mu_{av} = \int_{p_1}^{p_2} \frac{\mu}{(p_1 - p_2)}\, dP$$

applicable to the particular path length and assuming independence of temperatures and vapor pressure.

There is therefore no reason to expect that results on the same material by the two methods should be the same. As shown in Fig. 1 for a typical porous material at a particular temperature, the permeability of a material increases gradually at low RH levels but at much faster rates as the RH level increases. Thus the average permeability, μ_d, for the dry cup conditions is represented by the area under the curve between the 0 and 50% RH conditions. Similarly, that for the wet cup μ_w is the area between 50 and 100%. Thus μ_w is always higher than μ_d as will be seen in the data presented later.

It can be seen that for any one material many such individual tests would be required in order to develop permeability values to cover a full range of temperature and relative humidity conditions such as those experienced in buildings, especially if a significant effect of thickness is also present. It must be realized also that these wet and dry cup methods are "steady state" and are never representative of the transient conditions experienced in a building.

The differences between the two conditions can be quite significant for some materials. Thus it must be recognized that any comparison of data for a material should only be undertaken using values obtained by the same method. Furthermore, in choosing a material for a particular building application, the appropriate permeability to be used is that obtained under the set of service conditions most closely representing those of the application.

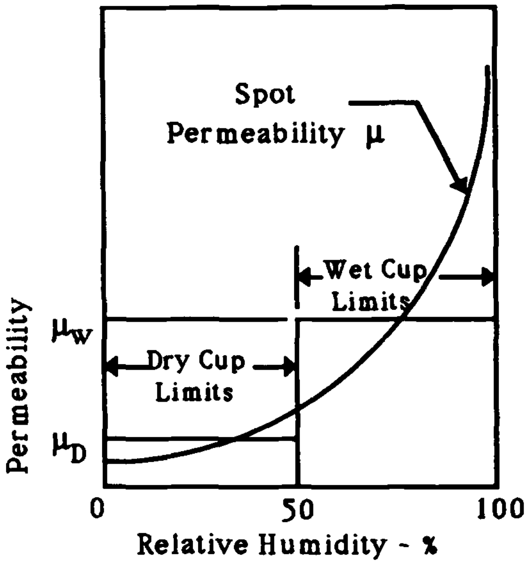

FIG. 1—Typical relationship between dry- and wet-cup methods and spot permeability for many building materials (schematic representation).

The above factors relate to specific limitations based on the behavior of inhomogeneous material and the physics of moisture transfer. However, in examining the literature on test methodology and specifically some recently obtained limited information on interlaboratory (or round-robin) comparisons by E 96 or its European counterpart [4], it is found that very large differences can exist in measured water vapor transmission data for the materials that were examined. Method E 96, for example, contains estimates of probable levels of uncertainty due to a number of factors. These estimates differ depending on the individual procedure and on the type of material retarder and its thickness. In general, the maximum errors (worst case) due to a combination of known factors are estimated to be the order of ±25 to 30% while ±10% is considered an acceptable norm. However, in some of the earlier measurements the results indicated that uncertainties of the order of ten times and greater than the worst case value were not uncommon.

The method appears to be very operator dependent. In addition, both the choice of the cup form used and particularly the method of sealing the specimen to the cup have major influences on the measurement. More standardization and less operator choice on these two apparently vital parameters is therefore necessary. In fact, there is general consensus that ASTM E 96 and similar methods used elsewhere need a thorough revision with attention paid specifically to specimen assembly, choice of temperature, and humidity conditions and the subsequent evaluation and interpretation of the results.

Some revisions have been made to the method recently in an attempt to provide the operator with more specific directions. In addition, several candidate reference materials covering a range of permeabilities have been identified. The results of an interlaboratory comparison of measurements by the new technique as five materials are shown in Table 4. These results are encouraging and show some improvement due to the tightening of the specifications, but more work is still required on the method.

Some research directed towards improved methodology is ongoing in North America and Europe. For example, at the National Research Council in Canada, attempts are being made currently by Kumaran and his colleagues [5] to combine the two cup procedures into a single one using two cups in a controlled environmental temperature for studies on fibrous and other thermal insulations. In addition, the wet cup is placed on a heating unit while a cold plate is placed over the dry cup. These modifications have been added to make sure the temperature and vapor pressure gradients are in the same direction.

At the University of Lund in Sweden, studies of moisture permeability materials, especially of concretes in high-moisture conditions, are being carried out [6]. One end of a core specimen is placed in water or in a 100% RH environment and the other end in an impermeable box containing an environment held at a constant RH using a saturated solution of an appropriate salt contained in a cup which is weighed at regular intervals. Tubes placed in holes drilled in the core at several positions along its length provide a means to measure the relative humidity in the specimen at any time. The com-

TABLE 4—Precision results from interlaboratory testing according to E 96.

DESICCANT METHOD AT 23°C

Material	Thickness, mm	WVT (Mean), Perm	Repeatability[a]			Reproducibility[a]		
			S	CV%	LSD	S	CV%	LSD
A	0.025	0.606	0.0166	2.70	0.047	0.098	15.0	0.278
B	0.140	0.0129	0.0028	22.1	0.008	0.0055	42.6	0.016
C	12.7	0.0613	0.0044	7.22	0.012	0.0185	30.6	0.052
D	25.4	0.783	0.0259	3.30	0.073	0.0613	7.8	0.174
E	0.356	0.0461	0.0023	4.99	0.007	0.0054	11.7	0.015

WATER METHOD AT 23°C

Material	Thickness, mm	WVT (Mean), Perm	Repeatability[a]			Reproducibility[a]		
			S	CV%	LSD	S	CV%	LSD
A	0.025	0.715	0.0134	1.95	0.039	0.156	21.9	0.44
B	0.140	0.0157	0.0022	13.8	0.0062	0.0021	19.4	0.006
C	12.7	0.097	0.0055	5.7	0.016	0.0195	20.9	0.055
D	25.4	1.04	0.0192	1.8	0.054	0.217	20.9	0.62
E	0.356	0.0594	0.0034	5.7	0.010	0.0082	13.8	0.023

[a] For this data,
S = Standard deviation.
CV = Percent coefficient of variation (S × 100/mean).
LSD = Least significant difference between two individual test results based on a 95% confidence level = $2\sqrt{2}S$.
Report was issued in perm units. To convert: 1 perm = 57.2 $ng/m^2 \cdot s \cdot Pa$.

bination of mass change and relative humidity provides moisture permeability values and their dependence on humidity.

It is also unfortunate that an adequate range of so-called reference materials is not yet available to enable workers to check their individual techniques. In the United States, Mylar, the low-permeability standard reference material which could be utilized to check both wet and dry cup techniques from 21 to 27°C and 50% RH, is no longer available. However, a cooperative test program is currently ongoing to develop at least three materials of varying permeabilities. Once established, these should enable improved measurements to be made such that published values by any technique can be viewed with more reliance.

Equilibrium Moisture Content

Although no standard test method has been developed, essentially all absorption information is obtained using one form of a steady state isothermal technique under either absorption or desorption conditions as it picks up or loses moisture. The specimen is placed in an environmental chamber maintained at constant temperature/constant humidity conditions and allowed to attain an equilibrium mass for a set of conditions. In general, the temperature remains unchanged while the relative humidity is varied. The results of these measurements at the various humidity conditions are reported as sorption isotherms. Currently work is ongoing both in the United States and Germany to extend this concept to undertaking measurements under temperature/humidity gradients covering a broad range of conditions of both parameters. The work at the University of Minnesota [*7*] is encouraging since the apparatus has recently been commissioned for tests covering broad temperature and moisture gradient parameters. This followed an extensive series of verification tests undertaken on a selected particle board material having known "steady state" permeance properties. Very good agreement was obtained (<4%) between the values obtained using this technique and the standard E 96 method.

In another area of dynamic moisture tests, after an initial study [*8*] further investigations are continuing in Canada and the United States under the auspices of ASHRAE to develop data under simulated conditions representing those of typical daily air conditioning cycles. For these measurements, moisture gain is evaluated by including load cells in the environmental chamber to evaluate mass changes as a function of time as the temperature and relative humidity of the chamber are changed.

This work includes attempts to develop criteria for a standard test method while also adding to the database. In addition, the effects of the response of the environmental chamber itself to the changing conditions is also being investigated.

DATA

It is a somewhat formidable task to provide a collection of specific or representative values for water vapor transmission and equilibrium moisture contents for building materials since so many types and combinations are involved. To compound the problem the reported data are often highly variable due to materials inhomogenities, the many and varied parameters influencing performance, the problems associated with a measurement technique, and the lack of a standard procedure. In general, to obtain a specific value for a particular material, one must either rely on the manufacturer or supplier or undertake a direct measurement to provide the information.

It is possible only to provide some comparative information on the typical performance of different types and forms of materials where appropriate or available for some composites and materials systems typical for building applications.

Permeability/Permeance

The major source of collected information for those properties are:

- the *ASHRAE Handbook of Fundamentals* [*1*]
- the Computerized Material Moisture Property Data Base developed by the Florida Solar Energy Center [9]
- summaries of the various investigations carried out by Tveit at the Norwegian Building Research Institute [*10*]
- a critical evaluation of different experimental data by Pragnell [*11*]
- recent initial data from a study by Burch and colleagues at NIST [*12*]

Following an examination of this information base, Table 5 has been prepared. This contains typical values of permeance and resistance of various materials types for appropriate thicknesses. In addition, values for permeability and resistivity are included where appropriate for a thickness range. Values specifically measured by the E 96 different cup methods are identified. However, the other values have been determined by different methods deemed at the time to be more appropriate for the material type or thickness used.

The computerized database contains some very useful information on a variety of materials and products and their combinations. A number of these are very specific to particular products. However, they are very useful in illustrating relative overall performance including effects of holes and imperfections, etc. The data are presented in the form of a water vapor diffusion resistance factor, Δ. If required, a water vapor diffusivity, δ, can be evaluated using the following relationships

$$\delta = D_A/\Delta \qquad D_A = 0.083(1000/p)(T/273)^{1.81}$$

where D_A is the molecular diffusion of water vapor in air, T is the absolute, and p is the barometric pressure in Pa.

The report values are representative for a very limited temperature range within the limit of the test methods. Tviet undertook a somewhat comprehensive study of the effects of relative humidity on water vapor transmission. This covered a range of typical building materials, including thermal insulation and some wood-based materials. His results are published in the form of graphs of collected results for specific materials types. In general, the behavior follows the typical curve form shown schematically in Fig. 1. In addition, they have been included in the referenced database in the form of a regression equation involving four coefficients.

The results of the most recent and ongoing study by Burch and colleagues are of specific interest. The initial study covered only six common wood-based materials and products. The results indicated that the permeance values for some similar or corresponding products measured by other workers were in reasonably good agreement at relative humidity levels below 50%. However, for some specimens, quite significant increases in value were found as the humidity increased to much higher levels. These results indicate that it is unwise to accept a single value for all conditions. Other more homogeneous materials are now being evaluated, and it will be interesting to see if similar trends exist.

Equilibrium Moisture Content

The corresponding major sources for this information include:

- the first three mentioned under Permeability/Permeance
- a catalogue of sorption isotherms developed by Hansen at the Technical University of Denmark (now available as a database on a PC computer floppy disc) [*13*]
- results of investigations by Ahlgren at University of Lund in Sweden [*14*]
- recent initial data from a study by Richards and colleagues at NIST [*15*]

It should be mentioned that the two databases use different equations for their curve fits as does a third database from Lawrence Berkeley Laboratories that is being developed specifically for wood.

Table 6 contains values selected from the Florida Solar Energy Center database as an illustration. The materials selected are those for which corresponding data are available for water vapor transmission over the same humidity range. These data, similar to those for permeability, are in the form of a regression equation

$$U = a\phi^b + c\phi^d$$

where U is dry moisture content (kg/kg) and ϕ is relative humidity (0 to 1).

Finally, Table 7 contains some of the initial data obtained from the dynamic tests carried out on 15 materials mentioned earlier [*8*]. Table 7a provides details of the exposure conditions chosen for the first series of tests. Table 7b contains the results of the mass changes and relative differences for the various cycles and steady exposure tests. The letters in the last column represent a ranking of the materials based on fitting the data of Table 7b with an equation forced through 0 kg/m^2 at 0% RH. The authors discuss the ranking in terms of their being high (H), low (L), and moderate (M) moisture load materials in order to assist in the quantification of latent cooling loads.

SUMMARY

Building materials other than thermal insulations and wood-based materials have been reviewed with regard to the factors relating to and affecting their moisture pickup and transmission characteristics. While sufficient materials of different types can be chosen from the many available in order to fulfill necessary functions in a correctly designed and constructed building, significant problems appear to exist. New or improved standard test methods are required for many properties and characteristics, especially under more representative conditions experienced by buildings.

Where sufficient data are available, relevant data are presented for adequate comparison and discussion. However, it is clear that more information is required for certain material properties under more representative conditions. A broad matrix of overall requirements can be suggested from which decisions on the most important parameters can be drawn

TABLE 5—Typical water vapor transmission characteristics for some common building materials.

Material	Thickness, mm	Permeance, ng/s·m^2·Pa	Resistance, TPa·m^2·s/kg	Permeability, ng/s·m·Pa	Resistivity, TPa·m·s/kg
AIR (STILL)				174	0.0057
BOARD					
Acrylic (glass fiber reinforced)	1.4	6.9	0.145		
Asbestos Cement	3	229 to 458	0.0035 to 0.0017		
Asbestos Cement (oil base finish)		17 to 29	0.052 to 0.0034		
Compressed Strawboard					0.147 to 0.046
Corkboard	25		0.0069 to 0.0025		
Fiberboard	12		0.0008 to 0.0004		
Gypsum Wall	9.5	2860	0.00035		
Gypsum Sheathing (asphalt impreg.)	13		29		
Hardboard	3.2	630	0.0016		
Hardboard (tempered)	3.2	290	0.0034		
Plasterboard	10		0.0005 to 0.00035		
Polyester (glass fiber reinforced)	1.2	2.9	0.345		
Strawboard	50		0.0079 to 0.0039		
Structural Insulating (sheathing)				29 to 73	0.035 to 0.014
Structural Insulating (interior uncoated)	13	2860 to 5150	0.00035 to 0.00019		
BRICK					
Boom					0.17 to 0.09
Brickwork	100		0.025 to 0.017		
Building (1560)†					0.04
Masonry	100		0.022 to 0.017		
Perforated (1100)					0.037
Solid Sand Lime (1770)					0.107
CONCRETES					
Concrete (various)					0.44 to 0.03
1.2.4 Mix				4.7	0.21
Aerated (1350 to 730)					0.053 to 0.040
Block (cored, limestone aggregate)	200	137	0.0072		
Cellular					0.047 to 0.034
Expanded Clay (1350)					0.16
Natural Aggregate (2130)					0.196
Pumice (880 to 1100)					0.070 to 0.053
Tile (glazed masonry)	100	6.9	0.14		
FILMS AND FOILS					
Aluminum	0.025	0	0.345		
Al on Paper	0.009	2.9	0.874		
Cellulose Acetate	0.25	263	0.0038		
Cellulose Acetate	3.2	18			
Mylar	0.025		0.025d, w.		
Polyethylene	0.25 to 0.05	1.7 to 9.1	0.59 to 0.110		
Polyvinylchloride	0.1		0.026		
Polyester	0.19 to 0.025	4.6 to 42	0.22 to 0.042		
PAINTS AND COATINGS					
Exterior Acrylic (1 coat)	0.004††	313	0.0032		
Primer-Sealer (1 coat)	0.003††	360	0.0028		
Vapor Retarder (1 coat)	0.007††	26	0.038		
Vinyl Acrylic Enamel (1 coat)	0.004††	491	0.002		
Al Varnish on Wood (2 coats)		17 to 29	0.059 to 0.034		
Asphalt Paint on Wood (2 coats)		23	0.043		
Enamel on Smooth Plaster (2 coats)		29 to 86	0.034 to 0.012		
Flat on Insulation Board (2 coats)		229	0.0044		
Primer & Sealer on Insulation Board (2 coats)		20 to 51	0.05 to 0.02		
Water Emulsion on Insulation Board (2 coats)		1716 to 4863	0.00058 to 0.0002		
Exterior Lead and Oil on Wood (2 coats)		17 to 57	0.0059 to 0.017		
Exterior Lead Zinc Oxide on Wood (3 coats)		51	0.02		
Asphalt Cut Back Mastic	4.8 to 1.6††	8.0	∞ to 0.125		
Asphalt Hot Melt	[0.6 & 1.1]†††	2.9 & 5.7	0.34 & 0.175		
Styrene-Butadiene Latex Coating	[0.6]	629	0.0016		
Polyvinyl Acetate Latex	[1.2]	315	0.0032		
Chlorosulphonated Polyethylene Mastic	[1.1]	97	0.010		
PAPERS					
Asphalt Coated Insulation Backing	[0.30]	240w/23d	0.0042w/0.043d		
Asphalt Felt	[0.73]	320w/57d	0.0031w/0.017d		
Asphalt Infused Sheathing			0.0006 to 0.0027		
Asphalt Saturated, Coated	[0.42]	34w/14d	0.029w/0.071d		
Asphalt Saturated, Uncoated	[0.21]	1160w/190d	0.00086w/0.0053d		
Bitumen Impregnated			0.011		
Kraft-Single			0.00022		
Kraft-Single (double)	[0.16]	2400w/1170d	0.0004w/0.0009d		

TABLE 5—Typical water vapor transmission characteristics for some common building materials (*continued*).

Material	Thickness, mm	Permeance, ng/s·m²·Pa	Resistance, TPa·m²·s/kg	Permeability, ng/s·m·Pa	Resistivity, TPa·m·s·/kg
Kraft 3 Ply			0.00050		
Kraft 5 Ply			0.00062		
Kraft, Asphalt Laminated	[0.33]	103w/17d	0.0097w/0.059d		
Laminated Paper			0.042		
Oilcloth			0.018		
Roofing Felts			0.1 to 0.0044		
Saturated and Coated Roofing	[3.18]	14w/2.9d	0.071w/0.34d		
Sheathing		130	0.008		
Sheathing, Tar Infused			0.0006 to 0.0027		
Tar Felt	[0.68]	1040w/230d	0.001w/0.0043d		
Waxed Medium Weight			0.109 to 0.194		
Waxed Heavy Weight			0.020 to 0.154		
PLASTER					
Plaster					0.060
On Gypsum Lath	22	1140	0.00085		
On Metal Lath	19	860	0.0012		
On Wood Lath	25	630	0.0016		
RENDERING					
Cement Render					0.1
"Haller" Render (2000)			0.0085		
Lime Render (2000)			0.002		
Lime-Cement (2000)			0.0065		
STONE AND TILE					
Massangis Stone					0.43 (ave)
Savonnieres Stone					0.15 (ave)
Clay Tile			0.0015w		
Vitreous Ceramic Tile			0.043w/1.7d		
THERMAL INSULATIONS					
Ebonite, Expanded (64)	25		0.33		
Ebonite, Expanded (various)					60 to 11
Fibreboard, Insulating	7		0.00015		
Fibreboard, Insulating	20		0.0004		
Glass, Celluar				0d	∞
Mineral fiber				245w	0.006
Phenolic Foam, Unfaced				38	0.26
Polystyrene, Expanded				2.9 to 84d	0.34 to 0.12
Polystyrene, Expanded Beadboard (16)	25		0.0067		
Polystyrene, Expanded Beadboard (24)	25		0.0105		
Polystyrene, Extruded				1.7d	0.59
Polystyrene, Extruded (32)	25		0.033		
Polystyrene, Extruded (40)	25		0.033		
Polyurethane, Foam				0.58 to 2.3d	1.72 to 0.43
Polyurethane, Foam (31)	25		0.015d,w		
Polyurethane, Foam (Closed Cell)					1
Polyurethane, Foam (Open Cell)					0.029
Polyurethane, Foam, Rigid (32)	25		0.009		
Polyvinylchloride, Expanded (40)	25		0.020		
Polyvinylchloride, Expanded (72)	25		0.033		
Rubber Road, Synthetic, Flexible				0.029d	34 to 4.6
Ureaformaldehyde, Foam (16)	25		0.0006		
Woodwool, Loose				0.04 to 0.015	
Woodwool, Board				0.042 to 0.014	
Woodwool, Board	25		0.0003		
WOODS					
Pine	12		5.9 to 10		
Pine	25		12.5		
Plywood					0.5 to 0.14
Plywood, Fir, Interior Glue	6.4		0.009 to 0.003		
Plywood, Fir, Exterior Glue	6.4		0.025 to 0.038		
Sugar Pine				0.58 to 7.8	1.72 to 0.13
Timber, Air Dry					0.07 to 0.046
Timber, Wet					1 to 0.125

NOTE:

( )† = Value in parentheses is density in kg/m^3.

†† = Dry thickness.

[ ]††† = Value in parentheses is mass/unit area in kg/m^2.

d = Dry cup method.

w = Wet cup method.

TABLE 6—Equilibrium isotherms for selected building materials.

Material	Temperature, °C	Density, kg/m^3	Experiment[a]	Regression Constant			
				a	*b*	*c*	*d*
Brick**	5–45	1720	A	0.003744	22.18477	0.002230	0.255390
	5–45	1840	A	0.002792	0.171445	0.010522	40.664750
Brick, Parnell	5	N/A	A	0.021053	1.017150	0.022365	11.285520
			D	0.016666	8.512250	0.025856	0.440512
	15	N/A	A	0.012472	10.991360	0.024344	0.827079
			D	0.028790	0.372192	0.011002	8.601620
	25	N/A	A	0.033034	0.980717	0.026450	12.295280
			D	0.034723	0.641719	0.026817	10.622700
Brick, Red	0–35	1700	A	0.000467	0.316240	0.004855	3.902922
Brick, Tripoli	0–35	480	A	0.041267	8.227257	0.029995	1.294379
Brick, Veneer	5	N/A	A	0.031400	1.003493	0.056273	11.495130
			D	0.062256	9.819442	0.044448	0.588723
	15	N/A	A	0.040598	0.994565	0.064208	11.514430
			D	0.073844	10.107640	0.048598	0.631752
	25	N/A	A	0.031499	0.898868	0.026590	10.757700
			D	0.027000	9.634520	0.033587	0.589986
Cellulose cement, asbestos	5	N/A	A	0.096110	11.147460	0.073510	1.006053
			D	0.094228	0.646410	0.073170	9.301769
	15	N/A	A	0.086370	10.748620	0.085423	0.941907
			D	0.111499	0.640592	0.066360	9.385046
Cement, sand mortar	20	N/A	A	0.009190	0.620995	0.007892	3.478130
Concrete block	5	N/A	A	0.025650	1.056735	0.032420	11.775380
			D	0.031797	0.420070	0.027364	8.172718
	15	N/A	A	0.023947	10.498800	0.037525	0.849945
			D	0.046040	0.380106	0.022665	7.882967
	25	N/A	A	0.016777	10.437430	0.022899	0.859457
			D	0.010940	9.342740	0.026754	0.565665
Cellular concrete**	5–45	460	A	0.061126	11.952830	0.009406	0.182729
	5–45	510	A	0.015204	0.330670	0.040595	8.402223
Concrete, gypsum slag	20	N/A	A	0.109930	0.756610	0.000000	0.000000
Concrete, slag	0	920	A	0.015743	6.435342	0.020692	0.455288
	35	920	A	0.011303	9.171323	0.023003	0.878349
Cork	5–45	155	A	0.008486	0.368864	0.023822	5.623263
Building felt, rag**	5–45	500	A	0.155030	8.918695	0.051232	0.671865
Building felt, rag asphalt impregnated.**	5–45	920	A	0.038228	0.604026	0.101920	8.058596
Building paper, cellulose**	5	600	A	0.174677	5.504476	0.069182	0.461679
	25	600	A	0.115488	5.794530	0.074729	0.655132
	45	600	A	0.064367	0.695687	0.091640	4.865170
Expanded polystyrene**	5–45	17.2	A	0.000380	9.493858	0.000109	0.088410
Fiberglass (batts)	5	N/A	A	0.047027	10.685760	0.021958	0.833640
			D	0.022563	0.524178	0.048903	10.066120
	15	N/A	A	0.037590	0.787187	0.024539	9.990723
			D	0.027127	9.186606	0.047953	0.631495
	25	N/A	A	0.015703	12.318370	0.058579	0.835330
			D	0.024384	7.171313	0.047110	0.363655
Glass fibers							
$d = 6\ \mu m;\ \tau = 5.7\%$	50	20	A	0.009220	5.995554	0.002562	1.259258
$d = 5\ \mu m;\ \tau = 9.7\%$	50	70	A	0.005782	2.037040	0.003840	11.324680
$d = 6\ \mu m;\ \tau = 0.0\%$	50	100	A	0.064990	26.158060	0.002017	2.207223
$d = 6\ \mu m;\ \tau = 12.8\%$	50	100	A	0.005940	0.832067	0.007492	7.734360
$d = 12\ \mu m;\ \tau = 11.0\%$	50	121	A	0.001610	7.092125	0.007607	1.701209
Macerated paper, ammonium	15	N/A	A	1.724364	16.231570	0.330080	1.548526
Sulphate treated			D	1.647258	14.051750	0.349080	1.066276
Macerated paper, borax or	15	N/A	A	0.610468	11.060000	0.295197	0.925237
Boric acid treated			D	0.265016	0.629843	0.708032	10.971130
Mineral wool board	5–45	175	A	0.007836	0.459843	0.012023	11.362020
Mineral wool board	5–45	400	A	0.013022	14.113446	0.005810	0.490509
Polyester foam	5–45	55.2	A	0.000400	11.598490	0.002020	1.054990
Polyether foam	5–45	26.6	A	0.000230	1.080185	0.000235	1.606183
Polyester bonded fiberglass	5–45	165	A	0.001573	0.442072	0.020743	7.829979
Rockwool batt	5–45	100	A	0.002713	6.401205	0.001300	0.183926
Urea formaldehyde	15	N/A	A	0.168378	10.906000	0.257984	0.930105
			D	0.124615	10.318120	0.329326	0.685490
Wool felt	5–45	200	A	0.021749	0.751252	0.038275	5.774993
Wool felt	5–45	300	A	0.037812	0.621772	0.052028	7.767620
Leather	5	940	A	0.214082	0.354347	0.268030	6.811124
	25	940	A	0.203852	0.408090	0.197957	6.898870
	45	940	A	0.122817	4.128172	0.172875	0.350514
Linoleum**	5	2.1	A	0.047436	0.351589	0.065578	4.771276
	25	2.1	A	0.052246	0.546057	0.074477	7.927515
	45	2.1	A	0.045499	0.654287	0.055819	6.076293

TABLE 6—Equilibrium isotherms for selected building materials (*continued*).

Material	Temperature, °C	Density, kg/m^3	Experiment[a]	Regression Constant			
				a	*b*	*c*	*d*
Newsprint	N/A	N/A	A	0.062463	4.516385	0.070962	0.488255
Writing paper	N/A	N/A	A	0.091019	0.481886	0.081807	3.626582
Fiberboard (customwood)	15	N/A	A	0.074068	10.711130	0.140360	0.845134
			D	0.064680	9.303152	0.167399	0.570157
Fiberboard flooring grade	15	N/A	A	0.039886	12.824160	0.173809	0.818840
			D	0.038640	10.917420	0.181065	0.578242
Hardboard standard	15	N/A	A	0.054039	11.113080	0.124834	0.864770
			D	0.040177	11.140190	0.151654	0.686398
Hardboard (weatherside)	15	N/A	A	0.118229	0.861080	0.035555	12.091490
			D	0.034932	10.728560	0.125596	0.657796
Particleboard, medium density	15	N/A	A	0.172828	0.871116	0.106296	10.465220
			D	0.111049	8.704210	0.184115	0.589516
Particleboard, flooring grade	15	N/A	A	0.061760	11.416090	0.168788	0.853995
			D	0.184835	0.612104	0.061449	9.845212
Wood fiberboard, oil impregnated	5	1040	A	0.122333	0.480190	0.223703	12.711260
	25	1040	A	0.106470	8.282250	0.101024	0.394569
	45	1040	A	0.093349	0.436143	0.067794	6.437566
Cement asbestos board**	5–45	775	A	0.068560	10.145370	0.006334	0.203290
Fibrous plasterboard	5	N/A	A	0.012815	1.099860	0.165694	0.001642
			D	0.014144	8.186860	0.007130	0.353847
	15	N/A	A	0.071556	0.789930	0.070008	1.082794
			D	0.032028	5.042665	0.075389	0.088672
	25	N/A	A	0.052222	1.133502	0.079102	0.800598
			D	0.027129	4.951737	0.068760	0.075860
Gypsum plaster (without paper)	5	N/A	A	0.051696	0.078536	0.051687	0.066278
			D	0.010779	6.413036	0.018440	0.270059
	15	N/A	A	0.089808	0.910320	0.005713	24.171370
			D	0.029796	0.172585	0.029790	0.131583
	25	N/A	A	0.005670	24.378500	0.090078	0.913910
			D	0.026176	4.987109	0.063273	0.079312
Gypsum plaster (with paper)	5	N/A	A	0.027987	1.147282	0.085804	0.006580
			D	0.023536	7.570097	0.23213	0.346970
	15	N/A	A	0.048344	1.147645	0.049887	0.809267
			D	0.037363	5.560157	0.055749	0.125103
	25	N/A	A	0.052940	1.131866	0.054927	0.801622
			D	0.030856	5.307925	0.055687	0.104699
Plaster board	5–45	730	A	0.009620	0.202660	0.196697	11.476600
Limestone	0–35	1300	A	0.001990	5.917070	0.001715	1.772220
Cotton	20	N/A	A	0.121512	5.142645	0.075312	0.378559
Cotton (Absorbent)	N/A	N/A	A	0.143152	0.690200	0.143768	0.690754
Wool (Australian Merino)	N/A	N/A	A	0.178457	0.583749	0.095156	3.517180
Viscose nitrocellulose	N/A	N/A	A	0.082018	2.281830	0.100294	0.393952
Wood, Abachi	5	370	A	0.075048	4.242048	0.051257	0.476255
	25	370	A	0.050703	0.584309	0.059790	4.702588
	45	370	A	0.047384	0.652608	0.054343	4.835848
Wood, Balsa	5	125	A	0.016722	0.489309	0.030714	5.690960
	25	125	A	0.014022	0.503004	0.027242	5.852653
	45	125	A	0.013965	0.655414	0.033013	8.259300
Wood, Doussie	5	660	A	0.072679	0.281146	0.070776	2.664116
	25	660	A	0.067990	3.441290	0.072336	0.370192
	45	660	A	0.057296	2.957994	0.064834	0.371123
Wood, Pine**	5	530	A	0.072922	0.362360	0.087706	3.419070
	25	530	A	0.075279	0.473989	0.088280	5.094006
	45	530	A	0.075908	3.832880	0.061398	0.407650
Wood, pinus radiata untreated	15	N/A	A	0.087617	11.071180	0.191523	0.885963
			D	0.209907	0.734253	0.087260	10.255360
Wood, pinus radiata boric treated	15	N/A	A	0.105062	10.755220	0.198055	0.882426
			D	0.107040	9.772727	0.210712	0.718040
Wood particle board	5	560	A	0.195618	9.349666	0.071074	0.479738
	25	560	A	0.064765	0.516527	0.118435	8.472525
	45	560	A	0.097213	8.386842	0.059689	0.552162
Wood fibre board**	5	215	A	0.063235	8.896166	0.031560	0.437160
	25	215	A	0.042429	7.153105	0.027772	0.462162
	45	215	A	0.024302	0.457866	0.036924	7.118702
Wood fibre board	5	610	A	0.077594	0.515816	0.130736	9.915459
	25	610	A	0.076060	9.480125	0.072070	0.577840
	45	610	A	0.091168	10.538700	0.065759	0.636717
Wood fibre board	5	870	A	0.341020	15.426120	0.120110	0.484537
	25	870	A	0.109178	7.646888	0.102728	0.464374
	45	870	A	0.058039	4.792619	0.089273	0.493884

TABLE 6—Equilibrium isotherms for selected building materials (*continued*).

Material	Temperature, °C	Density, kg/m^3	Experiment[a]	Regression Constant			
				a	*b*	*c*	*d*
Wood fibre board	5	960	A	0.222922	8.532650	0.114930	0.407768
	25	960	A	0.105460	0.456258	0.120703	7.037468
	45	960	A	0.050020	3.664755	0.093789	0.459456
Wood fibre board, 6% asphalt impregnated**	5–45	280	A	0.045129	6.820820	0.030594	0.370256
Wood fiberboard, 6% asphalt impregnated	5	860	A	0.171722	7.877448	0.109843	0.529206
	25	860	A	0.109566	0.633299	0.112747	8.717624
	45	860	A	0.074648	6.204236	0.097166	0.676350
Wood fiberboard, 6% asphalt impregnated	5	960	A	0.334598	14.894890	0.119088	0.482093
	25	960	A	0.106248	0.477882	0.113566	11.542490
Wood, Spruce with vertical fibers	5	410	A	0.064266	0.476742	0.078134	5.556426
	25	410	A	0.065073	6.581450	0.060809	0.540779
	45	410	A	0.044383	0.461255	0.047097	3.410469
Wood, Spruce with horizontal fibers	5	450	A	0.075874	3.948554	0.069492	0.465295
	25	450	A	0.066900	0.550567	0.062213	4.273869
	45	450	A	0.058135	3.465735	0.053732	0.528938
Wood, Teak	5	600	A	0.067164	2.418370	0.056589	0.333554
	25	600	A	0.073147	4.013810	0.058984	0.414012
	45	600	A	0.064765	2.772287	0.043498	0.357033
Wood	0	N/A	A	0.138353	6.958823	0.161059	0.660522
	20	N/A	A	0.151862	0.727746	0.131848	6.866099
	40	N/A	A	0.132223	0.737857	0.133018	6.029177
Wood, timber average	N/A	N/A	A	0.151457	3.711355	0.125610	0.639215
Wood, pine pulp	N/A	N/A	A	0.125643	0.626416	0.000000	0.000000
Wood, slab	N/A	N/A	A	0.156522	0.944302	0.000000	0.000000

*A—absorption; D—desorption.

**In terms of volumetric moisture content, all others in terms of dry weight.

TABLE 7a—Nominal exposure conditions at 24°C.

Exposure No.	Type (%RH)	Relative Humidity, %	Cycle Time, Days	Exposure
1	Steady	45	Continuous	8
2	Dynamic	40	11	28
	Cycle A	90	13	
3	Steady	90	Continuous	7
4	Dynamic	90	13	14
	Cycle B	40	11	
5	Steady	75	Continuous	11
6	Dynamic	75	13	15
	Cycle C	40	11	
7	Steady	60	Continuous	15

and appropriate test methods developed. Limitations in current test methodology, especially for water vapor transmission, reinforce the requirement for improved evaluation techniques.

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TABLE 7b—Summary of dynamic and steady exposure tests at 24°C.

Material	Dynamic Exposure, Mass Loss, kg/m^2 cycle[b]			Steady Exposure, Moisture Difference, kg/m^2[a] Exposure[b]			Ranking
	A 52%[b]	B 47%	C 36%	3	5	7	
2 × 10 dimension lumber	0.072	0.067	0.044	0.39	0.28	0.061	E
Tongue & groved plywood	0.054	0.053	0.035	0.43	0.39	0.22	K
Reinforced concrete	0.052	0.034	0.029	−0.08	−0.24	−0.53	M
Concrete block	0.069	0.067	0.059	0.51	0.41	0.15	D
Painted gypsum board	0.083	0.055	0.037	0.088	0.050	0.020	F
Prefinished plywood panel	0.053	0.051	0.040	0.20	0.14	0.029	J
Prefinished parquet floor	0.057	0.057	0.047	0.38	0.34	0.12	H
Vinyl floor tile	0.015	0.015	0.016	0.20	0.23	0.15	O
Acoustical ceiling tile	0.064	0.055	0.036	0.060	0.032	0.000	I
Carpet-on-pad	0.079	0.080	0.053	0.47	0.43	0.21	C
Wool cushion	0.066	0.064	0.042	0.078	0.052	0.015	G
Cotton cushion	0.049	0.046	0.032	0.053	0.040	0.013	L
Polyester/cotton drapery	0.020	0.020	0.015	0.019	0.013	0.004	N
Newspaper	0.13	0.14	0.11	0.19	0.13	0.008	A
Letters	0.093	0.087	0.086	0.15	0.19	0.061	B

[a] Relative to exposure 1 (see Table 7a).

[b] Relative humidity difference.

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4

Effects of Moisture on the Thermal Performance of Insulating Materials

by Catherine Langlais,[1] *Anne Silberstein,*[1] *and Per Ingvar Sandberg*[2]

PREDICTING THE THERMAL PERFORMANCE of insulating materials in the presence of moisture is a complex problem. It is possible to define the apparent thermal conductivity of a moist insulant, but measuring this conductivity is very difficult because moisture flow and phase changes also affect heat transfer.

On the other hand, it is important to distinguish carefully between moisture effects in service and those in laboratory conditions (during a test). Two options are possible:

1. Study the fundamentals of heat and mass transfer in porous media and solve the complete set of equations to evaluate the effects of moisture.
2. Choose a more pragmatic approach and use some kind of correction to be applied to the dry thermal conductivity.

In this chapter, we discuss these two options to show that if, in theory, Option 1 should be recommended, in practice the most feasible way of handling this problem is Option 2. Enough information is given to allow the reader to choose between the two approaches—the basic equations of heat and mass transfer are described. A more qualitative description of the different effects of moisture on overall thermal performance is provided, and guidelines are given for estimating "design values" representative of service conditions.

Moisture is significant among the parameters that may affect the thermal performance of insulating materials. Such phenomena as water vapor adsorption, condensation (due to water vapor diffusion or air leakage), or even accidental water infiltration may alter thermal performance. Moisture can also affect aging, dimensional stability, and mechanical characteristics, which may indirectly influence the thermal performance of insulating materials. This aspect of the problem is studied in Chapter 3 of this manual. This chapter deals only with the effects of moisture on the effective thermal conductivity, around ambient temperature, of the main types of insulating materials: expanded and extruded polystyrenes, PVC and phenolic foams, polyurethane, mineral wool, cork, perlite, vermiculite, and aerated concrete.

After indicating essential facts on heat transfer through dry insulating materials, the different effects of moisture on overall thermal performance are described qualitatively. Then, after a short literature survey of existing simultaneous heat and mass transfer models and measurement techniques, we give the technical background necessary to understand in which conditions one can define the thermal conductivity of a wet insulating material. We then propose a test method, in laboratory conditions, to measure this "moist thermal conductivity" and give guidelines to determine the thermal performance of a wet insulant in real conditions of use. Finally, we report and comment on data found in the literature on various types of moist insulating products pertaining to both their dry and wet insulating properties.

HEAT TRANSFER MECHANISMS THROUGH DRY INSULATING MATERIALS

The Three Heat Transfer Modes

Generally speaking, three modes of heat transfer occur simultaneously within a dry confined insulating material:

1. **Heat transfer by conduction** is the physical representation of Brownian motions, i.e. microscopic atomic vibrations (phonons) undergone by all *solid or gaseous bodies* as soon as the temperature is greater than 0 Kelvin.
2. **Heat transfer by natural convection** occurs in *a gaseous phase* submitted to a temperature gradient. It is the consequence of macroscopic particle displacements caused by a gradual change in density of the gas depending on its temperature.
3. **Heat transfer by radiation** is the consequence of the propagation of electromagnetic waves (photons) in the infrared range (1 to 50 μm). It takes place in *gases and in a vacuum.*

Fourier's Law

Fourier's law is the fundamental law for heat transfer by conduction. It establishes the proportionality between the density of heat flux, q (amount of heat going through the material per unit time and unit surface) and the temperature gradient, T, or temperature difference per unit thickness of material. The proportionality constant, called *thermal conductivity,* is an intrinsic physical property of the homogeneous material.

$$\vec{q} = -k \cdot \vec{\nabla} T \qquad (1)$$

One can also define the *thermal resistance* characteristic of the insulating capacity of a given product

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$$R = \frac{e}{k} \tag{2}$$

where e is the product's thickness.

Concept of Apparent Thermal Conductivity

A thermally insulating material, when submitted to a temperature difference between its parallel faces, must by definition maintain the heat losses across it to a given low level. According to Eq 2, this means that, for a given thickness, it must have a low thermal conductivity value.

An observation of the thermal conductivity values of readily available homogeneous materials (Table 1) shows the excellent position of gases such as air and freons. However, gases under a temperature gradient can easily be subjected to natural convection and are transparent to infrared radiations, both of which drastically increase the global heat transfer. To reduce it, one should therefore try to confine the gas in solid cells whose dimensions would be small enough to prevent the formation of any convective movements and to partly block the propagation of the radiation: this is accomplished in natural and man-made porous materials. These materials are thus heterogeneous, composed of two phases: a gas and a solid matrix.

As shown, Fourier's law of heat transfer is the main simple existing tool to determine the thermal resistance required to maintain the density of heat flux under a given level. But it makes the assumption of pure conduction, which breaks down in the case of the highly porous, semi-transparent materials discussed previously, where thermal radiation and under certain conditions convection contribute to a large extent to the heat transfer.

If one assumes that heat transfer across the material is the result of the contributions of conduction in the solid and fluid phases, radiation and convection, and that there is little or no interaction between the various modes of heat transfer, then

$$\vec{q}_T = \vec{q}_{cd} + \vec{q}_{cv} + \vec{q}_{rd} \tag{3}$$

where q_T, $q_{cd} = q_s + q_g$, q_{cv}, and q_{rd} are, respectively, the density of heat fluxes corresponding to the total conduction in the solid and gaseous phases and convection and radiation heat transfers.

If one further assumes that, for each mode of heat transfer (noted as subscript i), the density of heat flux across a layer of a porous body confined between infinite, parallel, and planar surfaces can be expressed as

$$\vec{q}_i = -k_i \cdot \vec{\nabla} T \tag{4}$$

one can then easily derive the relation

$$\vec{q}_T = -k^* \cdot \vec{\nabla} T \tag{5}$$

with

$$k^* = k_s + k_g + k_{cv} + k_{rd} \tag{6}$$

where k_s, k_g, k_{cv}, k_{rd} are, respectively, the solid conduction, gas conduction, and convective and radiative thermal conductivities. We see here the commonly used concept of "apparent" thermal conductivity, k^*, developed for heterogeneous materials, that takes these two additional modes of heat transfer into account.

In usual cases of application of the porous materials (i.e. ambient temperature range, $\Delta T < 50°C$, confined material), convection of the fluid phase within the product is entirely negligible. This is particularly the case in fibrous insulating materials where, as shown in Fig. 1, the measured apparent thermal conductivity can unambiguously be related to the contributions of the solid and gaseous conduction and of radiation.

TABLE 1—Thermal conductivity of various homogeneous materials at 20°C in W/mK. The numbers next to the material categories show the order of magnitude encountered in that category (from "Handbook of Chemistry and Physics," 66th ed).

Metals:	10^1–10^2	Liquids:	10^1
Silver	427	Water	0.6
Copper	398	Oil	0.2
Iron	80		
Antemony	24		
Dielectrics:	10^0–10^1	Gas:	10^{-2}
Ice	2.1	Air	0.024
SiO_2	12.6 6.7	CO_2	0.017
Glass	0.8–1.0	Freon	0.007

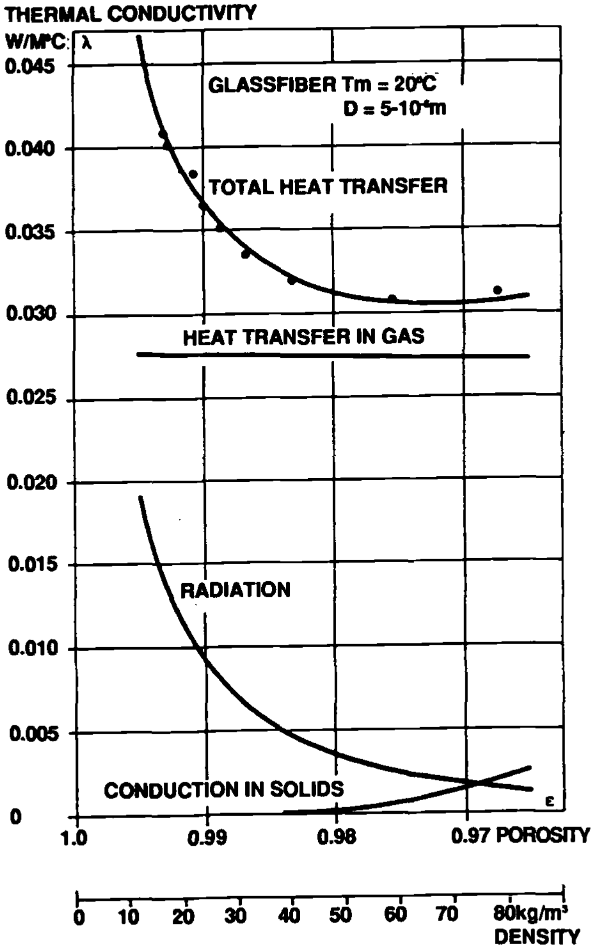


FIG. 1—Heat transfer mechanisms in a fibrous insulating material (from Ref *44*).

Some Data

The apparent thermal conductivity of insulating materials will obviously depend on the thermal conductivities of the two constituting phases, but due to the strong contribution of heat transfer modes other than conduction, it will also depend largely on the structure of the solid matrix and in particular on the material's density, pore sizes, and the fibers' diameters and arrangements.

Therefore, the data we report pertaining to dry insulating materials at ambient temperature (see Fig. 5, shown later in this chapter), tries to reflect these dependencies when available in the literature (we only cite the specific products used for subsequent measurement of wet thermal conductivity). In particular, there is a large scatter of the thermal conductivity values of most foams (UF, phenolic, PUR, XPS) that can most probably be attributed to aging of the products (not reported) and to a lesser extent to the type of gas used as a blowing agent.

CONTRIBUTION OF MOISTURE AND MOISTURE TRANSFER TO HEAT TRANSFER

Since water and ice have a much higher thermal conductivity than air or other gases in the pores of thermal insulation materials, a moist material has a higher thermal conductivity than a dry material. The moisture in the pores will short-circuit the insulation or act as parallel resistances, which reduces the thermal resistance. Many attempts have been made to quantify this effect by describing the material as a mixture of air–solid material–water and calculate the resulting thermal resistance. In most materials, however, the pore structure is so complicated that the agreement between calculated and measured values is poor.

Figure 2 shows the most important heat flows caused by a temperature gradient in a moist porous material:

1. Conduction in the solid material (1a) and in the (humid) air in the pores of the material (1b).
2. Conduction of water bound to the pore walls.
3. Evaporation and condensation within a pore or a local area. The moisture moves one way in the vapor phase and then back again in the liquid phase. Note that this is a local process caused by temperature differences between the pore walls and takes place even if the moisture gradient is equal to zero. It must not be confused with the effects of a large-scale moisture flow or redistribution of the moisture in the material.
4. Radiation between the pore walls.
5. Convection in the pores. In most practical cases this can be neglected.

When moisture is moving through a material, it carries its enthalpy and consequently contributes to the heat transfer. Moisture flows in the vapor phase have much higher enthalpy than moisture flows in the liquid phase because when phase changes occur, energy is released and absorbed. In some cases, too, the solid phase (ice) may be found and changes between all three phases must be considered.

To describe and to treat the different effects of moisture on heat transfer, it is convenient to divide the heat flow into three components:

Effect I: heat flux q_I	Heat flow caused by a temperature gradient in a condition of moisture equilibrium, that is, no moisture transfer. This flow is affected by various mechanisms, among them the moisture content of the material.
Effect II: heat flux q_{II}	Heat transfer by moisture flow. The water vapor and the water carry their respective enthalpies. It should be observed that the enthalpy of water vapor differs from the enthalpy of water by the latent heat of evaporation. The mechanisms of moisture transfer are assumed to be fully described by a gradient in temperature and a gradient in moisture content together with relevant material properties. Moisture transfer by air movements (moisture convection) is assumed to have only local effects and is consequently not considered in this chapter.
Effect III: heat flux q_{III}	Heat transfer due to phase changes.

The amount and distribution of moisture in a material always affects q_I. To be able to determine q_I it is necessary to know the moisture conditions in the material and the relationship between moisture content and the effects on the thermal conductivity. This relationship is specific for the material.

Components q_{II} and q_{III} depend entirely on the occurrence and magnitude of moisture transfer in the material. To determine these components, it is necessary to know the moisture movements in the materials.

Let us look at the magnitude of these components of heat flow. Consider as a numerical example the following case: a 0.1-m-thick polystyrene board with a temperature difference between the surfaces. $T = 20$ K. We assume that k^*_{dry} is 0.035 W/(mK). The heat flow through the dry material then becomes

$$q_{Idry} = 7\ \text{W/m}^2$$

With a moisture content of, say 50 kg/m^3, uniformly distributed, the moist thermal conductivity is about 0.040, which means a heat flux for the moist material.

$$q_I = 8\ \text{W/m}^2$$

and an increase of 1 W/m^2. We further assume a typical moisture flux (diffusion) through this material of

$$g = 4 \cdot 10^{-8}\ \text{kg/m}^2\cdot\text{s}$$

The contribution due to moisture movements would then be

$$q_{II} = 0.001\ \text{W/m}^2$$

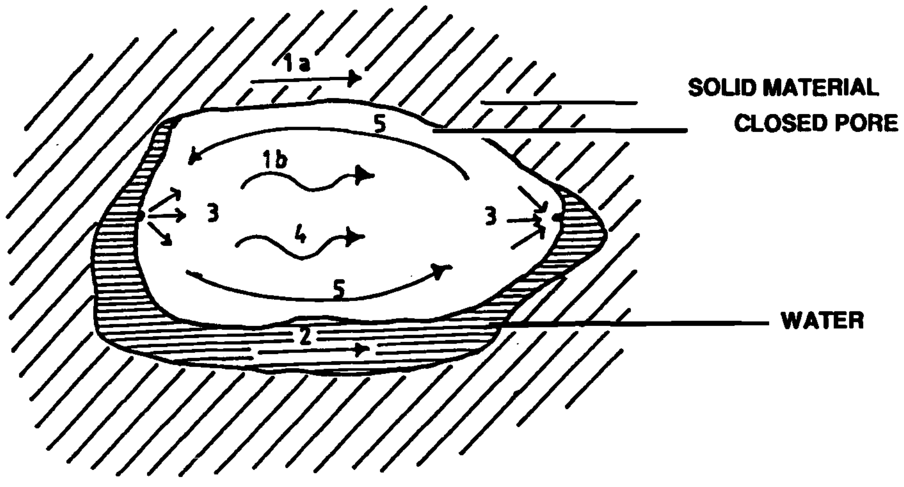


FIG. 2—Heat transfer mechanisms in the pore of a moist material.

If the moisture condenses in the material, heat is liberated and

$$q_{III} = 0.1\ \mathrm{W/m^2}$$

The calculated magnitudes show that, for materials similar to polystyrene foam, q_{II} and q_{III} may be neglected. The reason for this is that the moisture flows are small since the material is relatively impermeable to vapor diffusion.

For a material such as mineral wool with quite a different pore structure, the corresponding heat fluxes are roughly

$$\begin{aligned} q_{I\mathrm{dry}} &= 7\ \mathrm{W/m^2} \\ q_{I} &= 8\ \mathrm{W/m^2} \\ q_{II} &= 0.03\ \mathrm{W/m^2} \\ q_{III} &= 1.7\ \mathrm{W/m^2} \end{aligned}$$

However, q_{II} is still negligible and can be neglected in all insulating materials under normal service conditions.

Heat transfer due to phase changes must be taken into account for mineral wool and similar permeable materials; as such, heat transfer may be of the same magnitude as the increase due to the presence of moisture in the material.

Calculation of Effect III is needed in the case of change in moisture content or moisture content distribution. In most cases, only net changes during the period studied are of interest.

There is, however, one important exception: If moisture migrates in one direction in the vapor phase and then back in the liquid phase (Effect II), effects of phase changes (Effect III) may be considerable even if no net change in the moisture content occurs (see examples d and e in Fig. 3).

Figure 3 illustrates some examples in which effects of phase changes may have to be taken into consideration:

(a) *Drying of the initial moisture content.* The moisture content decreases. The heat of vaporization is taken mainly

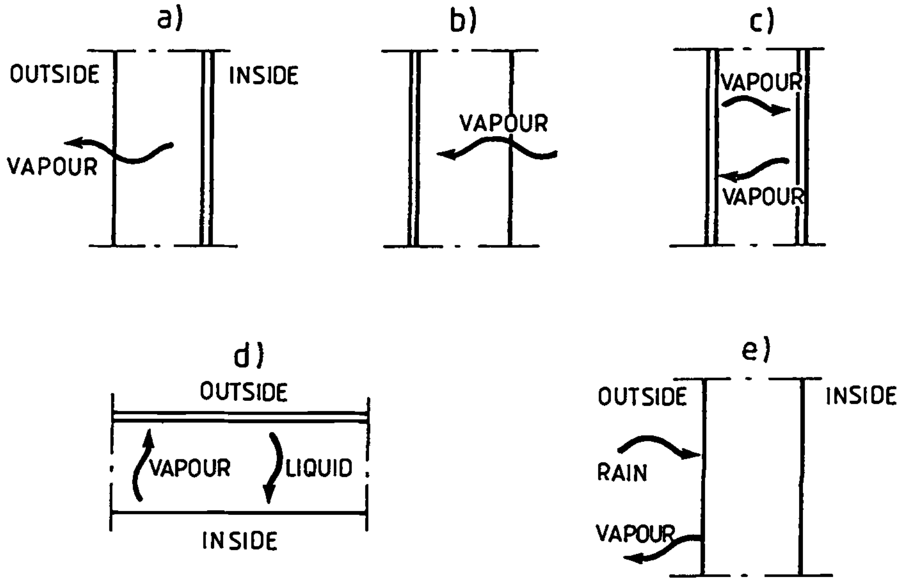


FIG. 3—Some examples in which moisture effects may have to be taken into consideration.

from the inside, which causes an increased heat flow at the wall's inner surface, and the thermal resistance of the wall seems to deteriorate.

(b) *Condensation against a cold outer surface.* Heat is released in the condensation zone but is then mainly lost to the outside air. A slight rise of temperature at the outer surface will occur, and the thermal resistance seems to be improved.

(c) *Periodic moisture flowing between the surfaces in a closed building element.* Heat will be liberated and absorbed alternately at the inner and outer surface, and the net effect over several periods is negligible. Daily oscillations, for example, are not of interest when a heating season is studied. During a laboratory test, however, which may last for only a couple of hours and constitute only part of a period, the effects may be significant, and they must be taken into consideration when the test results are evaluated. This is why Effect III should be avoided or carefully considered during the test. The effects during the test may be considerable while the effects averaged over a longer period are negligible.

(d) *Vapor flow in one direction and liquid flow in the other.* During the winter, moisture in a roof construction may be transported upwards in vapor phase by diffusion and back downwards in the liquid phase by capillary suction or the action of gravity. The heat of vaporization is taken mainly from the inside while the heat of condensation is lost to the outside. Although the moisture content is the same, the thermal resistance of the roof is reduced.

(e) *The same principle as in (d).* Liquid (rain) hits the wall and is absorbed. When the wall dries out again, the heat of vaporization is taken partly from the inside. The thermal resistance of the wall seems to deteriorate.

LITERATURE SURVEY

Simultaneous Heat and Mass Transfer Models

A complete understanding of heat and mass transfer mechanisms in porous media is necessary in order to:

- define the apparent thermal conductivity of a wet insulation
- evaluate the heat flow increase due to the presence of moisture

The complexity of the problem is due to the simultaneous heat and mass transfers and consequently to the coupling between temperature and moisture content, described by a set of two coupled equations derived from the writing of mass and energy conservation laws.

Heat and mass transfer in porous media has been studied in the past by several authors, in particular: Philip and De Vries [*1*], Krischer [*2*], Luikov [*3*], and Whitaker [*4*].

Combined heat and moisture transfer models found more recently in the literature [*5–9*] are mostly based on the De Vries or Luikov approach. They differ by the number of assumptions made to simplify the set of equations.

The classical models take into account two driving forces to express mass transfer: temperature and moisture gradients. Then, it is generally assumed (as stated previously) that the heat transfer due to mass flows (Effect II) is small compared to heat transfer due to phase changes (Effect III).

The derivation of the equations within these assumptions is well beyond the scope of this chapter. It can be found in Ref *10* as

$$\frac{\partial\theta_1}{\partial t} = \nabla \cdot (D_\theta \nabla\theta_l + D_T \nabla T) - \frac{\partial K_l}{\partial z} \tag{7}$$

$$(\rho c)^* \cdot \frac{\partial T}{\partial t} = \nabla \cdot (\rho_l L D_{\theta v} \nabla\theta_l + (k^* + \rho_l L D_{Tv}) \nabla T) \tag{8}$$

where

θ_l = liquid content (by volume),
$D_{\theta i}, D_{Ti}$ = moisture transport coefficients of phase i (l = liquid, v = vapor),
$D_\theta = D_{\theta v} + D_{\theta l}$ = moisture diffusivity,
$D_T = D_{Tv} + D_{Tl}$ = thermal moisture diffusivity,
t = time,
T = temperature,
L = latent heat of vaporization,
$(\rho c)^*$ = equivalent heat capacity of porous medium,
K_l = permeability of the medium to the liquid phase,
ρ_l = liquid density,
z = vertical coordinate, and
k^* = apparent thermal conductivity of the moist porous medium.

Different forms of this set of equations can be found in the literature. In particular, moisture content can be expressed by mass (ω) and not by volume (in this case $\theta_l = \rho_0/\rho_l$, where ρ_0 is the apparent density of the dry material) and gravity effects may be neglected ($\partial K_l/\partial z = 0$).

A comparison of the different types of models can be found in Ref *10*. To our knowledge, the most general set of equations has been recently proposed by Degiovanni [*11*], who introduced the total pressure gradient in the gaseous phase as a third driving force in addition to temperature and moisture gradients.

At the other extreme, we can also mention a very common simplified method used to calculate moisture distributions and developed by Glaser [*12*]. This method accounts only for vapor diffusion as the transport process and assumes stationary conditions that almost never occur in reality.

Measurement Methods

Whatever the degree of perfection of a given heat and mass transfer model may be, it must be realized that the accuracy of the results depends greatly on the material parameters fed into this model. Coming back to Eqs 7 and 8, one can see that one needs

- the moisture transport coefficients (D_θ, D_T)
- the apparent thermal conductivity of the moist material (k^*)

Moisture Transport Coefficients

Experimental data on thermal insulating materials are very scarce. Many of the research works deal with sand or clay.

Data on cellular concrete have been published by Kooi [*13*]. Transport properties of aerated concrete, wood, brick, and expanded polystyrene have been measured by Kohonen [*6*]. Mineral wool (glass and rock fibers) have been studied by Crausse [*14*], Cid [*15*], and Kumaran [*16,17*]. Some of the data published by these authors can be found in the Appendix to this chapter in Figs. 6 and 7.

The description of the measurement methods is beyond the scope of this chapter. The same types of techniques have been used by these authors, although it should be mentioned that these methods are not yet standardized. They are based on unidirectional capillary rise and infiltration experiments as fully described in Ref *14*.

Apparent Thermal Conductivity, k*

We can divide the published thermal conductivity measurements of moist insulating materials into two main families:

- measurements made in stationary conditions in guarded hot plate or heat flow meter apparatus in accordance with ASTM Test Method for Steady-State Heat Flux Measurements and Thermal Transmission Properties by Means of the Guarded-Hot-Plate Apparatus (C 177) or ASTM Test Method for Steady-State Heat Flux Measurements and Thermal Transmission Properties by Means of the Heat Flow Meter Apparatus (C 518) for dry materials.
- Measurements made using transient heat flow methods; these methods are not standardized yet for dry materials; most derive thermal conductivity from the temperature rise induced by a heating probe introduced in the tested material (see, for instance, Ref *33*).

Table 2 recaps the main references we have found in our literature survey. Figure 5, mentioned earlier and shown later in this chapter, illustrates the different results found in these references. A rather large scatter is observed in these data, some results being contradictory, especially those on high water vapor permeability products such as mineral wools.

The interested reader will also find complementary sources of information regarding the measurements of wet insulants and their interpretation in Refs *33* to *44*. A large source of discrepancy between the literature data comes from the measurement techniques and also from the definition of thermal conductivity reported by the authors. How to define the thermal conductivity of a moist material and what property to measure in a given experiment are two fundamental questions that need to be solved.

TABLE 2—Main references reporting measurements of the thermal conductivity of wet insulating materials.

Authors	Reference	Type of Material
Cammerer	*26*	Extruded polystyrene
Zehendner	*24*	
Tobiasson et al.	*27–28*	
Knab et al.	*29*	
Dechow et al.	*23*	
Jespersen	*21*	
Jespersen	*21*	Expanded polystyrene
Cammerer	*26*	
Fauconnier	*25*	
Tobiasson et al.	*27–28*	
Dechow et al.	*23*	
Zehendner	*24*	
Cammerer	*26*	Polyvinylchloride foam
Fauconnier	*25*	
Zehendner	*24*	
Cammerer	*26*	Phenolic foam
Fauconnier	*25*	
Zehendner	*24*	
Sandberg	*32*	Aerated concrete
Fauconnier	*25*	
Cammerer	*26*	
Jespersen	*20*	
Cammerer	*26*	Polyurethane foam
Zehendner	*24*	
Fauconnier	*25*	
Knab et al.	*29*	
Dechow et al.	*23*	
Tobiasson et al.	*27–28*	
Jespersen	*21*	
Cammerer	*26*	Cork
Fauconnier	*25*	
Jespersen	*20*	
Tobiasson	*27*	
Cammerer	*26*	Perlite
Knab et al.	*29*	
Tobiasson	*27*	
Jespersen	*21*	Urea formaldehyde foam
Cammerer	*26*	
Jespersen	*20–21*	Mineral wool
Cammerer	*26*	
Fauconnier	*25*	
Knab et al.	*29*	
Langlais et al.	*30–31*	
Tobiasson	*27*	
Jespersen	*21*	Vermiculite
Anquez	*22*	

HOW TO DEFINE THE APPARENT THERMAL CONDUCTIVITY, *k** OF A WET INSULATING MATERIAL

As noted earlier, the density of heat flux through a dry insulating material can be written as

$$\vec{q} = -k^*_{\text{dry}}\,\vec{\nabla}T$$

where k^*_{dry} is the apparent thermal conductivity of the dry material. This relation also holds for moist media and can be used to define the "true" apparent thermal conductivity of a wet material, "true" meaning it is derived from the writing of Fourier's law. In this case k^* is a function of both temperature, T, and moisture content, θ_l

$$k^* = f(T, \theta_l)$$

In a moist material, however, the density of heat flux is the sum of a Fourier's type term and of a mass transfer term corresponding to the heat transfer due to mass flows

$$\vec{q} = \underbrace{-k^*\vec{\nabla}T}_{\text{Fourier}} + \underbrace{\vec{g}_v h_v + \vec{g}_l h_l}_{\text{Mass Transfer}} \tag{9}$$

where

g_i = density of moisture flow, and
h_i = enthalpy of phase i.

The additional mass transfer term raises the problem of measuring k^*.

Transient Heat Flow Measurements

As soon as a difference of temperature is applied to a wet material, there is a movement of both liquid and vapor. It is, of course, necessary to aim at avoiding moisture movements in order to determine k^*.

Transient heat flow techniques have thus been proposed. In dry materials, dynamic measurements are based on the heat conduction law

$$\rho c \frac{\partial T}{\partial t} = \nabla \cdot (k^*_{\text{dry}} \nabla T) \tag{10}$$

In the case of wet materials, we have seen in Eq 8 that

$$(\rho c)^* \frac{\partial T}{\partial t} = \nabla \cdot [\rho_l L D_{\theta v} \nabla \theta_l + (k^* + \rho_l L D_{Tv}) \nabla T]$$

which gives in the case of no redistribution of moisture and for a uniform moisture distribution at time $t = 0$ ($\nabla \theta_l = 0$)

$$(\rho c)^* \frac{\partial T}{\partial t} = \nabla \cdot ((k^* + \rho_l L D_{Tv}) \nabla T) \tag{11}$$

Comparing Eqs 10 and 11, we see that dynamic methods can only measure an "equivalent" thermal conductivity

$$k_{\text{eq}} = k^* + \rho_l L D_{Tv} \tag{12}$$

Steady State Measurements

In the general case, in a closed system when steady state is reached

$$\vec{g} = \vec{g}_v + \vec{g}_l = 0 \tag{13}$$

Equation 9 then becomes

$$\vec{q} = -k^* \vec{\nabla} T + \vec{g}_v (h_v - h_l) \tag{14}$$

or

$$\vec{q} = -k^* \vec{\nabla} T + \vec{g}_v L \tag{15}$$

with (see Ref *10*)

$$\vec{g}_l = -\rho_l (D_{\theta l} \vec{\nabla} \theta_l + D_{Tl} \vec{\nabla}_T) + \rho_l K_1 \vec{z} \tag{16}$$

$$\vec{g}_v = -\rho_l (D_{\theta v} \vec{\nabla} \theta_l + D_{Tv} \vec{\nabla} T) \tag{17}$$

combining Eqs 15, 16, and 17 we get

$$\vec{g}_v = -\rho_l \left(D_{\theta v} \frac{D_T}{D_\theta} + D_{Tv} \right) \vec{\nabla} T \tag{18}$$

which in most cases can be reduced to

$$\vec{g}_v \approx -\rho_l D_{Tv} \vec{\nabla} T \tag{19}$$

Equations 15 and 19 finally give

$$\vec{q} = -(k^* + \rho_l D_{Tv} L) \vec{\nabla} \mathrm{T} \tag{20}$$

which enables us to define again an "equivalent" thermal conductivity

$$k_{eq} = k^* + \rho_l L D_{Tv} \tag{21}$$

similar to the one defined earlier in Eq 12.

The important point that we can conclude from Eqs 12 and 21 is that in steady state as in non steady state, the measured thermal conductivity is an *equivalent* thermal conductivity generally different from the "true" thermal conductivity, k^*.

Special Cases

When liquid movement can be neglected ($\vec{g}_l = 0$)

$$\vec{q} = -k^* \vec{\nabla} T + \vec{g}_v h_v$$

or

$$\vec{q} \approx -k^* \vec{\nabla} T + \vec{g}_v L$$

Two cases are then of interest

- $\vec{g}_v L \ll k^* \vec{\nabla} T$. This is the case of impermeable materials for which vapor diffusion is very low, for instance, polystyrene.
- $\vec{g}_v = 0$. This is the case in a closed system once steady state is reached.

In both cases, we then have, in the case of one-dimensional flow, the classical

$$q \approx k^* \frac{dT}{dx}$$

We are now in a better situation to understand why the literature survey showed large discrepancies between authors. The thermal conductivity they report may indeed be k^* or k_{eq}. It shows that a complete understanding of the experimental conditions together with the knowledge of the corresponding heat and mass transfer equations are necessary to find out what property is measured.

DETERMINATION OF k^* OF A MOIST MATERIAL

In order to deal with the effects of moisture on heat transfer and temperature distribution in the design process, it is necessary to have some sort of strategy which guarantees that all moisture effects are considered. Simulation of all the moisture effects in a test procedure is unrealistic and unnecessary. Effect III depends entirely on the occurrence and size of moisture transfer in the material. If this effect is allowed during the test, it is difficult to assess a material property or a building component property. There will also be a risk of overestimating the effect of phase changes.

Therefore the suggested strategy to follow is:

A. To determine Effect I (thermal conductivity of the moist material) by testing.
B. To determine Effect III (effects of phase changes) by calculations or estimations based on experience.

Steps A and B together will yield something we may call "design (or practical or effective) thermal resistance of a moist building component." This resistance value, which will represent an average over, say, a year or a heating season, varies not only with the material and its thickness but also with the boundary conditions. See the next section for guidance on the evaluation of the performance of moist insulation.

A test method for the determination of k^* has been worked out within ISO and presented as ISO/DP 10 051 "Thermal insulation—Moisture effects on heat transfer—Determination of thermal transmissivity of a moist material." The standard specifies a method to provide the thermal conductivity of a moist material (k^*), a property of a moist material under steady state conditions, i.e. not affected by moisture movement. It is measured using standardized guarded hot-plate and heat-flow-meter methods at temperatures above 0°C.

The reasons for specifying steady state methods are that these methods are well known, widely used, and standardized within ISO. In addition, transient methods do not guarantee that problems with moisture movements are avoided (see previous section); dynamic methods also have the disadvantage that normally only small volumes of the material are involved in the test and the results require a more complicated analysis.

The reason for using temperatures above freezing is to avoid the further effects of phase changes (ice-liquid or ice-vapor).

Determination of the thermal conductivity of a moist material always requires a temperature gradient. Normally a temperature gradient causes a redistribution of the moisture in the material, which leads to two types of problems.

1. Redistribution of the moisture means that the test is carried out on a material with a changing and unknown moisture distribution.
2. Redistribution of the moisture simultaneously induces phase changes and heat transfer by moisture flow. These effects are unlikely to be exactly the same extent as the moisture effects in the material under service conditions, which is why these effects should be negligible or well known during the test. Note that working at low-temperature gradients is not a guarantee for negligible effects of phase changes.

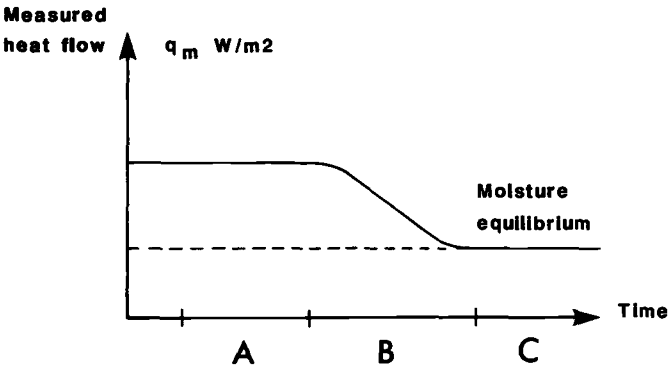


FIG. 4—Variation of heat flow during a test of a moist material.

During a test of a moist material in a guarded hot plate or heat flow meter apparatus, the heat flow measured at the warm or cold surface will vary essentially as shown in Fig. 4; an initial Phase A, with more or less constant heat flow due to the combined effects of conduction, moisture flow, and phase changes; a transition Phase B; and, finally, a Phase C with moisture equilibrium.

Phase A is the period of time during the test when the rate of evaporation at the specimen's hot face is constant. This is only possible as long as the moisture content is above the hygroscopic range (relative humidity in the pores ≈ 100%) and consequently the distribution of vapor pressure unaffected by changes in distribution of moisture content.

It can be derived, see previous section, that the measured heat flux at the warm and cold surface may be expressed as

$$q_m = (-k^* \cdot dT/dx)_{sur} + (g_v \cdot L)_{sur}$$

where

q_m = measured heat flux at the surface,
dT/dx = temperature gradient at the surface (one-dimensional case), and
g_v = vapor flow at the surface (= rate of evaporation/condensation).

To determine k^*, the following must be known: moisture content distribution, temperature gradient, and heat flow. g_v must be estimated or deemed negligible, which is true either if the material has a low-vapor permeability or if the test is carried out under moisture equilibrium (see previous section).

The specimen shall be conditioned as close as possible to the desired moisture content and moisture distribution. The conditioning can be by water immersion with or without vacuum, absorption in humid air, spraying of water on the specimen, or by subjecting the specimen to a temperature gradient. Combinations of these methods are also possible.

In theory either Phase A or Phase C can be selected for determining k^*. In practice, however, only one of the phases should be recommended depending on material properties and moisture content and distribution.

The following guidance may be given:

1. *Vapor permeability.* For materials with a low-vapor permeability, a very long time is needed to reach moisture equilibrium (Phase C) and at the same time the effects of moisture movements are small during Phase A. For these materials Phase A is recommended. An alternative is to condition the specimen to the equilibrium of Phase C and measure during this phase.
2. *Moisture distribution.* An almost uniform moisture distribution may be maintained only during Phase A. In Phase C, the moisture content is always nonuniform. The rate of redistribution is smaller and the equilibrium moisture content less nonuniform when working at low-temperature gradients. If the moisture distribution during the test cannot be monitored simultaneously, it shall be estimated either by measurements of moisture distribution before and after the test or by measurement of the moisture distribution before or after the test and a calculation of the rate of redistribution. If there is a risk of moisture redistribution by gravity, the evaluation of the results must be carried out extremely carefully.

3. *Hygroscopicity and moisture content level.* Phase A requires a moisture content above the hygroscopic range, where changes in moisture content do not affect the distribution of the vapor pressure. For materials with negligible effects of moisture transfer, Phase A may be used for any moisture content level. In Phase C the major part of the material has a moisture content in the hygroscopic range.
4. *Thermal conductivity of dry material.* In materials with a high thermal conductivity, the relative importance of the moisture effects is small and they may be neglected. The relation vapor permeability/thermal conductivity is determined (see also next section).

USE OF k^* TO DETERMINE THE EFFECTIVE THERMAL PERFORMANCE OF A MOIST INSULATION

To consider the effects of moisture on the thermal performance of an insulation, there are two options:

1. *To calculate the coupled effects of heat and mass transfer in the material using relevant thermal and moisture material characteristics and boundary conditions.* An example of such a mathematical model is given in Chapter 2 of this manual and in Refs *8* and *9*. Note that in addition to k^*, the moisture transfer properties must also be known. Calculations of this kind are complicated, and it is often desirable to have a simpler option at hand in the design process. Therefore "design values" are widely used (see below).
2. *To use "design values" for the thermal conductivity,* k_{design}. This value can be used in the ordinary heat transfer equations to calculate, for instance, heat flux and temperature distribution. The value of k_{design} shall be determined in such a way that it includes all relevant effects of moisture on the thermal performance of the material. From this it follows that k_{design} may be different for different applications even if the material is the same.

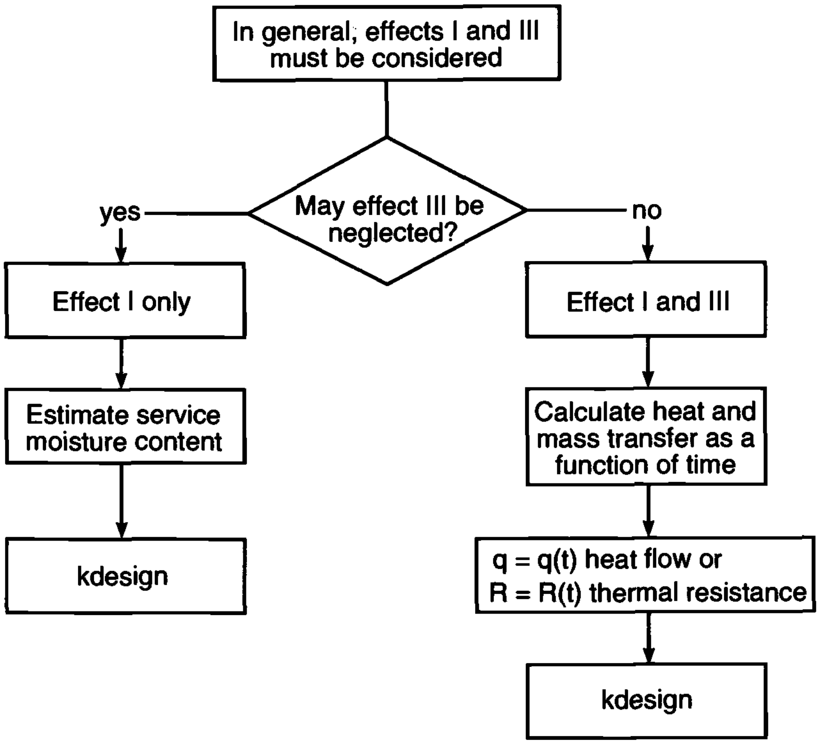
The process to determine the design values is described below, and a number of material data found in the literature, from which design values can be estimated, are given in the next section (Fig. 5).

The process to determine k_{design} is described in the flow chart on this page.

In general we have to consider moisture Effects I and III (conduction in a moist material and phase changes). Effect II is negligible. In several cases, also, Effect III may be negligible. The determining factor is the quotient: thermal conductivity/vapor permeability (or k^*/D_{Tv}), see previous section. This clause treats the conditions during the test, but the same equations are, of course, also valid under service conditions. As a rule of thumb, we may assume that for materials with a high value of k^*/D_{Tv} such as

- plastic foam
- aerated or light-weight concrete
- wood fiber board
- brick

Effect III may be neglected, while for materials with a low value of k^*/D_{Tv}, such as fibrous insulation or highly porous material, the effects of phase changes may have to be considered.



For materials of the first group, the whole effect of moisture is described by k^*. The next step is to estimate the normal service moisture content, w_{service}, and to calculate k_{design}.

An example used in the Swedish National Board of Housing, Building and Planning assumes a linear relationship between k^* and the moisture content w (in kg/m^3)

$$k^* = k^*_{\text{dry}} + K \cdot w \tag{22}$$

Table 3 lists officially used K values for a number of insulating materials. In most cases, it is enough to know w_{service} as a mean value, and it is not necessary to bother about the distribution in the material, so

$$k_{\text{design}} = k^*_{\text{dry}} + K \cdot w_{\text{service}}$$

Only for extremely nonuniform moisture distributions need the effects of moisture distribution be considered. For materials of the second group, both Effects I and III may have to be considered. Examples of these cases when Effect III is not negligible are given in a previous section. For these cases it is necessary to consider the coupled effects of heat and mass transfer as just described and estimate the heat flux or thermal resistance as a function of time. Design values may then be established.

Some guidance may be found in the literature on how to treat materials in the second group. Hedlin [*41,42*] and Sandberg [*7*] have made measurements and calculations on flat roofs. Effective thermal conductivities as high as three times the dry values were found during limited periods. An increase of 18% on an annual basis and 28% during the heating season was found for one set of external conditions. For externally insulated basement walls, an increase of roughly 10% was calculated (Sandberg [*7*]) as a consequence of a number of wettings caused by heavy rains. These examples are by no means generally applicable but show the magnitude of the effects, and the reports give some ideas on how to consider effects of phase changes.

Finally, it should be pointed out that in some instances very capillary materials such as some types of aerated or lightweight concrete can also be subjected to cyclic condensation-evaporation as the capillary forces are then strong enough to draw the water away from the cold side of the insulant (the so called "heat pipe effect"). In this case, as well as for applications where gravity effects are predominant, moisture effects must be carefully considered.

DATA FOR THERMAL INSULATING MATERIALS

As already discussed, the measurement of the thermal conductivity of a wet material is rather tricky and very strategy dependent, especially if the material has a high water vapor permeability. This, plus the wide varieties of products available for a same type of material, partly explains the broad range of thermal conductivity values (wet and dry) found in the literature.

To give an exhaustive listing of all these data would be extremely tedious and probably confusing. Rather, as a guideline, we chose to report the extreme values found in the literature in the graphs of Fig. 5 as well as in the references relevant for each of the considered products, where the interested reader will find more detailed information (see Table 2).

TABLE 3—Typical list of moisture proportionality factors K of Various Insulating Materials as Proposed by the Swedish National Board of Housing, Building and Planning.

Type of Material	K, W/m^2/(Kg·K)	Average Hygroscopic Moisture Content, Kg/m^3
Expanded polystyrene	0.00013	<2
Extruded polystyrene	0.00010	<2
Cellulose fiber	0.0005	3
Aerated concrete		
300 kg/m^3	0.0009	7
600 kg/m^3	0.0009	<14

For the dry materials, experimental results have been reported as $k^* = f(\text{density})$ curves. For the wet materials, the ratio $k^*_{\text{wet}}/k^*_{\text{dry}}$ is given as a function of the moisture volume content of the material. Except for mineral fiber products, for which results obtained in both Phases A and C could be found, all measurements were done in Phase A.

When available, we also provide the maximum reported water pickup in service conditions. However, as moisture content strongly depends on actual service conditions, the use of these figures first supposes a thorough evaluation of the average moisture state in the product.

As indicated in the last section, if we are dealing with materials of the first group, for which Effect III is negligible, knowledge of the average moisture content is in first approximation enough to have access to k_{design}.

For materials of the second group, however, for which both Effects I and III may be equally important, one has to be extremely careful as to the use of experimental data. As a guide, we may say that in building applications the main cause of moisture penetration can usually be attributed to accidental rain infiltrations. When this liquid penetration occurs in particular constructions (for instance, insulated cavity walls or externally insulated basement walls), liquid water will penetrate from the cold side of the insulant and should remain there before evaporating in the summer; and data obtained in Phase C are then probably most representative of these configurations. Roofs in which the direction of the gradient of temperature may vary during the day could be a limiting case, and reported design k values lie in between the Phase A and the Phase C curves obtained in laboratory conditions [*7,41,42*]. The same effect may also occur in walls, particularly those on which the sun shines part of the day. Care should also be taken upon consideration of very capillary materials such as aerated or light-weight concrete following daily temperature swings. Such products will undergo evaporation-condensation cycles driven by diffusion and capillary suction phenomena (the so called "heat pipe effect").

Not enough data were available on cellulose fibers to be represented on a graph. The interested reader will find some information on this in Table 3.

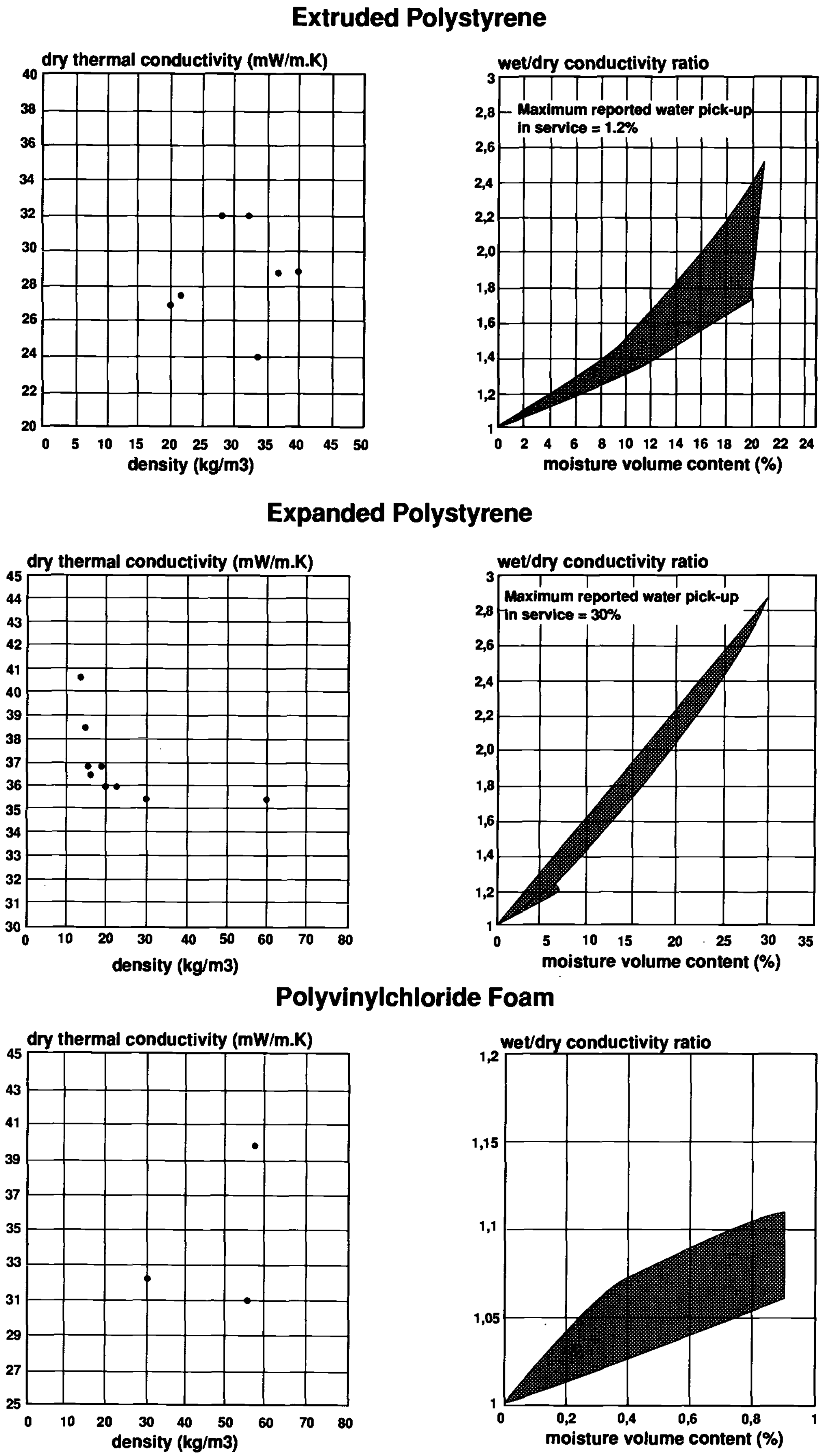
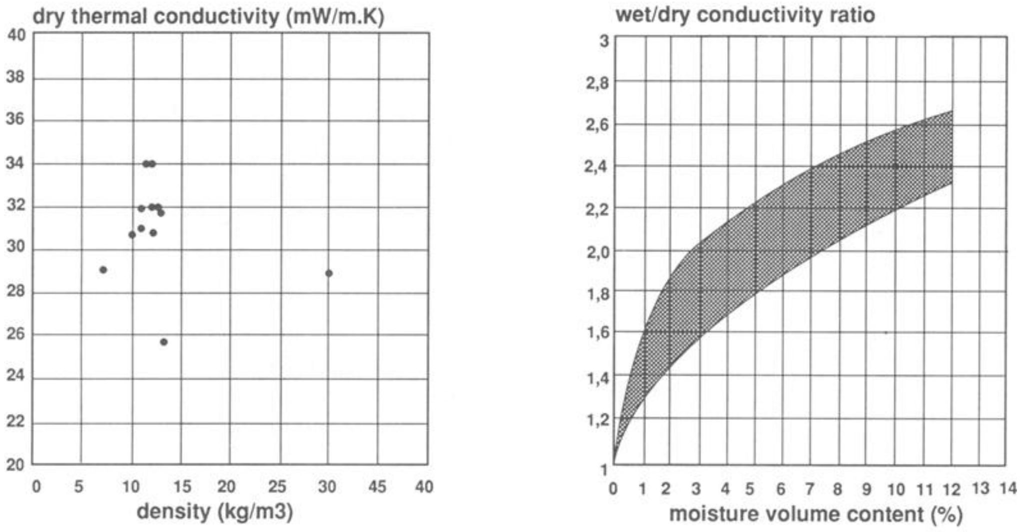
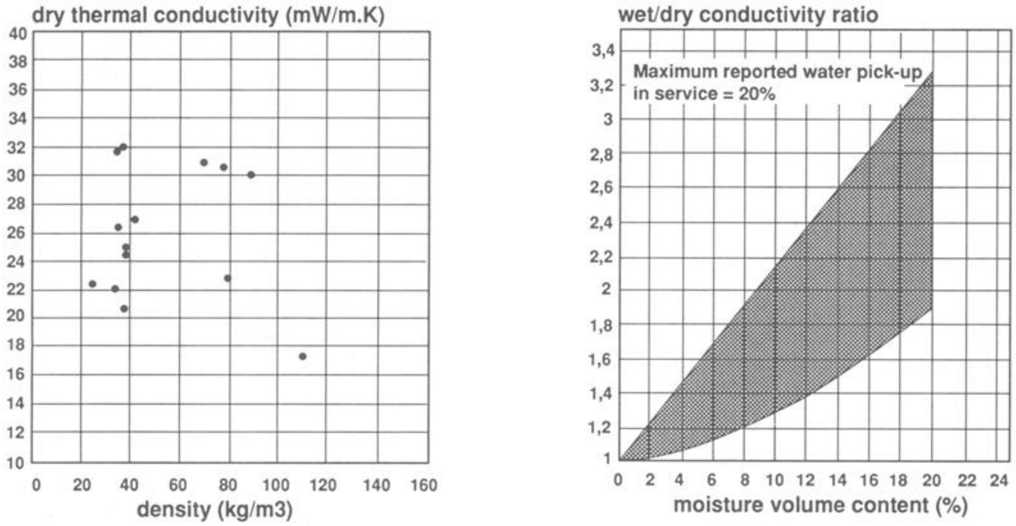


FIG. 5—The increase of thermal conductivity of various insulating materials with average moisture content (related to the dry product's thermal conductivity value) and corresponding product density and dry apparent thermal conductivity.

Urea Formaldehyde Foam



Polyurethane Foam



Perlite

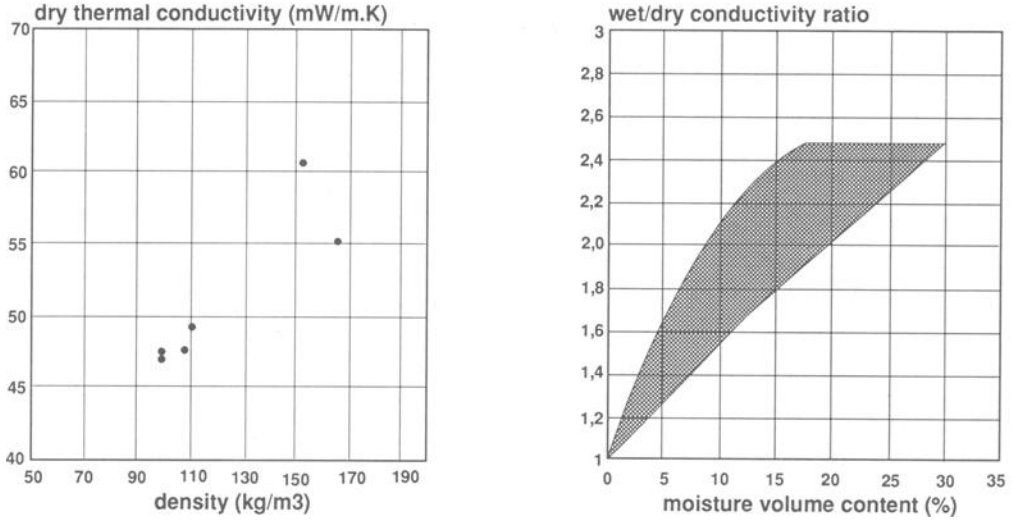
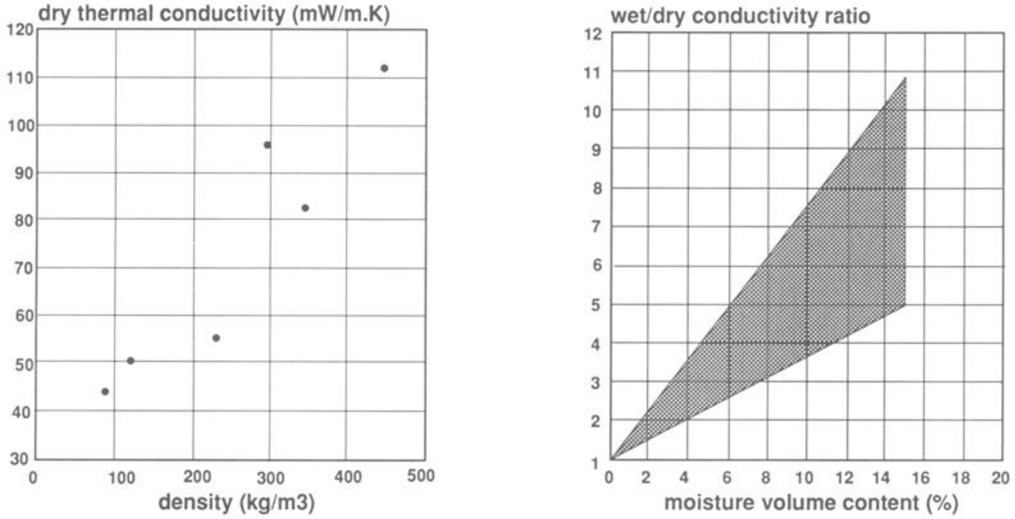
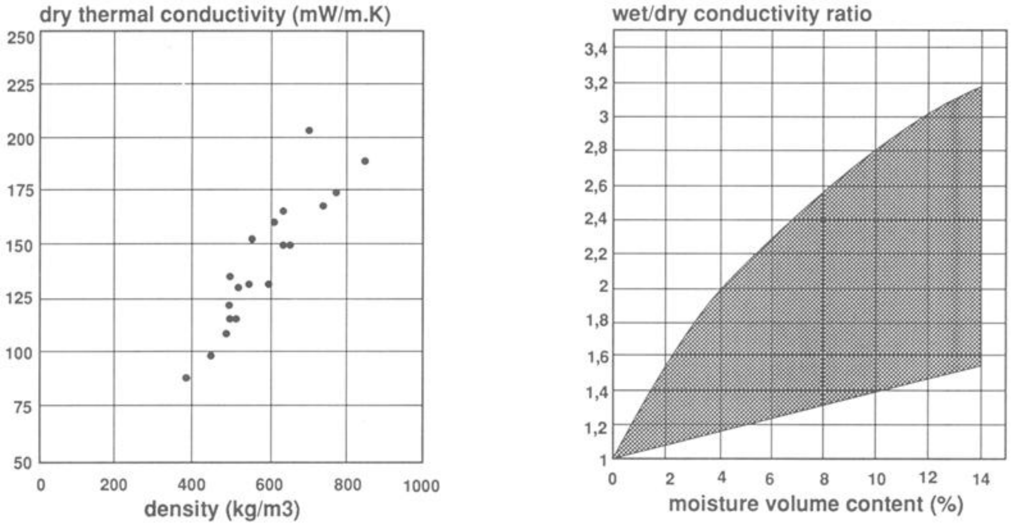


FIG. 5—(*continued*).

Vermiculite



Aerated Concrete



Phenolic Foam

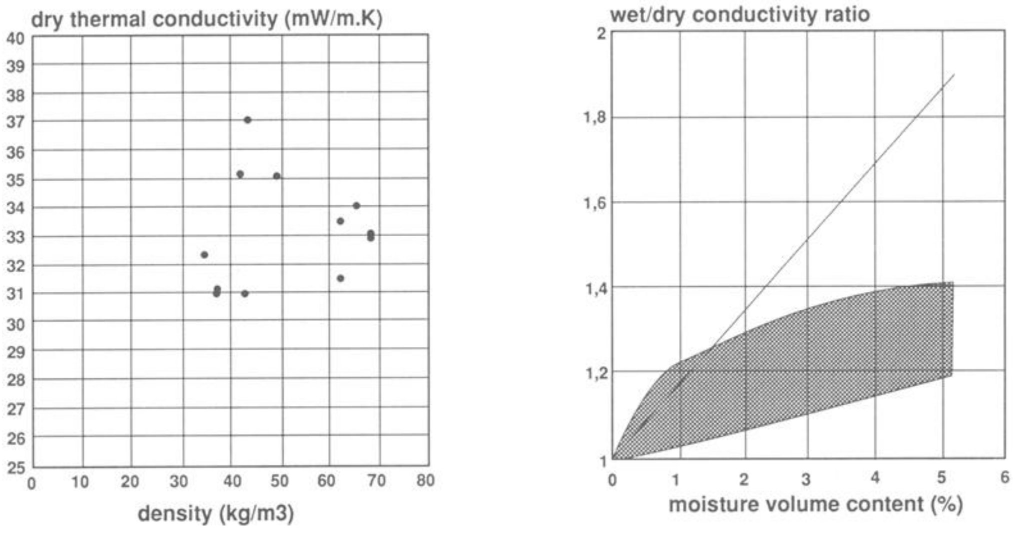
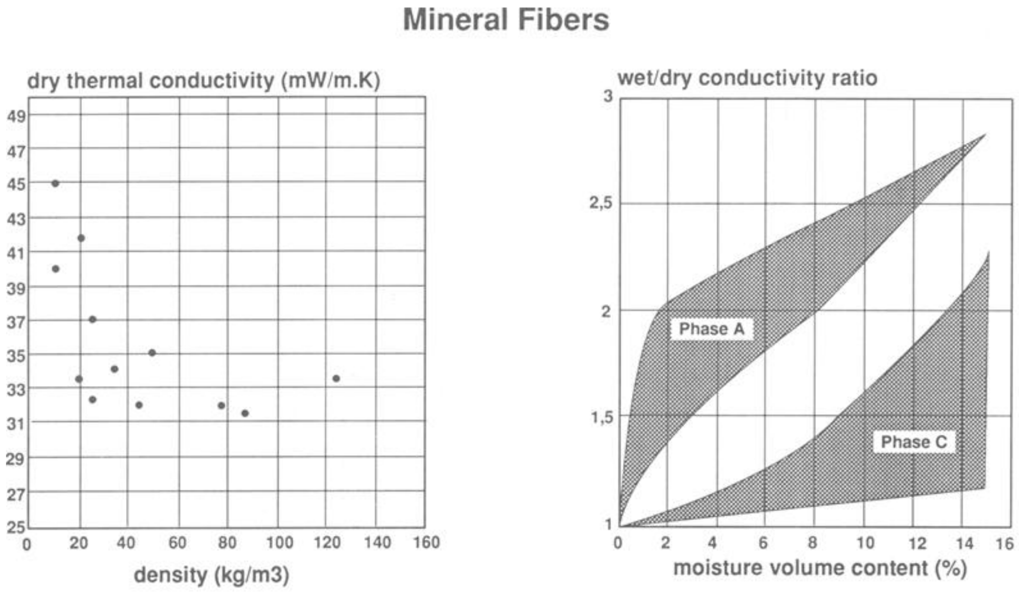


FIG. 5—(*continued*).



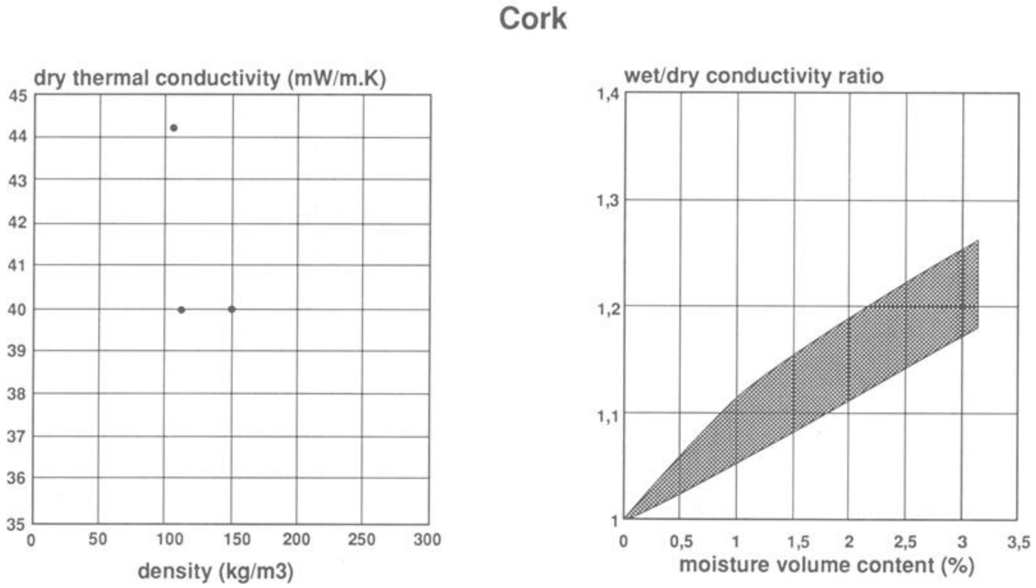


FIG. 5—(*continued*).

CONCLUSIONS AND THE NEED FOR FUTURE WORK

In this chapter we have seen that, to consider the effects of moisture on the thermal performance of insulating materials, we could either calculate the coupled effects of heat and mass transfer in the material or try to estimate "design values" representative of service conditions.

In both cases, a knowledge of the apparent thermal conductivity, k^*, as a function of moisture content is necessary. Available data are unfortunately few and contradictory; because the determination of the conductivity of moist materials is complex, test results in some cases are wrongly interpreted and information on test conditions is not always given together with the test results.

There is a need to establish standardized procedures to determine a correctly defined thermal conductivity, k^*. The ISO work that we have presented is a first step in this direction.

It should also be recalled that, in many instances, thermal insulation applied in buildings remains dry. In particular, polystyrene and mineral wool are by nature nonhygroscopic and their water intake by absorption remains very low even at high relative humidities ([*37*, *46–48*]).

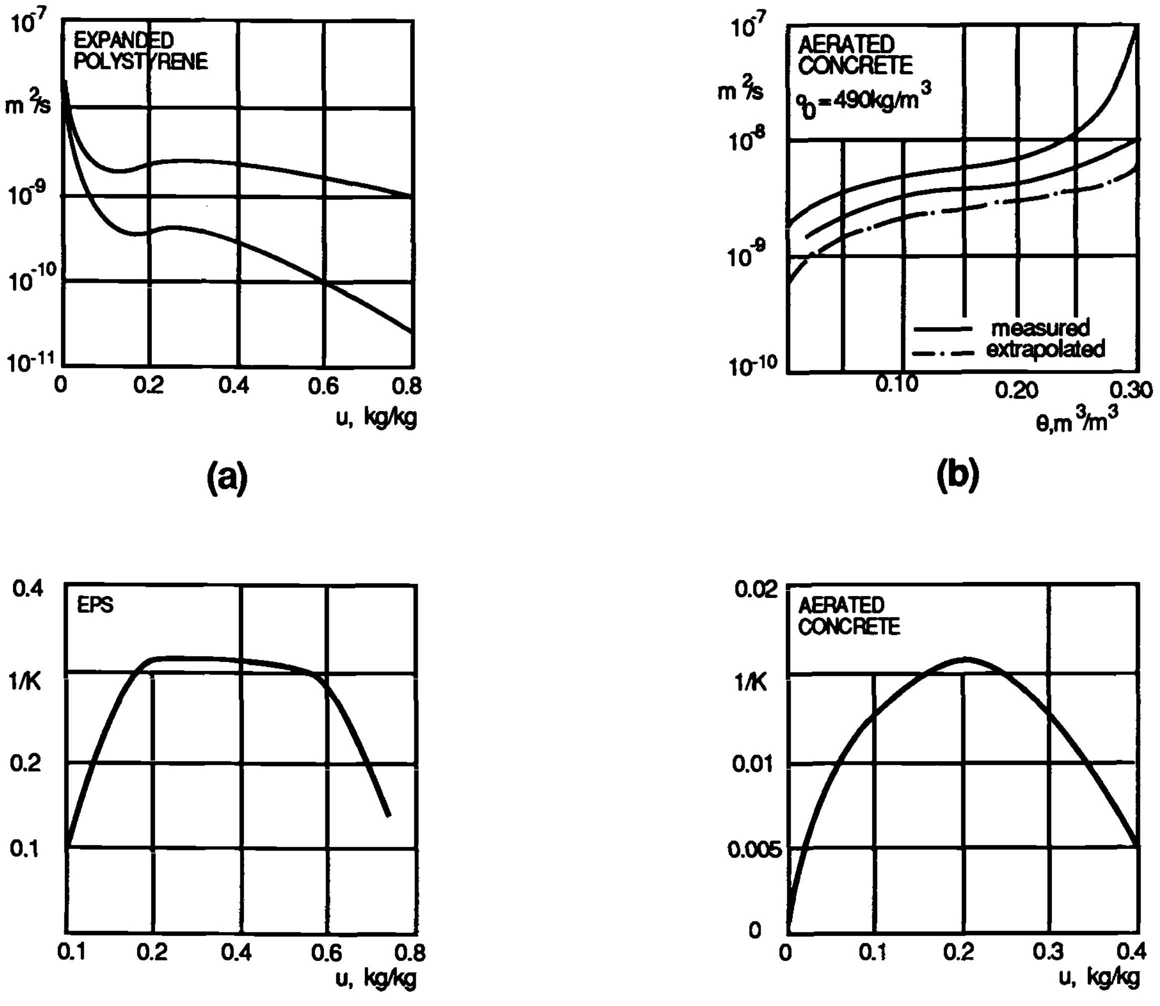
It is clear that one should always aim at keeping the insulant dry. If this is not the case, however, use of a design value in the classical heat transfer equations is often sufficient. This value can be calculated as an addition to the dry thermal conductivity term.

For many materials, only the *presence of moisture* affects the heat flow, and the design value may be determined from a knowledge of k^* as a function of moisture content and a knowledge of actual moisture content under service conditions. In some cases, however, *moisture movements* also have to be considered. This holds for vapor permeable materials with a low thermal conductivity undergoing changes in net moisture content or subjected to cyclic variations in temperature (winter-summer or day-night). This may also be true for very capillary materials such as some types of aerated or lightweight concrete subjected to condensation-evaporation cycles (heat pipe effect) and for all materials whenever gravity effects are predominant. All those cases sensitive to effects of moisture movements should be treated individually.

The complete solving of the coupled effects of heat and mass transfer in the materials as opposed to the design value procedure appears in theory as the ideal treatment of moisture problems. In practice, the complexity of the equations and the lack of physical data on materials make an accurate treatment extremely difficult. Here again, there is a strong need for:

- First, establishing common models and terminology—the use of different symbols and assumptions makes the comparison between authors extremely complex.
- Second, standardizing the test methods in order to determine the moisture transport coefficients and obtain reliable data on usual insulating materials, currently available results being indeed scarce and not homogeneous.

APPENDIX—Moisture Transport



(a)

(b)

(c)

FIG. 6—(a) Moisture vapor diffusivity (m^2/s) as a function of gravimetric water content (kg/kg) of expanded polystyrene at two temperatures (from Ref 6); (b) Moisture (liquid + vapor) diffusivity (m^2/s) as a function of volumetric water content (m^3/m^3) of aerated concrete at three temperatures (from Ref 6); (c) values of the ratio D_t/D_{Tv} (moisture diffusivity/thermal moisture diffusivity) as a function of gravimetric water content (kg/kg) for expanded polystyrene and aerated concrete (from Ref 6).

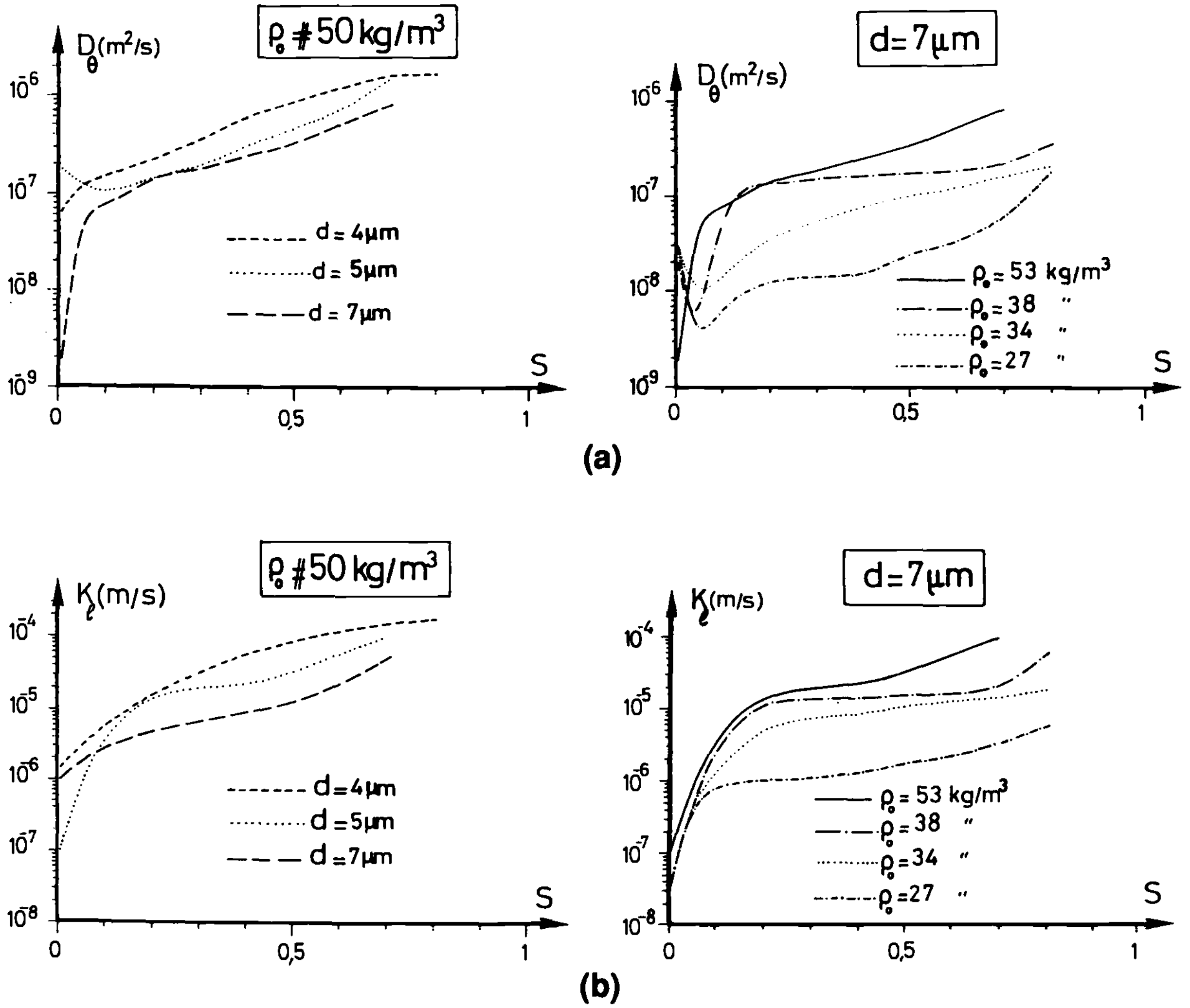


FIG. 7—(a) Permeabilities of glass wool products to water as a function of degree of saturation ($S = \partial_l$/porosity) for different densities, ρ_0, and different mean fiber diameters, d (from Ref 15); (b) Moisture diffusion coefficients (water + vapor) as a function of degree of saturation ($S = \theta_l$/porosity) for different densities, ρ_0, and different mean fiber diameters, d (from Ref 15).

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See also Ref 37.

5

Moisture-Related Properties of Wood and the Effect of Moisture on Wood and Wood Products

by Gerald E. Sherwood[1]

MOISTURE IS THE SINGLE MOST IMPORTANT factor in the performance of wood and wood products. It affects the dimensional stability of wood and under certain conditions can cause major deformation. The extent of physical changes due to moisture depends on the density of the wood and the fiber orientation in reference to the direction of cut. Moisture is necessary for growth of decay fungi with consequent degradation of wood. Insect attack is also influenced by the presence of moisture.

Wood dried below its fiber saturation and maintained at a reasonably constant moisture level will perform well nearly indefinitely. This performance can be observed in wooden structures over three thousand years old. However, wooden buildings not designed for moisture control can be short lived or require excessive maintenance.

The information that follows is primarily taken from *Wood Handbook—Wood as an Engineering Material* [*1*].

STRUCTURE OF WOOD

Cellular Structure

The fibrous nature of wood is a major factor in its moisture-related properties. Wood is composed mostly of hollow, elongate, spindle-shaped cells arranged parallel to each other along the trunk of a tree. Cavities in the cells are called lumens. Lumens play a major role in the transport of water in the living tree as well as in wood products. Water stored in cell walls is referred to as bound water, while water in the lumens is free water. When cell walls are saturated, bound water represents about 30% of the dry wood weight. Any additional water is in the lumens and is free to move in the direction of fibers. This free water has no effect on the shrinking or swelling of wood, but only free water is available for use of wood decay fungi.

Growth Rings

With most species grown in temperate climates, there is sufficient difference between wood formed early (springwood) and wood formed late (summerwood) in a growing season to produce well-marked annual growth rings (Fig. 1). The inner part of the growth ring formed first in the growing season is called earlywood, and the outer part formed later in the growing season is called latewood. Earlywood is characterized by cells having relatively large cavities and thin walls. Latewood cells have smaller cavities and thicker walls. In many tropical regions, growth may be practically continuous throughout the year, and no well-defined annual rings are formed.

Growth rings play a major role in the way wood expands and contracts. The greatest expansion with moisture is tangential to the growth rings because fibers swell in diameter (Fig. 2). A lesser magnitude of expansion occurs across or perpendicular to the rings. Expansion parallel to fibers is nearly imperceptible.

Sapwood and Heartwood

Sapwood is located in the outer portion of a tree. It contains both living and dead cells and functions primarily in the storage of food and the mechanical transport of water or sap. The sapwood layer may vary in thickness and in the number of growth rings contained in it. As a rule, the more vigorously growing trees have wider sapwood layers. Many second-growth trees of merchantable size consist mostly of sapwood because the tree is not old enough to have deposited large amounts of extractives that result in heartwood. Sapwood is generally lighter in color than heartwood.

Heartwood consists of inactive cells that do not function in either water transport or food storage. The transition from sapwood to heartwood is accompanied by an increase in the extractive content. Frequently these extractives darken the heartwood and give species such as black walnut and cherry their characteristic color. However, some species do not darken to a great extent. Heartwood extractives in some species such as black locust, western red cedar, and redwood make the wood resistant to fungi or insect attack. All dark-colored heartwood are not resistant to decay, and some nearly colorless heartwood provide decay resistance, as in northern white cedar. Sapwood of all species, however, is not resistant to decay. Heartwood extractives may also reduce the permeability, making the heartwood slower to dry and more difficult to impregnate with chemical preservatives. However, this property of heartwood increases dimensional stability with changing moisture conditions.

In some species such as the ashes, hickories, and certain oaks, the pores (vessels) become plugged to a greater or lesser degree with ingrowths known as tyloses. Heartwood having pores tightly plugged by tyloses, as in white oak, is suitable for tight cooperage since it prevents the passage of liquid through the pores. Tyloses also make impregnation with liquid preservatives difficult.

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[1] Wood Structures Consultant, 9123 Blackbird Ave., Fountain Valley, CA 92708.

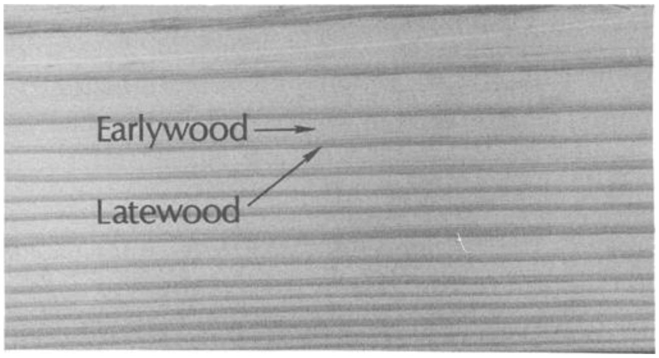

FIG. 1—Earlywood and latewood bands in southern pine [1].

SPECIES VARIABLES

Density

Density of wood is a major factor in dimensional stability as affected by moisture content changes. Lightweight woods have less dimensional change with moisture changes than heavy woods. The density of wood, exclusive of water, varies greatly both within and between species. While the density of most species falls between about 32 and 72 kg/m^3 (20 and 45 lb-mass/ft^3), the range of densities actually extends from about 16 kg/m^3 (10 lb-mass/ft^3) for balsa to over 104 kg/m^3 (65 lb-mass/ft^3) for some other imported woods. A coefficient of variation of about 10% is considered suitable for describing the variability of density within common domestic species.

Decay Resistance of Heartwood

The heartwoods of common native species of wood have varying degrees of natural decay resistance. Untreated sapwood of substantially all species has low resistance to decay and usually has a short service life under decay-producing conditions. The decay resistance of heartwood is greatly affected by differences in the preservative qualities of the wood extractives, the attacking fungus, and the conditions of exposure. Considerable difference in service life may be obtained from pieces of wood cut from the same species, even from the same tree, and used under apparently similar conditions. There are further complications because, in a few species, such as the spruces and the true firs (not Douglas fir), heartwood and sapwood are so similar in color they cannot be easily distinguished.

Precise ratings of decay resistance of heartwood of different species are not possible because of differences within species and the variety of service conditions to which wood is exposed. However, broad groupings of many native species—based on service records, laboratory tests, and general experience—are shown in Table 1. Similar groupings of some imported woods are shown in Table 2.

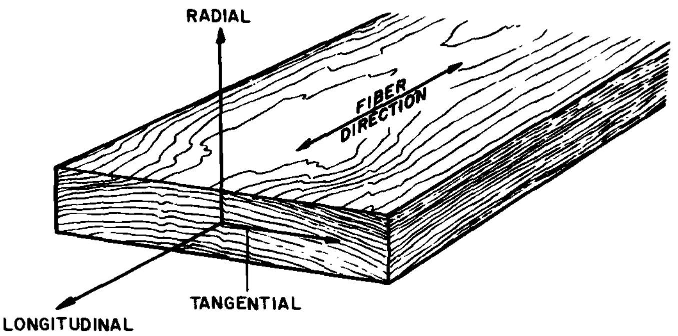

FIG. 2—The three principal axes of wood with respect to grain direction and growth rings [1].

TABLE 1—Grouping of some domestic woods according to approximate relative heartwood decay resistance [1].

Resistant or Very Resistant	Moderately Resistant	Slightly Resistant or Nonresistant
Bald cypress (old growth)	Bald cypress (young growth)	Alder
Catalpa	Douglas fir	Ashes
Cedars	Honeylocust	Aspens
Cherry, black	Larch, western	Basswood
Chestnut	Oak, swamp chestnut	Beech
Cypress, Arizona	Pine, eastern white	Birches
Junipers	Southern Pine	Buckeye
Locust, black	Longleaf	Butternut
Mesquite	Slash	Cottonwood
Mulberry, red	Tamarack	Elms
Oak		Hackberry
Bur		Hemlocks
Chestnut		Hickories
Gambel		Magnolia
Oregon white		Maples
Post		Oak (red and black species)
White		Pines (other than longleaf, slash, and eastern white)
Osage orange		Poplars
Redwood		Spruces
Sassafras		Sweetgum
Walnut, black		True firs (western and eastern)
Yew, Pacific		Willows
		Yellow poplar

TABLE 2—Grouping of some woods imported into the United States according to approximate relative heartwood decay resistance [1].

Resistant or Very Resistant	Moderately Resistant	Slightly Resistant or Nonresistant
Angelique	Andiroba	Balsa
Apamate	Apitong	Banak
Brazilian rosewood	Avodire	Cativo
Caribbean pine	Capirona	Ceiba
Courbaril	European walnut	Jelutong
Encino	Gola	Limba
Goncalo alves	Khaya	Lupuna
Greenheart	Laurel	Mahogany, Phillipine
Guijo	Mahogany, Phillipine	Mayapis
Iroko	Almon	White lauan
Jarrah	Bagtikan	Obeche
Kapur	Red Lauan	Parana pine
Karri	Tanguile	Ramin
Kokrodua (Afromosia)	Ocote pine	Sande
Lapacho	Palosapis	Virola
Lignumvitae	Sapele	
Mahogany, American		
Meranti		
Peroba de campos		
Primavera		
Santa Maria		
Spanish cedar		
Teak		

MOISTURE TRANSPORT IN WOOD

Moisture both in the form of water and water vapor is transported very quickly in the direction of wood fibers (longitudinally); however, moisture will move across the grain (radially), but at a much slower rate. Water vapor in the atmosphere is absorbed by the wood until an equilibrium condition is achieved. In the case of air that is drier than wood, water will be removed from the wood until an equilibrium condition is achieved. This equilibrium is the moisture content at which wood neither gains nor loses moisture when surrounded by air at a given relative humidity and temperature. Equilibrium moisture contents of wood are shown in Table 3. As indicated in the table, even at the highest relative humidity possible, fiber saturation (30% moisture content) is not reached. The presence of liquid water is required for fiber saturation and to fill the cavity with free water.

The time required for wood to achieve equilibrium moisture content depends on the area of wood surface exposed, the cross section of the member, and the proportion of surface with end grain exposed. For example, a short member will reach equilibrium quickly because moisture will be transported in the direction of fibers through the length of the member. A long, thick member, such as a log or a sawn heavy timber, may take several years to reach equilibrium.

Wood is generally listed as having a high permeability to water vapor; however, permeability has been found to vary with moisture content of wood and with temperature. Ongoing research is being conducted at the National Institute of Science and Technology to quantify the permeability of selected species of wood at temperatures and moisture contents that normally occur.

DIMENSIONAL CHANGE FACTORS

Wood is dimensionally stable when the moisture content is above the fiber saturation point. It changes dimension as it gains or loses moisture below that point. Wood shrinks when losing moisture from the cell walls and swells when gaining moisture in the cell walls. Wood is an anisotropic material with respect to shrinkage characteristics (Fig. 2). It shrinks most in the direction of the annual growth rings (tangentially), about one half as much across the rings (radially), and only slightly along the grain (longitudinally).

Data have been collected to represent the average radial, tangential, and volumetric shrinkage of numerous domestic species by methods described in ASTM Method of Testing Small Clear Specimens of Timber (D 143) [*2*]. These shrinkage values, expressed as a percentage of the green (about 30% moisture content) dimension, are summarized in Table 4. Shrinkage values collected from the world literature for selected imported species are summarized in Table 5. These data can be used to estimate shrinkage from the green condition to any moisture content:

$$S_m = S_o \ [(30 - m)/30]$$

Where S_m is shrinkage (in percent) from the green condition to moisture content m (below 30%) and S_o is total shrinkage (in percent) from Table 4 or Table 5. If the moisture content at which shrinkage from the green condition begins is known to be other than 30% for a species, the shrinkage estimate can be improved by replacing 30 in the equation with the appropriate moisture content.

EFFECTS OF DIMENSIONAL CHANGE

Dimensional change may be uniform within a member or it may cause distortion due to differences in grain direction (Fig. 3). Distortion is caused by the combined effects of radial and tangential shrinkage, which occur at different rates. In addition, large timbers develop checks on the surface because the outer portion of the member dries much faster than the inner portion. Various types of warp may also occur if boards are not restrained during the drying process (Fig. 4).

Connectors

Shrinkage causes loosening of connectors such as bolts or split-ring connectors. This is a particular problem where large timbers are used since these timbers may require several years to dry and because they are usually installed in the structure in the green state. Therefore, connectors in heavy timbers must be tightened periodically for the first few years after construction and rechecked at longer intervals throughout the life of the building.

Structural Members

Large differential shrinkage in members that support a structure can cause excessive or uneven settlement of the structure with consequent racking of walls and opening. Shrinkage around window and door openings can also rack these openings out of shape, resulting in window and door closure problems. An extreme case of shrinkage is demonstrated by log buildings, which require details at doors and windows to allow for a major amount of shrinkage.

Siding and Trim

Siding and trim are affected by both shrinkage and swelling. Where the material has been installed at a high moisture content, gaps may open at joints as the wood shrinks. This can be unsightly and provide openings for water to enter. Shrinkage in the thickness may also loosen nails, resulting in loose or sagging boards. Where siding boards are double nailed, shrinkage may split the boards. If siding and trim are not adequately protected from rain, boards may swell, resulting in buckling or other types of distortion and possibly the crushing of wood fibers at joints. Alternate swelling and shrinking can be particularly damaging as the movement may completely pull out nails.

Plywood

Panel products perform slightly differently than boards. Because the grain direction is perpendicular in alternate plies of plywood, these panels are somewhat more stable than wood. However, a slight gap should be left between adjacent panels to allow for swelling. If adjacent panels are butted firmly against each other and major swelling occurs, edges

TABLE 3—Moisture content of wood in equilibrium with stated dry-bulb temperature and relative humidity in percent [1].

Temperature, dry-bulb °F	5	10	15	20	25	30	35	40	45	50	55	60	65	70	75	80	85	90	95	98
30	1.4	2.6	3.7	4.6	5.5	6.3	7.1	7.9	8.7	9.5	10.4	11.3	12.4	13.5	14.9	16.5	18.5	21.0	24.3	26.9
40	1.4	2.6	3.7	4.6	5.5	6.3	7.1	7.9	8.7	9.5	10.4	11.3	12.3	13.5	14.9	16.5	18.5	21.0	24.3	26.9
50	1.4	2.6	3.6	4.6	5.5	6.3	7.1	7.9	8.7	9.5	10.3	11.2	12.3	13.4	14.8	16.4	18.4	20.9	24.3	26.9
60	1.3	2.5	3.6	4.6	5.4	6.2	7.0	7.8	8.6	9.4	10.2	11.1	12.1	13.3	14.6	16.2	18.2	20.7	24.1	26.8
70	1.3	2.5	3.5	4.5	5.4	6.2	6.9	7.7	8.5	9.2	10.1	11.0	12.0	13.1	14.4	16.0	17.9	20.5	23.9	26.6
80	1.3	2.4	3.5	4.4	5.3	6.1	6.8	7.6	8.3	9.1	9.9	10.8	11.7	12.9	14.2	15.7	17.7	20.2	23.6	26.3
90	1.2	2.3	3.4	4.3	5.1	5.9	6.7	7.4	8.1	8.9	9.7	10.5	11.5	12.6	13.9	15.4	17.3	19.8	23.3	26.0
100	1.2	2.3	3.3	4.2	5.0	5.8	6.5	7.2	7.9	8.7	9.5	10.3	11.2	12.3	13.6	15.1	17.0	19.5	22.9	25.6
110	1.1	2.2	3.2	4.0	4.9	5.6	6.3	7.0	7.7	8.4	9.2	10.0	11.0	12.0	13.2	14.7	16.6	19.1	22.4	25.2
120	1.1	2.1	3.0	3.9	4.7	5.4	6.1	6.8	7.5	8.2	8.9	9.7	10.6	11.7	12.9	14.4	16.2	18.6	22.0	24.7
130	1.0	2.0	2.9	3.7	4.5	5.2	5.9	6.6	7.2	7.9	8.7	9.4	10.3	11.3	12.5	14.0	15.8	18.2	21.5	24.2
140	0.9	1.9	2.8	3.6	4.3	5.0	5.7	6.3	7.0	7.7	8.4	9.1	10.0	11.0	12.1	13.6	15.3	17.7	21.0	23.7
150	0.9	1.8	2.6	3.4	4.1	4.8	5.5	6.1	6.7	7.4	8.1	8.8	9.7	10.6	11.8	13.1	14.9	17.2	20.4	23.1
160	0.8	1.6	2.4	3.2	3.9	4.6	5.2	5.8	6.4	7.1	7.8	8.5	9.3	10.3	11.4	12.7	14.4	16.7	19.9	22.5
170	0.7	1.5	2.3	3.0	3.7	4.3	4.9	5.6	6.2	6.8	7.4	8.2	9.0	9.9	11.0	12.3	14.0	16.2	19.3	21.9
180	0.7	1.4	2.1	2.8	3.5	4.1	4.7	5.3	5.9	6.5	7.1	7.8	8.6	9.5	10.5	11.8	13.5	15.7	18.7	21.3
190	0.6	1.3	1.9	2.6	3.2	3.8	4.4	5.0	5.5	6.1	6.8	7.5	8.2	9.1	10.1	11.4	13.0	15.1	18.1	20.7
200	0.5	1.1	1.7	2.4	3.0	3.5	4.1	4.6	5.2	5.8	6.4	7.1	7.8	8.7	9.7	10.9	12.5	14.6	17.5	20.0
210	0.5	1.0	1.6	2.1	2.7	3.2	3.8	4.3	4.9	5.4	6.0	6.7	7.4	8.3	9.2	10.4	12.0	14.0	16.9	19.3
220	0.4	0.9	1.4	1.9	2.4	2.9	3.4	3.9	4.5	5.0	5.6	6.3	7.0	7.8	8.8	9.9	. . .	. . .	. . .	. . .
230	0.3	0.8	1.2	1.6	2.1	2.6	3.1	3.6	4.2	4.7	5.3	6.0	6.7	. . .	. . .	. . .	. . .	. . .	. . .	. . .
240	0.3	0.6	0.9	1.3	1.7	2.1	2.6	3.1	3.5	4.1	4.6	. . .	. . .	. . .	. . .	. . .	. . .	. . .	. . .	. . .
250	0.2	0.4	0.7	1.0	1.3	1.7	2.1	2.5	2.9	. . .	. . .	. . .	. . .	. . .	. . .	. . .	. . .	. . .	. . .	. . .
260	0.2	0.3	0.5	0.7	0.9	1.1	1.4	. . .	. . .	. . .	. . .	. . .	. . .	. . .	. . .	. . .	. . .	. . .	. . .	. . .
270	0.1	0.1	0.2	0.3	0.4	0.4	. . .	. . .	. . .	. . .	. . .	. . .	. . .	. . .	. . .	. . .	. . .	. . .	. . .	. . .

TABLE 4—Shrinkage values of domestic woods [1].

Species	Shrinkage from Green to Oven-Dry Moisture Content, %		
	Radial	Tangential	Volumetric
	HARDWOODS		
Alder, red	4.4	7.3	12.6
Ash			
Black	5.0	7.8	15.2
Blue	3.9	6.5	11.7
Green	4.6	7.1	12.5
Oregon	4.1	8.1	13.2
Pumpkin	3.7	6.3	12.0
White	4.9	7.8	13.3
Aspen			
Bigtooth	3.3	7.9	11.8
Quaking	3.5	6.7	11.5
Basswood, American	6.6	9.3	15.8
Beech, American	5.5	11.9	17.2
Birch			
Alaska paper	6.5	9.9	16.7
Gray	5.2	—	14.7
Paper	6.3	8.6	16.2
River	4.7	9.2	13.5
Sweet	6.5	9.0	15.6
Yellow	7.3	9.5	16.8
Buckeye, yellow	3.6	8.1	12.5
Butternut	3.4	6.4	10.6
Cherry, black	3.7	7.1	11.5
Chestnut, American	3.4	6.7	11.6
Cottonwood:			
Balsam poplar	3.0	7.1	10.5
Black	3.6	8.6	12.4
Eastern	3.9	9.2	13.9
Elm			
American	4.2	9.5	14.6
Cedar	4.7	10.2	15.4
Rock	4.8	8.1	14.9
Slippery	4.9	8.9	13.8
Winged	5.3	11.6	17.7
Hackberry	4.8	8.9	13.8
Hickory, Pecan	4.9	8.9	13.6
Hickory, True			
Mockernut	7.7	11.0	17.8
Pignut	7.2	11.5	17.9
Shagnut	7.0	10.5	16.7
Shellbark		12.6	9.2
Holly, American	4.8	9.9	16.9
Honeylocust	4.2	6.6	10.8
Locust, Black	4.6	7.2	10.2
Madrone, Pacific	5.6	12.4	18.1
Magnolia			
Port-Orford-Western redcedar	4.6	6.9	10.1
	2.4	5.0	6.8
Douglas fir			
Coast	4.8	7.6	12.4
Interior north	3.8	6.9	10.7
Interior west	4.8	7.5	11.8
Fir			
Balsam	2.9	6.9	11.2
California red	4.5	7.9	11.4
Grand	3.4	7.5	11.0
Noble	4.3	8.3	12.4
Pacific silver	4.4	9.2	13.0
Subalpine	2.6	7.4	9.4
White	3.3	7.0	9.8
Hemlock			
Eastern	3.0	6.8	9.7
Mountain	4.4	7.1	11.1
Western	4.2	7.8	12.4
Larch, western	4.5	9.1	14.0
Pine			
Eastern white	2.1	6.1	8.2
Jack	3.7	6.6	10.2
Loblolly	4.8	7.4	12.3
Lodgepole	4.3	6.7	11.1
Longleaf	5.1	7.5	12.2

TABLE 4—Shrinkage values of domestic woods (*continued*).

	Shrinkage from Green to Oven-Dry Moisture Content, %		
Species	Radial	Tangential	Volumetric
Pitch	4.0	7.1	10.9
Pond	5.1	7.1	11.2
Ponderosa	3.9	6.2	9.7
Red	3.8	7.2	11.3
Shortleaf	4.6	7.7	12.3
Slash	5.4	7.6	12.1
Sugar	2.9	5.6	7.9
Virginia	4.2	7.2	11.9
Western white	4.1	7.4	11.8
Redwood			
Old-growth	2.6	4.4	6.8
Young-growth	2.2	4.9	7.0
Spruce			
Black	4.1	6.8	11.3
Engelmann	3.8	7.1	11.0
Red	3.8	7.8	11.8
Sitka	4.3	7.5	11.5
Tamarack	3.7	7.4	13.6

TABLE 5—Shrinkage for some woods imported into the United States [*1*].

	Shrinkage from Green to Oven-Dry Moisture. Content, %	
Species	Radial	Tangential
Afromosia *(Pericopsis elata)*	3.0	6.4
Albarco *(Cariniana spp.)*	2.8	5.4
Andiroba *(Carapa guianensis)*	3.1	7.6
Angelin *(Andira inermis)*	4.6	9.8
Angelique *(Dicorynia guianensis)*	5.2	8.8
Apitong *(Dipterocarpus spp.)*	5.2	10.9
Azobe *(Lophira alata)*	8.4	11.0
Balata *(Manilkara bidentata)*	6.3	9.4
Balsa *(Ochroma pyramidale)*	3.0	7.6
Banak *(Virola spp.)*	4.6	8.8
Benge *(Guibourtia arnoldiana)*	5.2	8.6
Bubinga *(Guibourtia spp.)*	5.8	8.4
Caribbean pine *(Pinus caribaea)*	6.3	7.8
Cativo *(Prioria copaifera)*	2.4	5.3
Courbaril *(Hymenaea courbaril)*	4.5	8.5
Cuangare *(Dialyanthera spp.)*	4.2	9.4
Determa *(Ocotea rubra)*	3.7	7.6
Ebony *(Diospyros spp.)*	5.5	6.5
Gmelina *(Gmelina arborea)*	2.4	4.9
Greenheart *(Ocotea rodiaea)*	8.8	9.6
Hura *(Hura crepitans)*	2.7	4.5
Ipe *(Tabebuia spp.)*	6.6	8.0
Iroko *(Chlorophora excelsa and regia)*	2.8	3.8
Jarrah *(Eucalyptus marginata)*	4.6	10.2
Kaneelhart *(Licaria spp.)*	5.4	7.9
Kapur *(Dryobalanops spp.)*	4.6	10.2
Karri *(Eucalyptus diversicolor)*	7.2	10.7
Kempas *(Koompassia malaccensis)*	6.0	7.4
Keruing *(Dipterocarpus spp.)*	5.2	10.9
Lauan *(Shorea spp.)*	3.8	8.0
Limba *(Terminalia superba)*	4.5	6.2
Macawood *(Platymiscium spp.)*	2.7	3.5
Mahogony, true *(Swietenia macrophylla)*	3.0	4.1
Manbarklak *(Eschweilera spp.)*	5.8	10.3
Manni *(Symphonia globulifera)*	5.7	9.7
Marishballi *(Licania spp.)*	7.5	11.7
Merbau *(Intsia bijuga and palembanica)*	2.7	4.6
Mersawa *(Anisoptera spp.)*	4.0	9.0
Mora *(Mora spp.)*	6.9	9.8
Obeche *(Triplochiton scleroxylon)*	3.0	5.4
Ocota pine *(Pinus oocarpa)*	4.6	7.5
Okoume *(Aucoumea klaineana)*	4.1	6.1
Opepe *(Nauclea spp.)*	4.5	8.4
Parana pine *(Araucaria angustifolia)*	4.0	7.9
Pau Marfim *(Balfourodendron riedelianum)*	4.6	8.8

TABLE 5—Shrinkage for some woods imported into the United States (*continued*).

Species	Shrinkage from Green to Oven-Dry Moisture Content, % Radial	Tangential
Peroba Rosa *(Aspidosperma spp.)*	3.8	6.4
Piquia *(Cartocar spp.)*	5.0	8.0
Pilon *(Hyeronima spp.)*	5.4	11.7
Primavera *(Cybistax donnell-smithii)*	3.1	5.1
Purpleheart *(Peltogyne spp.)*	3.2	6.1
Ramin *(Gonystylus spp.)*	4.3	8.7
Roble *(Quercus spp.)*	6.4	11.7
Roble (*Tabebuia spp.* Roble group)	3.6	6.1
Rosewood, Brazilian *(Dalbergia nigra)*	2.9	4.6
Rosewood, Indian *(Dalbergia latifolia)*	2.7	5.8
Santa Maria *(Calophyllum brasiliense)*	4.6	8.0
Sapele *(Entandrophragma cylindricum)*	4.6	7.4
Sepetir (*Pseudosindora* and *Sindora spp.)*	3.7	7.0
Spanish-cedar *(Cedrela spp.)*	4.2	6.3
Teak *(Tectona grandis)*	2.5	5.8
Wallaba *(Eperua spp.)*	3.6	6.9

will be crushed or the panel will buckle, depending on how the panel is nailed.

Reconstituted Products

Hardboard and particleboard both swell in thickness with increased moisture. Unprotected edges are particularly vulnerable to moisture absorption, which can result in edge thickness swelling. Dimensional stability of both hardboard and particleboard varies considerably depending on the type and quantity of adhesives used and the application of heat and pressure in the manufacturing process. Oriented strand board (OSB) is a type of structural particleboard with good dimensional stability in the plane of its faces because it is made in layers with fibers in alternate layers perpendicular to each other similar to plywood.

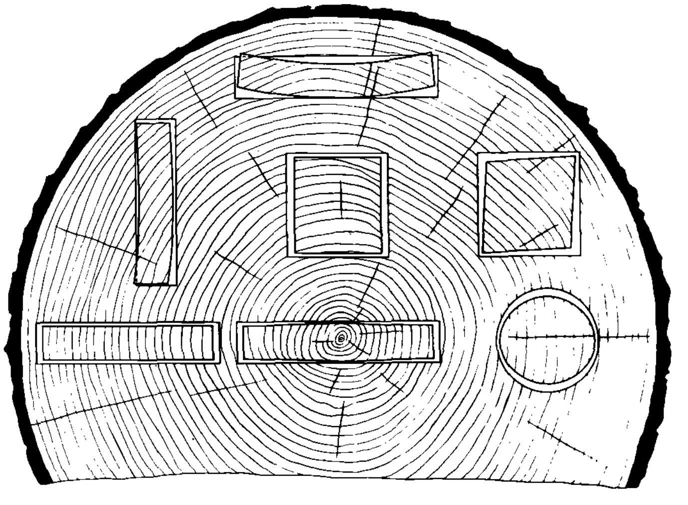

FIG. 3—Characteristic shrinkage and distortion of flats, squares, and rounds as affected by the direction of growth rings. Tangential shrinkage is about twice as great as radial [1].

Recommended Moisture Content

Regardless of the type of wood product used, the best performance is achieved when the material is installed at the average moisture content it will achieve in use. Where the material will be exposed to weather, it is essential that it be protected by a water-repellent finish to avoid large swings in

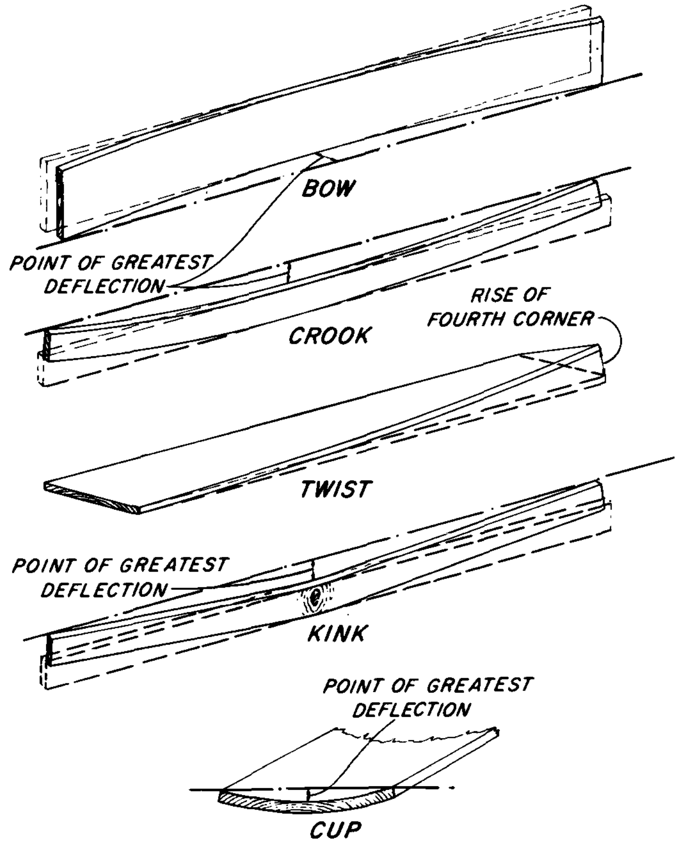

FIG. 4—Various types of warp [1].

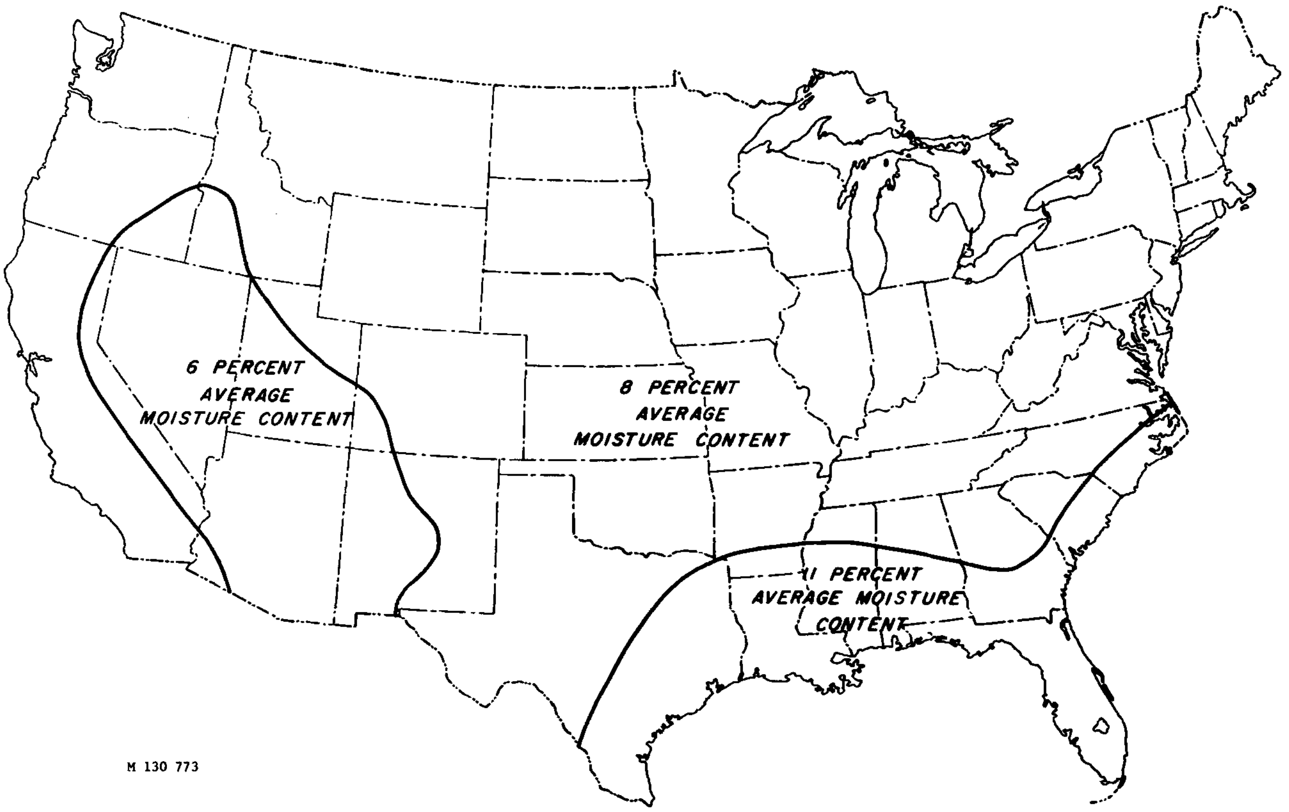

FIG. 5—Recommended average moisture content for interior use of wood products in various areas of the United States [*1*].

moisture content. Recommended average moisture content for interior use of wood products in various areas of the United States is shown in Fig. 5. More specific values for various wood items at time of installation are given in Table 6.

EFFECTS OF MOISTURE ON FINISHES

While a primary function of finishes is to protect wood from moisture, that same moisture plays a major role in degradation of finishes. Rain water erodes finish surfaces. When water gets behind film-forming finishes, it may cause blistering or chipping of the coating. Water also leaches out wood extractives and causes surface staining [*3*].

Film-Forming Finishes

Paints form a coating which resists the entrance of water from the exterior. That same coating prevents the escape of water that enters the wood through joints, through breaks in the coating, or as water vapor from the inside. Latex paints breath, so water vapor can escape through them even though they resist passage of water. However, if water accumulates faster than it can escape in the form of water vapor, the coating may be damaged. Also, extractives may leach through the latex paint unless a stain-resistant primer has been used. Oil base paints are resistant to water vapor diffusion, so water accumulation behind the coating may cause blisters. Water absorption in the wood may also cause boards to expand and pull apart the coating. Thick paint from many applications

TABLE 6—Recommended moisture content values for various wood items at time of installation [*1*].

	Moisture Content, %					
	Most Areas of United States		Dry Southwestern Area		Damp, Warm Coastal Areas	
Use of Wood	Average	Individual Pieces	Average	Individual Pieces	Average	Individual Pieces
Interior						
Woodwork, flooring, furniture wood trim, laminated timbers, cold-press plywood	8	6–10	6	4–9	11	8–13
Exterior						
Siding, wood trim, framing, sheathing, laminated timbers	12	9–14	9	7–12	12	9–14

may become especially brittle and thus be more vulnerable to failure from the expansion of wood. A good prime coat that is well adhered to the substrate is necessary for a lasting finish.

Natural Finishes

Natural finishes penetrate wood without forming a coating, so they do not have the type of failures that occur with paint. Stains used alone provide little moisture protection. A water repellent used alone or with stain retards the entrance of water and thus keeps boards dry so that dimensional change is minimized. The probability of mildew or other fungal attack is also greatly reduced. Application of water repellents to both sides of siding boards is often recommended as a pretreatment for paint. Water repellents cause water to bead up and run off rather than being quickly absorbed. Neither stains nor water repellents will prevent extractive staining from extractive-rich wood. Appropriate drying schedules for wood can fix extractives in the wood and thus prevent staining.

Fungal Attack

Fungus damage to wood may be traced to three general causes: (1) lack of suitable protective measures when storing logs or bolts; (2) improper seasoning, storing, or handling of the raw material produced from the log; and (3) failure to take ordinary simple precautions such as application of protective finishes and good construction practices [*4,5*] in using the final product. The incidence and development of molds, decay, and stains caused by fungi depend heavily on temperature and moisture. All fungi require free water and a temperature between about 3.3 and 37.8°C (40 and 100°F). High relative humidity will not support growth of fungi, but slight condensation of free water on surfaces will support fungal growth.

Mildew

Mildew is a fungus that grows only on the surface. It does not damage the wood, but can have a major effect on esthetics. It appears as gray to black blotches on the surface. Mildew needs only a thin film of condensation on a surface to grow. It is easily removed by applying a dilute solution of household bleach. A small drop of bleach solution will cause mildew to disappear completely. Of course the moisture source must be removed to prevent recurrence. Linseed oil is an excellent food source for mildew, so its use should be avoided in humid climates or humid indoor spaces.

Molds and Fungus Stains

Molds and fungus stains are confined largely to sapwood and are of various colors. Ordinarily, they affect the strength of the wood only slightly: their greatest effect is usually confined to strength properties that determine shock resistance or toughness. They also increase the absorptivity of wood, rendering it more susceptible to attack by typical wood-decay fungi. Stain- and mold-infected stock is practically unimpaired for many uses in which appearance is not a limiting factor, and a small amount of stain may be permitted by standard grading rules.

The principal fungus stains are usually referred to as "sap stain" or "blue stain." The distinction between molding and staining is made largely on the basis of the depth of discoloration. Typical sap stain or blue stain penetrates into the sapwood and cannot be removed by surfacing. Also, the discoloration as seen on a cross section of the wood often tends to exhibit radial alignment corresponding to the direction of the wood rays.

Mold discolorations usually first become noticeable as largely fuzzy or powdery surface growths, with colors ranging from light shades to black. On softwoods—though the fungus may penetrate deeply—the discoloring surface growth often can easily be brushed or surfaced off. On hardwoods, however, the wood beneath the surface growth is commonly stained too deeply to be surfaced off.

Decay

Decay-producing fungi may, under conditions that favor their growth, attack either heartwood or sapwood; the result is a condition often designated as decay or rot. Fresh surface growths of decay fungi may appear as fan-shaped patches, strands, or root-like structures, usually white or brown. Sometimes fruiting bodies are produced that take the form of toadstools, brackets, or crusts. The fungus, in the form of microscopic, thread-like strands, permeates the wood and uses parts of it as food. Some fungi live largely on the cellulose, which is a carbohydrate that forms the framework of wood cells; others use the lignin, which is the cementing layer between layers, as well as the cellulose.

Most decay can progress rapidly at temperatures that favor growth of plant life in general. For the most part, decay is relatively slow at temperatures below 10°C (50°F) and much above 26.7°C (90°F). Decay essentially ceases when the temperature drops as low as 1.7°C (35°F) or rises as high as 37.8°C (100°F). Because of many variables such as species, climate, exposure, wetting, dimension of timbers, and type of decay, it is difficult to put a time period on the development of decay. Observations of decay-susceptible species such as southern pine sapwood in frequently wetted, above-ground conditions, indicate decay may be apparent within a year. When wood is in ground contact, decay may be apparent in as little as two months.

Serious decay occurs only when the moisture content of the wood is above the fiber saturation point (average 30%). Readings of moisture content over 20% are considered to indicate danger of decay because average readings are generally higher than some single readings. Only when previously dried wood is contacted by water will the fiber saturation point be reached. Water vapor in humid air alone will not wet wood sufficiently to support significant decay, but it will permit development of some mold on the surface. Fully air-dry wood usually will have a moisture content not exceeding 20% and should provide a reasonable margin of safety against fungus damage. Thus wood will not decay if it is kept air dry—and decay already present from infection incurred earlier becomes dormant and will not progress. However, existing decay will not reverse, and if high moisture content returns, the decay reactivates.

Toughness, or the ability of wood to withstand impacts, is affected first by decay. This is generally followed by reductions in strength values related to static bending. Eventually all strength properties are seriously reduced. Strength losses during early stages of decay can be considerable, depending to a great extent upon the fungus involved and, to a lesser extent, upon the type of wood undergoing decay. In laboratory tests, losses in toughness have ranged from 6% to more than 50% by the time a 1% weight loss had occurred in the wood as a result of fungal attack. By the time weight losses due to decay have reached 10%, most strength losses may be expected to exceed 50%. As decay is detectable at such weight losses only through microscopical observations, it may be assumed that wood with visually discernible decay has been greatly reduced in all strength values.

INSECT ATTACK

Moisture plays a major role in insect attack. While free water is not necessary for insects as it is with fungi, most insects are attracted to damp or partially decayed wood. The main insects that attack buildings are termites (both subterranean and nonsubterranean), carpenter ants, and powder post beetles.

Subterranean Termites

Subterranean termites must have direct access to water; however, if there is no water in the wood, they will build tubes that connect the wood with damp soil. They normally do not establish themselves in buildings by being carried there in lumber, but enter from ground nests after the building has been constructed; however, an introduced species, the Formosan termite, is adept at initiating above-ground infestations where wood remains wet for prolonged period, such as from roof leaks.

Nonsubterranean Termites

Nonsubterranean termites do not require water and are often referred to as dry-wood termites. The amount of destruction they cause in the United States is much less than that caused by the subterranean termites. Their ability to live in dry wood without outside moisture or contact with the ground, however, makes them a definite menace in regions where they occur. Their principal damage is confined to an area in southern California, to parts of southern Florida, notably Key West, and to the islands of Hawaii. They are a localized problem in Arizona and New Mexico.

Carpenter Ants

Carpenter ants use wood for shelter rather than for food, usually preferring wood that is naturally soft or has been made soft by decay. They may enter a building directly, by crawling, or may be carried there in fuel wood. If left undisturbed, they can, in a few years, enlarge their tunnels to the point where replacement or extensive repairs are necessary. The parts of buildings they frequent most often are porch columns, porch roofs, window sills, and sometimes the wood plates in foundation walls. The logs of rustic cabins are also attacked.

PROTECTION FROM DEGRADATION

Three major methods of preventing degradation of wood exposed to water are: (1) application of finishes that prevent water entry, (2) use of the heartwood of durable species, and (3) use of preservative treatments.

Finishes

Finishes protect wood from degradation due to moisture by retarding the rate of water entry into the wood. Satisfactory performance is achieved when full consideration is given to the many factors that affect these finishes. These factors include the effect of the wood substrate, properties of the finishing material, details of application, and severity of exposure.

Water repellents can be used alone, in combination with penetrating stains, or as a pretreatment for paint. While water repellents allow the passage of water vapor, they retard the passage of free water. Joints and accessible end grain should be flooded with water repellent. When used alone, they do little to change the color or hide the grain of wood; however, they do not protect the wood from photodegradation due to ultra-violet light, so it will assume a weathered look in time. Water repellents require frequent reapplication for continued protection.

Paints form a film over wood and provide the best protection of any finish. However, they must be maintained by reapplication as they weather. Proper preparation and application is essential for good adhesion. The paint film can also be torn or broken by expansion or contraction of the wood with moisture changes. This is particularly a problem at joints.

Naturally Durable Species

Among decay-resistance species (see Tables 1 and 2), only the heartwood has significant resistance because the natural preservative chemicals in wood that retard the growth of fungi are essentially restricted to the heartwood. Natural resistance of species to fungi is important only where conditions conducive to decay exist or may develop. Where wood is subjected to severe decay conditions, such as in ground contact, pressure-treated wood rather than resistant heartwood is generally prescribed.

Preservative Treated Wood

Pressure-treated wood resists the attack of both fungi and insects even under the most severe conditions when treated to the recommended level of retention. Standard wood preservatives normally used in buildings are chromated copper arsenate (CCA), ammoniacal copper arsenate (ACA), and ammoniacal copper zinc arsenate (ACZA) in water solution.

CCA is used for hem/fir and southern pine; ACA and ACZA are used for Douglas fir. These preservatives are often used when cleanliness and paintability of the treated wood are required. Because they are applied with water, the wood should be redried after treatment to the moisture content it will achieve in use. When these preservatives are applied according to a prescribed pressure process, they become chemically bound to wood fibers and will not leach out.

Processes and retention levels are prescribed in standards developed by the American Wood Preservers Association (AWPA). Preservative effectiveness is influenced not only by the protective value of the preservative chemical itself, but also by the method of application and extent of penetration and retention of the preservative in the treated wood. Penetration can be increased by incising. Even with an effective preservative, good protection cannot be expected with poor penetration and substandard retentions. The species of wood, proportion of heartwood and sapwood, heartwood penetrability, and moisture content are among the important variables influencing the results of treatment. Treatment levels for ACA and CCA are stated in terms of km/m^3 (kg/m^3) or pounds of retention/ft^3 (lb/ft^3) of wood. One of three levels is commonly used in buildings:

1. 0.40 kg/m^3 (0.25 lb/ft^3) for above ground use.
2. 0.64 kg/m^3 (0.40 lb/ft^3) for soil and fresh water contact.
3. 0.96 kg/m^3 (0.60 lb/ft^3) for wood foundations.

When treated wood is field cut or drilled, a preservative must be brush applied to the cut surfaces.

Wood preservatives reported on and recommended here were registered for the uses described at the time this publication was prepared. Registrations of preservatives are under constant review by the Environmental Protection Agency. Therefore, consult a responsible state agency on the current status of any of these preservatives. Use only preservatives that bear a federal registration number and carry directions for use.

DESIGN FACTORS FOR WOOD PROTECTION

In addition to protecting wood with finishes or treatments, some general principles of construction need to be observed. These involve adequate separation from soil moisture, joints that drain rather than trap water, and protection of end grain from exposure to water [*4,5*].

Separation From Soil

All wood that is not specifically treated for ground contact must be kept a safe distance from the soil. The recommended minimum distance for framing from soil is 19.52 cm (8 in.); for siding the recommended minimum distance from the soil is 15.24 cm (6 in.) (Fig. 6). These distances provide some safety factor for buildup of ground level and for vegetation growing near the building. The 44.72-cm (18-in.) soil separation requirement under wood floors is primarily to allow space for inspection and maintenance if problems develop.

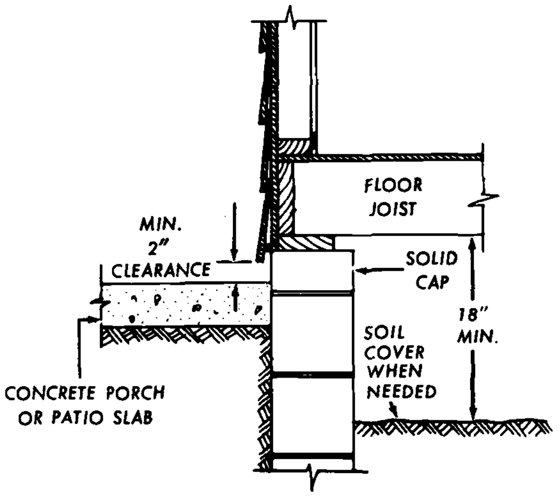

FIG. 6—Recommended clearance between wood siding and framing from soil [*3*]. (Printed with permission, National Forest Products Association.)

Joints Between Materials

All joints must drain rather than trap water. Some horizontal joints are protected by overlapping materials such as adjacent boards of lap siding. Where this overlap is not provided, flashing is required (Fig. 7), and a drip cap may be needed to prevent water from curling back under the flashing. Similar flashing is required over openings such as windows and doors (Fig. 8).

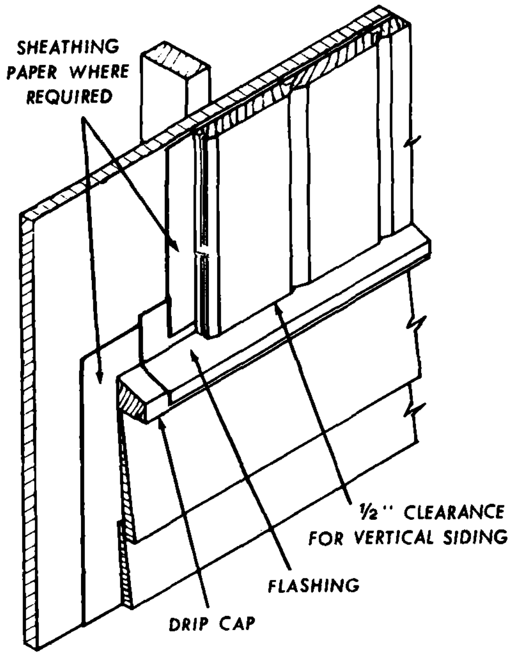

FIG. 7—Flashing where changes in exterior materials occur and air space for drying end grain of material [*3*]. (Printed with permission, National Forest Products Association.)

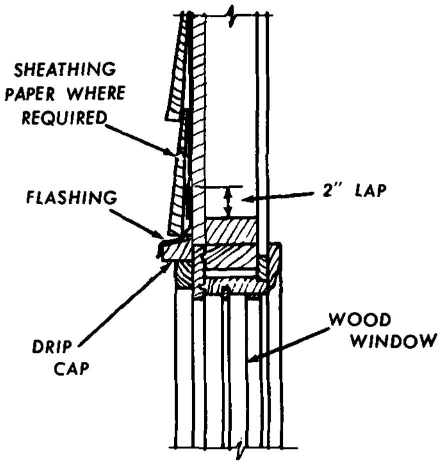

FIG. 8—Drip cap and flashing over exterior openings [3]. (Printed with permission, National Forest Products Association.)

Protection of End Grain

End grain of wood absorbs water so quickly that direct exposure to water should be avoided. Vertical members should have an air space between them and any horizontal surface so that water does not become trapped and soak into the end and so drying can occur if the end grain becomes wet (Fig. 7). Roof rafters and beams that extend outside the building should not extend beyond the roof line, and ends should be protected by a facia board or other type of cover. Connections and penetrations should be protected from exposure to rain. All end grain, such as butt joints of siding, should be flooded with a water repellent to reduce the rate of absorption of water.

SUMMARY

Control of moisture is the single most critical factor in good performance of wood and wood products. Moisture affects dimensional stability and can cause deformation of construction members. Excessive moisture can cause fungal growth with consequent degradation of wood. Moisture effects on wood can be controlled by following good construction practices as presented in available wood construction handbooks [4,5].

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6

Moisture, Organisms, and Health Effects

by Harriet A. Burge,[1] H. Jenny Su,[2] and John D. Spengler[3]

HISTORICALLY, MANKIND BEGAN THE SAGA of structure occupancy in caves, which were undoubtedly virtual mold gardens. As civilization advanced, indoor conditions became more and more hygienic, so that the Greeks and Romans lived in comparatively clean, dry environments. During the Middle Ages, however, hygiene was apparently forgotten. Rats (and probably cockroaches) were allowed to proliferate in occupied environments (leading to the black death), and straw was used to absorb all kinds of organic material on the floors of both castles and hovels (probably leading to exposure to allergenic, toxic, and possibly infectious fungi and bacteria). During these times, outdoor air, in spite of rain, snow, and hail, was far more healthy than indoor air.

Today, rats and cockroaches are not normally permitted in our living space, and straw is reserved for barns (sometimes leading to allergic and possibly toxic diseases in farm animals). We have designed and built homes and work places that are clean and that may be more healthy than the outdoor environment. Our interiors can be kept dry, and mechanical ventilation allows filtration of all entering air, providing a refuge from the fungus spores, bacteria, and other particles in outdoor air.

However, residential housing stock expands by approximately 1.5 million new units a year; over a decade, this represents more than 10% of our currently built residential environments. Changes in construction practices and materials are introduced at a rate exceeding our current capabilities to evaluate their implications. There is evidence that housing units are becoming smaller in size, more tightly constructed, and utilize more synthetic materials. Slab-on-grade foundations, carpets glued to concrete floors, and reduced air exchange rates can contribute to increased indoor humidity. Particle board flooring, counters, and cupboards can elevate formaldehyde concentrations, and these materials are more susceptible to microbial rot than solid wood.

In addition, throughout the 1980s, millions of square feet of commercial office space were added. Variable volume heating, ventilation, and air-conditioning (HVAC) systems, which supply ventilation air to interior spaces only on a temperature-based comfort demand, continue to be the common design. Man-made mineral fibers are used in ceiling tiles, decorative wall panels, and ventilation ducts. These fibers are produced from extruded or spun glass, slag, or rock wool, then fixed with water- or solvent-based binders, and can be coated with rubber adhesives such as neoprene. They provide an enormous surface on which hygroscopic dirt can accumulate and moisture can be retained.

Because outdoor air enters our buildings and because we use materials that can support microbial growth, strong sources of microorganisms (or other organisms) can occur indoors, and bioaerosols can become major health risks. The single most important factor that controls the presence, in buildings, of microorganisms and arthropods, such as cockroaches and mites, is moisture. This chapter will focus on the kinds of organisms that proliferate in buildings in response to moisture problems, the diseases that can result, and the factors that control colonization of building materials and spaces.

THE ORGANISMS

Fungi

The terms mold and mildew refer to the growth of organisms called fungi, much in the same way that the term "weed" refers to some plants and"pest" refers to some animals. Animals, plants, and fungi are all essential parts of the earth's natural environment. However, when animals such as cockroaches, rats, or mice invade human space, they are called"pests." When wild plants invade our cultivated fields and gardens, they are called "weeds." Likewise, when fungi grow on our clothing, our buildings, or our crops, they are called "molds" or "mildews"[*1*].

Like animals and plants, fungi are very common in the outdoor environment. Unlike most animals and plants, however, fungi produce spores which can reproduce the entire organism. These spores are designed to be transmitted through the air and are small enough to penetrate even small cracks in man-made structures. They are also readily carried into buildings in a dormant state on materials and clothing. Therefore, no environment is completely free of fungus spores [*2*].

The basic unit of the fungus is a cell which is bounded by a rigid cell wall. The cell wall of most fungi is composed of chitin (an acetyl-glucosamine polymer) rather than cellulose as is found in the plants. This is important because many fungi produce enzymes that allow degradation of cellulose for use

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as a nutrient. A few fungi (e.g., the yeasts) are unicellular. However, most fungal cells are organized into long chains called hyphae (Fig. 1). A mass of hyphae is called a mycelium. The mycelium is the white or black fluffy or filamentous material characteristic of visible fungal growth. The majority of fungi produce spores, each of which can reproduce the entire organism. Some are waxy and hydrophobic, and many contain a melanin pigment which allows survival during sunny, dry weather. Others are slimy, hydrophilic, and colorless and are often dispersed during rainy weather. Fungus identification is usually based on characteristics of spores and their method of production [3].

Unlike green plants, which can make their own food from carbon dioxide and water, the fungi require an environmental source for carbohydrates. Most obtain these nutrients by digesting complex organic materials such as dead parts of plants (including wood). The fungi accomplish this digestion by secreting enzymes that break down complex materials into simple sugars. Many fungi produce enzymes (called cellulase) that digest cellulose, which is the major structural material in most plants. Others produce ligninase (lignin is a major structural carbohydrate in wood) and enzymes that digest starch, sugars, and other compounds that plants use for food storage. The fungi are adaptable and can often "learn" to produce a specific enzyme to degrade almost any complex carbon-containing substance, including petroleum products [1].

Moisture is probably the most important factor controlling fungal growth on all substrates. Most fungi (with the exception of some yeasts) will not grow submerged in water because insufficient oxygen is available. This means that fungi do not generally grow in stagnant water, and those that actually rot wood fibers and cause loss of structural integrity will not grow in saturated wood. Note, however, that alternating periods of dryness and saturation allow decay fungi to flourish, and growth on surfaces of saturated wood that are exposed to air is inevitable.

Most fungus spores will not germinate and grow on wood (or other substrates) unless the moisture content is at least 25% [1]. Once a small area of wood has become wet enough and colonization has occurred, some fungi (especially the "dry rot" fungi) can carry adequate water to other parts of the substrate and the contamination can spread well beyond the original wet area. In addition, surface growth can change the surface even of treated wood from hydrophobic to hydrophilic, allowing more rapid absorption of available water.

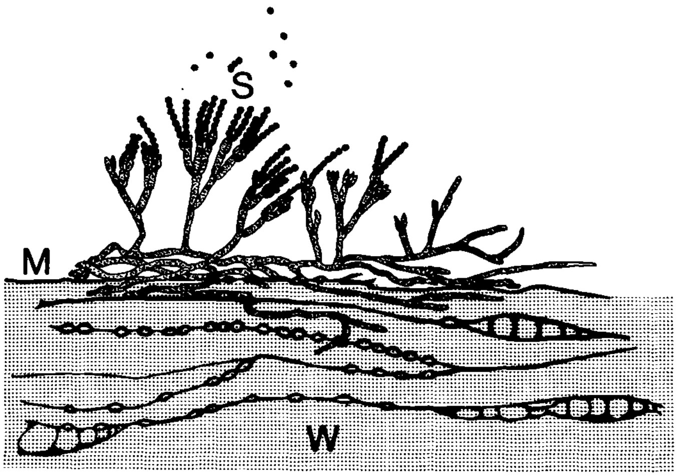

FIG. 1—Diagrammatic representation of fungal growth and population in and on the surface of wood: M = mycelium, S = spores, W = wood.

Fungal colonization of any substrate also depends on temperature. At a suitable moisture level, fungus growth rate is directly related to temperature up to an optimum [which is often between 80 and 90°F (27 to 32°C)]. Above the optimum, growth rate again declines, and the fungus may die. Cold temperatures halt fungus growth, but often do not cause death.

Light can inhibit growth of colorless (white) fungus mycelium, and some wavelengths of ultraviolet light probably kill such growth. Light has apparently less effect on brown fungi. However, some light is required for production of spores in many fungi.

Bacteria

Bacteria are primitive microorganisms that live primarily in soil and on plant surfaces. Bacteria can be transmitted through the air as single cells or carried on other particles and can penetrate buildings in this form. However, most bacteria in the indoor environment are those that colonize human skin surfaces and respiratory secretions. The skin surface bacteria are, by far, the most common type recovered from air in clean indoor environments. A few bacteria that penetrate indoor environments can colonize water reservoirs or very wet organic material and cause both deterioration of building products and human disease.

Most bacteria are unicellular or, at most, exist as chains of cells. The actinomycetes, a specialized group of bacteria, are filamentous. The unicellular bacteria can be spherical, rod shaped, or occasionally spiral shaped. Bacteria are also classified by the Gram reaction, which is a cell-wall staining procedure. Gram-positive bacteria retain a purple dye during treatment with alcohol. In this group are the common spherical bacteria that are shed into the air from human skin, and the genus *Bacillus* which produces very resistant spores called endospores. Some actinomycetes also produce endospores, including members of the genus *Thermoactinomyces*, which grow at high temperatures and are known to contaminate HVAC components [4]. Gram-negative organisms (including *Pseudomonas* and *Legionella*) can contaminate water reservoirs in buildings. The Gram-negative bacterial cell wall contains a lipopolysaccharide called endotoxin that has many biological effects (see below).

Bacteria generally require more water than fungi and can live submerged in standing water. Vegetative bacterial cells generally do not survive desiccation. Exceptions are the thermophilic actinomycetes and endospore-forming bacteria (e.g., *Bacillus*). Most bacteria live in a temperature range similar to fungi (and people). Once again, the thermophilic actinomycetes are an exception and prefer temperatures in excess of 50°C. Some *Bacillus* species also grow best at these elevated temperatures. Ultraviolet light is generally deadly to vegetative bacterial cells, although bacterial endospores are resistant.

Arthropods (Mites and Cockroaches)

Arthropods are invertebrate animals with jointed legs and segmented bodies. Included in this group are insects (e.g., cockroaches, ants, flies, etc.), arachnids (mites, ticks, spiders, scorpions), crustaceans (crabs, shrimp, lobsters, pill bugs), and the myriopods (millipedes and centipedes). Of these, cockroaches and mites are known to proliferate in indoor environments and are important causes of asthma. Pill bugs also can infest homes, but related health effects have not been reported. Cockroach infestation is related to access to food (readily digestible organic material) and moisture. Control of both factors is necessary to prevent contamination [*5*]. Mites can use human skin scales for food, so that food is always present. However, mites will not survive when relative humidity is consistently below 50% [*6*].

HUMAN HEALTH EFFECTS [7]

Hypersensitivity Diseases

Many of the biological agents that contaminate buildings cause allergic disease (i.e., they produce allergens). These allergens cause diseases such as allergic rhinitis (commonly known as hay fever), asthma, and a serious form of allergic pneumonia called hypersensitivity pneumonitis. All allergic diseases involve two steps: sensitization, which prepares specific cells or circulating molecules to recognize specific foreign material (e.g., a particular kind of fungus spore), and subsequent exposure to the same foreign material, which elicits symptoms. Frequent, often long-term, exposure is required for sensitization. This exposure may occur in outdoor air. Subsequent exposure in buildings then elicits symptoms.

Parts of fungi (spores, fragments) and high molecular weight metabolic products can act as allergens [*2*]. Probably all fungi can cause these diseases. In addition, a few kinds of bacteria can cause hypersensitivity pneumonitis (*Bacillus*, the thermophilic actinomycetes) and mites and cockroaches produce allergens that are common causes of asthma.

Infections

Some living microorganisms (bacteria and fungi) can invade living tissue and cause infectious disease when they encounter susceptible hosts. Most of the common airborne fungal infections are caused by fungi that do not grow on substrates in buildings (e.g., *Blastomyces, Coccidioides*). These fungi will attack all exposed people who have not developed specific protective immunity (i.e., who have not had the disease). *Histoplasma*, another virulent fungal infectious agent, will grow on bird droppings containing soil and moisture. Infections with common indoor fungi (such as *Aspergillus fumigatus*) occur only in people with very serious underlying disease or other factors that have damaged their ability to fight infections (e.g., AIDS, transplant patients).

Bacterial infections known to be related to moisture and structural contamination of indoor environments are Legionnaires' disease and (rarely) other opportunistic bacterial infections [*8*]. As with the opportunistic fungi, these infections occur only in people with damaged immunity, although for Legionnaires' disease the damage can be relatively slight (e.g., damage to lung immunity caused by smoking).

Toxicoses

Fungus growth on substrates in buildings can allow release into the environment of other substances that can affect both human comfort and health. Volatile organic compounds can be released that cause the characteristic odors associated with fungal growth. These compounds may cause irritation to mucous membranes and may have toxic effects that include headaches, dizziness, nausea, and possibly cancer with long-term exposure. The nature of the volatile compounds released by fungal growth depends on the kind of fungus present, the amount of water available, and the kind of substrate on which the fungus is growing [*9,10*]. In addition to volatile compounds, many fungi release higher molecular weight compounds known as mycotoxins. These low-molecular-weight but nonvolatile substances are among the most acutely toxic and carcinogenic substances known. They are produced by specific fungi and in some cases are produced only during degradation of specific materials [*11*]. Although not volatile, the mycotoxins readily enter the air with spores or other fragments of the fungus or when substrate materials become aerosolized [*12*].

Bacterial endotoxin [*13*] is a part of the cell wall of Gram-negative bacteria. These organisms can contaminate humidifiers and other water reservoirs and, when aerosolized, probably contribute to the typical symptoms of humidifier fever.

Epidemiology

Although we know these diseases occur, their prevalence and clear association with building-related exposure are only beginning to be examined. Several studies report an association between respiratory symptoms in children and home dampness and fungi [*14–19*]. These studies consistently demonstrate that self-reported mold on surfaces, water damage, and excessive moisture are strongly associated with excess reporting of upper and lower respiratory symptoms—wheeze, asthma, and other conditions.

Specifically, in the late 1980s the Harvard Six Cities Study surveyed a new cohort of elementary school-age children. Brunekreef et al. [*19*] analyzed the respiratory response for over 5000 white children whose parents completed and returned the questionnaire. Housing conditions, including the presence of molds and mildew, wet basements, and the occurrence of flooding or water damage, were assessed with the same questionnaire. After adjusting for smoking and other factors, all symptoms were strongly associated with mildew and a combined dampness index. Dales, Burnett, and Zwanenburg [*20*] investigated the association between home dampness and/or mold and health from questionnaires distributed to 14 799 households in 30 Canadian communities. Some 38% of the respondents reported the presence of home dampness and/or molds. Table 1 reports crude and adjusted odds ratios (with 95% confidence intervals) from the Canadian study. An important observation was that the associations between symptoms and dampness or mold were actually slighty stronger where allergies were not present (Table 2).

TABLE 1—Crude and adjusted odds ratios (OR) with 95% confidence intervals for the associations between symptoms and disorders and dampness and mold (from *American Review of Respiratory Diseases*, 1991, Vol. 143, pp. 505–509).

	Dampness/Mold	
Symptom/Disorder	Crude OR	Adjusted OR[a]
Upper respiratory symptoms	1.58 (1.47, 1.69)	1.50 (1.39, 1.61)
Lower respiratory symptoms	1.67 (1.54, 1.82)	1.62 (1.48, 1.78)
Chronic respiratory disease	1.66 (1.48, 1.85)	1.45 (1.29, 1.64)
Asthma	1.77 (1.42, 2.20)	1.56 (1.25, 1.95)
Eye irritation	1.76 (1.59, 1.95)	1.63 (1.46, 1.82)
Other symptoms	1.58 (1.47, 1.70)	1.46 (1.36, 1.58)

[a] Adjusted using SAS CATMOD procedure. Please see text for details.

These large studies of North American populations indicate that the prevalence of "dampness" conditions are wide spread, in the range of 40 to 60%. Further, the association of these conditions with respiratory symptoms are substantial, with odds ratios varying between 1.4 and 2.2. If these association are real, then moisture and mold conditions within our current housing stock are a substantial contribution to morbidity.

The link between measured indoor relative humidity and reported symptoms are not as clear. Melia et al. [*14*] examined primary school-age children from 183 homes in an urban area north of London. They measured relative humidity (RH) averaged over a week in the child's bedroom. The respiratory symptoms prevalence rates for RH greater than 55% and between 55 and 74.9% were quite similar. The prevalence rates of respiratory symptoms for children sleeping in bedrooms with week-long RH exceeding 75% are substantially elevated over the other categories. Strachan and Saunders [*21*] found no relationship between home RH and respiratory symptoms. Their study of 778 children (in 371 bedrooms) in Edinburgh did not experience, though, the wide range of bedroom RH reported by Melia. Ross and colleagues [*22*] examined 297 young children ages 24–59 months and found no association between respiratory tract symptoms and home temperature or humidity levels.

TABLE 2—Percentage prevalences and odds ratios (OR) of lower respiratory symptoms stratified by physician-diagnosed allergies and asthma (from *American Review of Respiratory Diseases*, 1991, Vol. 143, pp. 505–509).

		Dampness/Mold		
Indicator of Atopy		Absent, %	Present, %	Crude OR (95% CI)
Allergies[a]	Absent	14	21	1.59 (1.44, 1.75)[b]
	Present	37	46	1.46 (1.21, 1.76)
Asthma[a]	Absent	15.2	22.4	1.61 (1.47, 1.77)[b]
	Present	64.7	72.9	1.46 (1.06, 2.03)

[a] The presence of an allergy was defined as a positive response to the question "Has a doctor ever said that you [have] one or more allergies [to the following] dust, pollen, mold, animals?" Asthma was defined as a positive response to the question "Has a doctor ever said that you had asthma?"

[b] Odds ratios were not significantly different as determined by the Breslow-Day test for homogeneity: chi-square = 0.581, $p = 0.45$ for allergies; chi-square = 0.316, $p = 0.57$ for asthma.

These apparent disparities may be related to the fact that surface moisture can be adequate to support microbial growth in the absence of elevated relative humidity, and that many symptoms might be related to cold and damp conditions through associations with survival of mites, fungi, and bacteria.

ORGANISMS, MOISTURE, AND BUILDINGS

Aside from their effects on human health, fungal and bacterial growth causes deterioration of the appearance and structural integrity of building materials. Given time and appropriate conditions, a fungus can completely destroy organic building materials.

Fungal Substrates

Because wood is such an important building material, especially in residences, it is useful to further consider the effects of fungal growth on wooden substrates (see Chapter 5). Fungal colonization of wood products can be classified into four large categories based on the wood components utilized: brown rot, white rot, soft rot, and staining. The brown and white rot fungi penetrate throughout the wood, destroying its structural integrity, and often produce the familiar bracket or shelf fungi seen on dead or dying trees in the forest. When these fruiting bodies are produced in contaminated buildings, spore aerosols are produced that can cause asthma and hypersensitivity pneumonitis [*23*]. The brown rot fungi attack cellulose but not lignin and cause the wood to turn brown, break up into brick-shaped pieces, and finally crumble into powder. The white rot fungi (which attack mostly hardwood) can digest both cellulose and lignin. They cause the wood to turn into a whitish fibrous mass.

Soft rot is a surface rot caused by fungi that do not produce large fruiting bodies and can only degrade cellulose. These fungi produce hydrophilic spores that are often discharged in slimy masses. They are abundant in outdoor air during rainy weather, but have not yet been reported from sources indoors. Finally, the staining fungi are not able to digest the structural material of wood, but live on the sap sugars and other food components stored in wood. These same fungi can, however, degrade and destroy the structural integrity of wood chip/fiber products by digesting the binders. Many common fungi (often called molds) can cause this kind of rot as well as wood discoloration, odors, and, in the indoor environment, generate aerosols that can cause a wide variety of health effects (Table 3).

Other materials in buildings susceptible to mold contamination include natural and synthetic fabrics, paper, cellulose-based thermal and sound insulation materials, paints, and a variety of man-made polymers [*24*]. Many of these substrates can be rotted by the common fungi that cause only surface discoloration of solid wood. For example, such fungi can cause significant weight loss and structural deterioration of fiberboard [*25*]. In general, the same factors (i.e., temperature, moisture, light) control fungal colonization of these substrates as for wood, but they have not been as carefully studied. Fungi can also contribute to corrosion of metal in situations where moisture and a food source (e.g., some

TABLE 3—Summary of diseases caused by organisms that contaminate buildings.

Disease Type	Disease Name	Symptoms	Agents	Environmental Sources
Infections	Influenza	Fever, chills	Viruses	Humans
	Colds	Congestion, chills	Viruses	Humans
	Tuberculosis	Cough, fever	Bacteria	Humans
	Legionellosis	Pneumonia	Bacteria	Hot Water
Allergies	Hay fever	Congestion	Fungi	Damp surfaces & materials
	Asthma	Wheeze	Fungi	
			Mites	
			Cockroaches	
	Hypersensitivity pneumonitis	Pneumonia	Bacteria	Water, wet surfaces
			Fungi	Damp surfaces & materials
Toxicoses	Humidifier fever	Fever, chills	Endotoxin	Water, wet surfaces
	Cancer	Variable	Mycotoxins	Damp surfaces & materials
	Acute toxic symptoms	Variable	Mycotoxins	Damp surfaces & materials
	Irritation	Itching, watery eyes	Volatiles	Damp surfaces & materials

organic material) is present. In these situations, some fungi can produce acids and other chemicals that react with some metals (e.g., aluminum).

Bacterial Substrates

Although bacteria can also contaminate damp organic material to some extent, they are usually the dominant organisms in standing water. Humidifiers, cooling towers, and other water sources are nearly always contaminated with bacteria, and epidemics of disease have been reported from aerosolization of these organisms [*26,27*]. In addition, the thermophilic actinomycetes can contaminate elements of heating systems where water is available and where temperatures consistently reach 50°C [*28*].

Prevention of Contamination

Because fungi and bacteria are ubiquitous in air and on natural substrates, they are always available to attack any suitable material as soon as moisture and temperature conditions are appropriate. Although most organic materials used in buildings are treated in ways that, for practical purposes, sterilize the product, reinoculation inevitably occurs during storage, transport, and installation. Therefore, merely preventing intrusion of spores or bacterial cells into a building (e.g., by filtration) will not guarantee that fungal or bacterial growth will not occur.

As discussed above, food materials useful for fungi and bacteria are always available in the form of materials used in the structure and decoration of buildings. This means that limiting the use of organic-based materials to prevent microbial growth is impractical except under circumstances where water is certain to be present or where condensation is likely and access for removal of contaminated material is difficult. For example, organic materials should not be used in ventilation systems where relative humidity is expected to routinely exceed 75% or where removal of such material would be extremely costly. This means that organic fibrous insulation or fire-retardant material should not be used unless the costs associated with possible contamination are acceptable. For example, organic fibrous fire retardant was used throughout a hospital, subsequently became damp (because of condensation), and supported a luxurious growth of *Aspergillus fumigatus* (a fungus that can cause human infections). An epidemic of this disease occurred (resulting in deaths and lawsuits), and the material had to be removed from the entire hospital building [*24*]. Clearly, in this case, the possibly higher initial cost of inorganic fire retardants would have been the most economical choice. On the other hand, a home owner might be willing to take the risk of using organic attic insulation, recognizing that proper moisture control should prevent problems, and removal and reinstallation of new insulation would not be prohibitively expensive.

Because microorganisms are ubiquitous and their food sources are intrinsic parts of most buildings, growth will inevitably occur unless some other requirement for growth is eliminated. Since fungi and bacteria grow well over the entire range of temperature and light conditions suitable for human occupany, these factors cannot be used for contamination control.

Limitation of Access to Water

Fungal and bacterial growth can be prevented if moisture is not permitted or if necessary moisture is not allowed access to organic material. Moisture is present in buildings through inadvertent intrusion (floods, leaks), as part of building design (fountains, water reservoirs), and as water vapor (humidity).

Flooding is defined here as a rapid intrusion of large amounts of water into a building. If flood water is clean (rain water or potable water) and is removed and all substrates dried within 24 h, microbial growth is unlikely. Allowing wetted organic materials to remain wet for more than 24 h is likely to result in fungal growth (Fig. 2). Sewage water is always contaminated with bacteria, including human pathogenic organisms. Sewage-contaminated soft organic material usually must be discarded. However, unless thoroughly soaked, wood and most wood products (other than paper) can probably be saved. If flood water is allowed to stand for days, bacterial growth can occur in the water and fungal growth on adjacent wetted surfaces.

Leaks occur when rainwater is allowed to penetrate a building or when pipes carrying water become damaged or are improperly connected. These are usually preventable. Where leaks tend to be difficult to control (e.g., flat roofs, intersections between connected buildings, etc.), materials should be

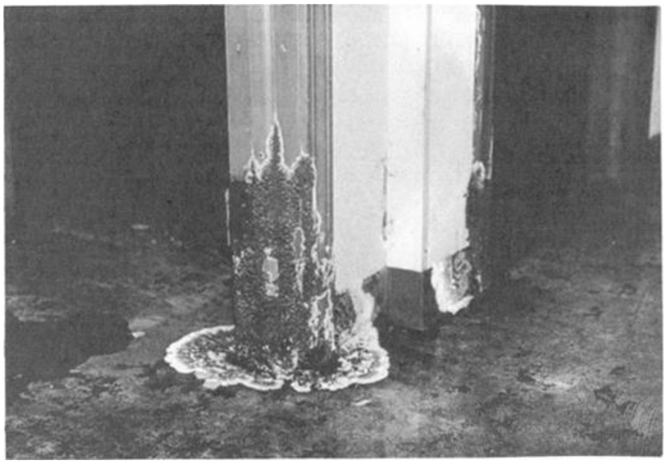

FIG. 2—*Penicillium sp.* contaminating flood-damaged wood and particle board. Photo courtesy of Adrienne Oudbier.

used that are not highly susceptible to fungal rot (e.g., hardwood or nonorganic structural materials) and care should be taken that the water cannot cause dampness that will result in surface growth of fungi in the occupied space.

Some water reservoirs are necessary in buildings. For example, cooling equipment is almost always associated with condensation and the condensate accumulates, at least briefly, in a reservoir. Such reservoirs always contain some bacteria. However, cooling systems can be designed so that water continually drips from the coils, thereby keeping surfaces washed free of dirt, which is often a good organic food source. Drip pans that collect condensate can be designed to drain so that stagnant water does not accumulate. Also, such systems can be designed so that access is provided for maintenance. Fungi and bacterial growth are encouraged by accumulated mineral scale and are much less likely to become a problem if metal surfaces are clean.

Humidification systems are sometimes installed in commercial buildings and are often a part of home heating systems. In general, systems relying on evaporation (as are used in most residences) cause little problem providing water reservoirs are kept reasonably clean (free of scale). The trickling common type of humidifier that uses clean, potable water that is not recirculated is the least susceptible to serious microbial contamination. In large buildings, steam humidification is often used. Microbial contamination is not a problem in the steam itself, but condensation and subsequent fungal and bacterial growth can occur on surfaces adjacent to the steam source. These surfaces should be bare metal and accessible for routine cleaning. Insulation on the surfaces (which could prevent condensation) should be external (i.e., not in contact with the humid air).

Control of relative humidity in the occupied space as well as in the ventilation system is an important factor for prevention of fungal contamination. Elevated relative humidity allows condensation on cool surfaces. It is almost impossible to completely avoid such cool surfaces in many environments. In winter, cold temperatures outdoors are transmitted to indoor surfaces by conduction through solid materials (glass, metal, even wood). Indoor relative humidity as low as 50% will allow condensation and resulting fungus growth on these cold surfaces. Prevention involves maintaining relative humidity below 50% in cold weather and insulating to prevent cold surfaces. In hot weather, condensation can occur when air conditioning systems fail or are subverted by open windows. Influx of warm, humid air allows condensation on cooled indoor surfaces, sometimes resulting in catastrophic fungal contamination. In humid climates, hotel rooms and homes with sliding glass doors leading to patios or balconies are common sites for this kind of problem. Sound insulation in air-handling units can provide a large surface area that could support the growth of fungi and bacteria. Such insulation should always be inorganic and, if possible, should have an inorganic smooth surface. An example of a paper-surfaced fiberglass insulation material that has rotted because of inadequate water control in a cooling system is shown in Fig. 3. Note that the resin binders in fiberglass insulation will also support fungal growth if adequate water is present, especially where carbonaceous dirt allows active growth to begin.

In addition to condensation, elevated relative humidity allows hygroscopic materials in the environment to absorb sufficient water to allow growth of some fungi. For example, the primary component of dust in most environments is human skin scales, which are extremely hygroscopic. At relative humidities above 50%, these particles absorb enough water to support growth of a number of fungal species, as well as the highly allergenic house dust mite. Minimizing dust accumulation is important in the control of this kind of contamination. However, dust can never be completely eliminated. For example, filters are designed to collect and retain dust. Under high humidity conditions, extensive growth of fungi can occur on dust-caked filters. Spores from this growth can subsequently be spread into the occupied space.

Biocides for Prevention of Contamination

The use of biocides to control potential microbial contamination is widespread. In some cases, treatment to prevent decay is the only option (e.g., for wood that will be continuously exposed to soil). However, biocides, by definition, are toxic, and must be used with great care in occupied environments. For example, biocides added to drip pans have as much chance of entering the air of occupied spaces as do the

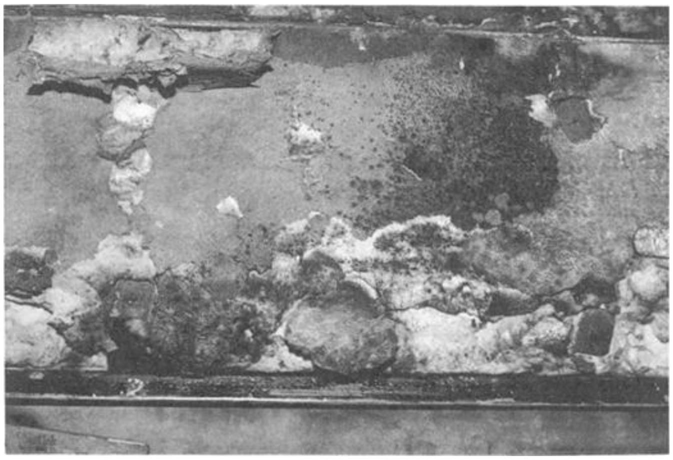

FIG. 3—*Cladosporium* and other fungi contaminating sound lining in an air handling system.

microorganisms they are designed to kill. Biocides should be used only when other means of controlling microbial contamination are not possible and only after careful consideration of the relative risks of exposure to the biocide compared to the fungus or other organism.

Remediation

Nonporous materials that have developed surface contamination with fungi or bacteria can be cleaned using water with or without detergents and biocides (e.g., bleach or peroxide). Surfaces should subsequently be dried thoroughly. However, note that conditions causing the contamination in the first place must be corrected or the problem will surely reoccur.

Contaminated porous materials can never be made completely free of fungus material (see Fig. 1), although the organisms can be killed. If simple killing and removal of surface growth is adequate, the same steps can be used as for nonporous materials. If significant decay has occurred (see Fig. 3), needless to say, the material will have to be removed and replaced with new. It is extremely important that all rotted material be removed, and that, as above, conditions that allowed the contamination to occur be corrected.

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7

Climate

by Frank J. Powell[1]

THE MOISTURE PERFORMANCE of a building is determined to a great extent by the climate at a particular geographic location. The prevailing climate also influences the type of preventative or remedial action that may be required. Climates in the United States and Canada can be generally classified as:

1. Hot/Warm and Dry
   SW, Arizona, New Mexico
2. Hot/Warm and Humid
   Florida, Gulf States
3. Moderate
   California, Oregon, Washington
4. Temperate
   Midwest, Northeast
5. Cold
   Upper tier of States, Canada

Each classification presents its unique moisture environment, and an analysis should be made using weather records keyed to the local conditions surrounding the building. For example, in a hot/warm and humid climate, the number of hours requiring air conditioning during the warmest six consecutive months is significant. Because of high outdoor levels of humidity, one of the principal concerns in this climate is mold and mildew in addition to rain penetration, groundwater, and possibly condensation.

In moisture evaluations, the indoor climate conditions are of primary importance. For human comfort and energy conservation, indoor dry-bulb air temperatures are often specified at about 21°C for winter heating and 25°C for summer cooling. The relative humidity at room temperature comfort conditions during heating months generally should not exceed 35% in cold, temperate, and moderate climates. For the hot/warm, moderate, and temperate climates, the relative humidity during cooling periods should not exceed about 50%.

Weather data are normally gathered and reported at weather stations at airports. For special conditions such as heat sinks (heat islands), as may be found within a group of high-rise buildings downtown in a large city, an experienced consulting meteorologist should evaluate such stringent requirements and local conditions. Designers often must interpolate weather conditions remote from weather stations where data are gathered. There appears to be no reliable mathematical way of interpolating, but designers routinely arrive at a reasonable estimate of local weather conditions between two or more stations. For example, the design winter dry-bulb temperature from data taken at the Philadelphia, PA, airport is −12°C and that of Scranton/Wilkes-Barre, PA, is −17°C (see page 108 in Appendix to this chapter, Ref *1*). For Stroudsburg, PA, which is about halfway between Philadelphia and Scranton/Wilkes-Barre, data are not listed. However, listed is Allentown, PA, also in the foothills of the mountains at a location near Stroudsburg. The winter design temperature for Allentown is given as −16°C. In this case, the designer would probably select −16°C for Stroudsburg, PA. Other special conditions of microclimate, such as intervening mountains, lakes, desert, and sun reflecting off snow cover, should be examined for any proposed building site. It is well known, for example, that the north slope of a mountain can have a distinctly different climate from the south slope only a few hundred feet or a few miles away. Such localized weather effects can be significant with regard to moisture evaluations.

PSYCHROMETRICS

Psychrometrics deal with the thermodynamic properties of moist air. Moist air is a mixture of dry air and water vapor. The amount of water vapor in moist air varies from zero for dry air to a maximum which depends on temperature and pressure. The maximum condition is called saturation.

The main variables of interest in moisture evaluations are:

- barometric pressure
- temperature
- wet-bulb temperature
- relative humidity
- dew point temperature
- water vapor pressure
- indoor-outdoor temperature difference
- indoor-outdoor water vapor pressure difference

When convective mass transfer is involved, the indoor-outdoor total pressure difference is of interest. The above variables and their relationship to each other can best be visualized by utilizing a psychrometric chart (reproduced on pages 92 and 93 as ASHRAE psychrometric Charts No. 1 and No. 2, Sea Level). Charts are also available for high temperatures, 10°C to 120°C, and for very high temperatures, 100°C to 200°C, at sea level. Other normal temperature charts are available for elevations of 750 m, 1500 m, and 2250 m. Figure 1 shows schematically on a partial grid of a psychrometric

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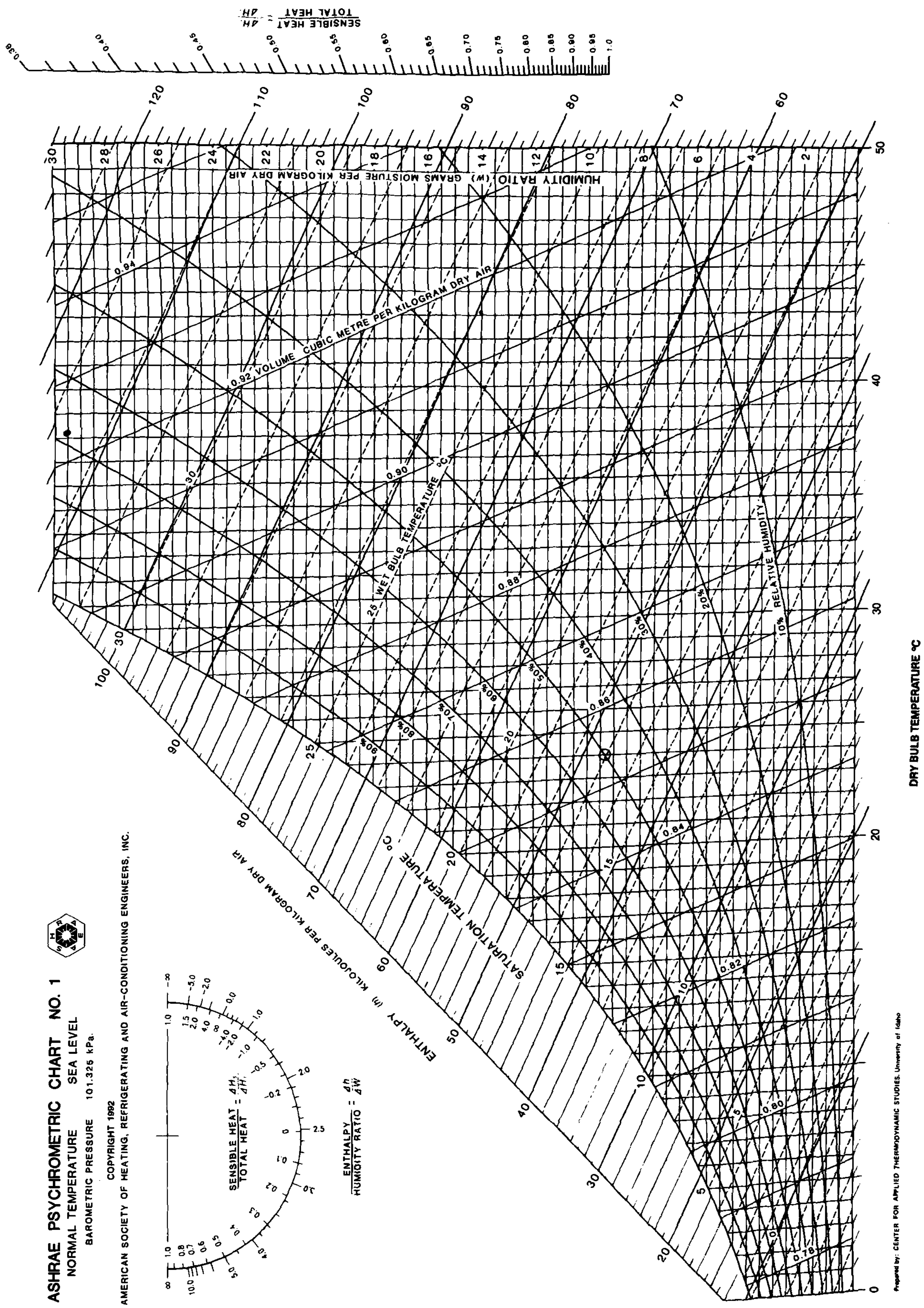
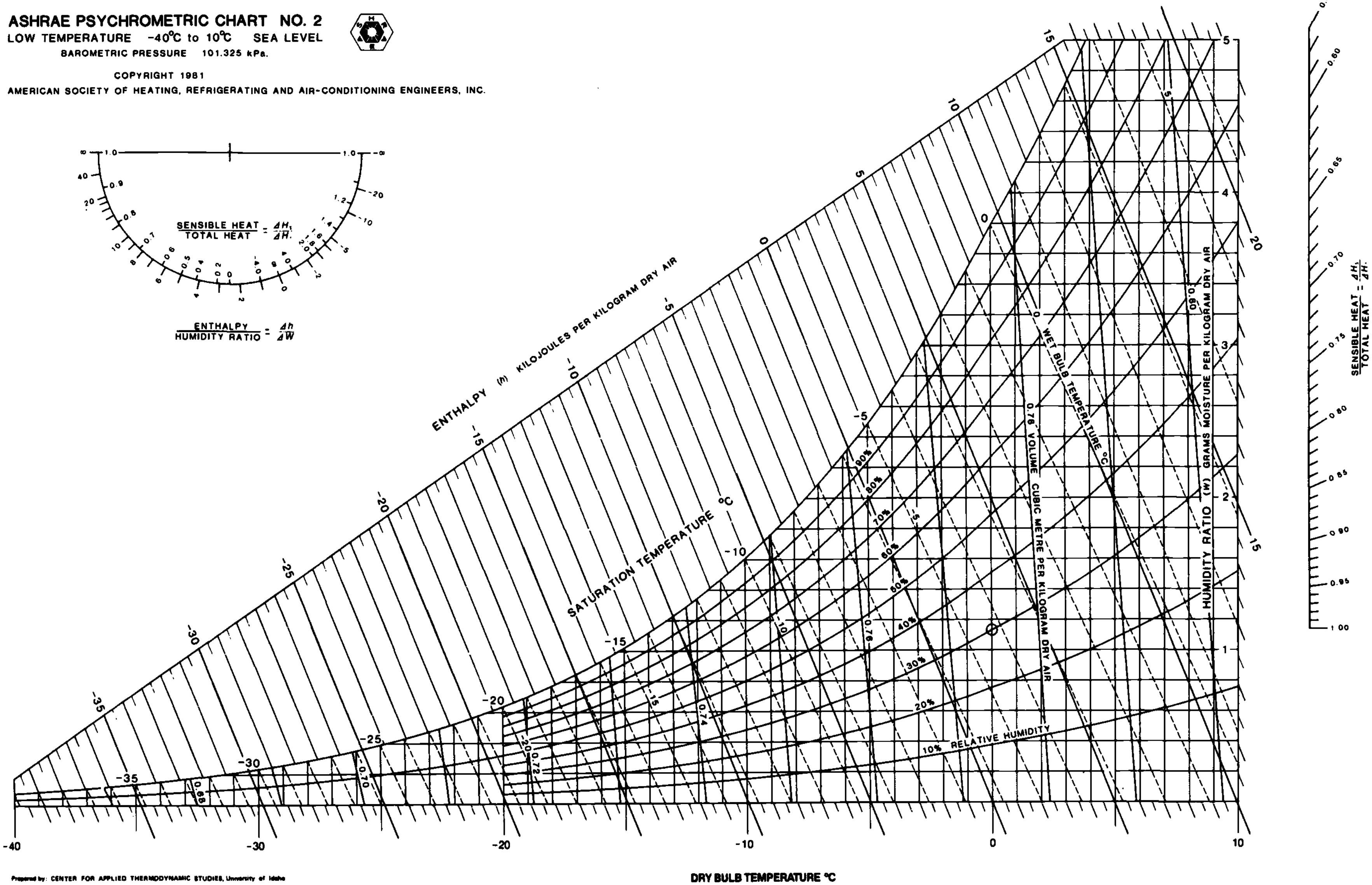


Prepared by: CENTER FOR APPLIED THERMODYNAMIC STUDIES, University of Idaho

ASHRAE Psychrometric Chart No. 1—Normal temperature, 0 to 50°C, sea level, barometric pressure 101.325 kPa. Reprinted with permission of the American Society of Heating, Refrigerating, and Air-Conditioning Engineers from the 1989 ASHRAE *Handbook—Fundamentals*.



ASHRAE Psychrometric Chart No. 2—Low temperature, −40 to 10°C, sea level, barometric pressure, 101.325 kPa. Reprinted with permission of the American Society of Heating, Refrigerating, and Air-Conditioning Engineers from the 1989 ASHRAE *Handbook—Fundamentals*.

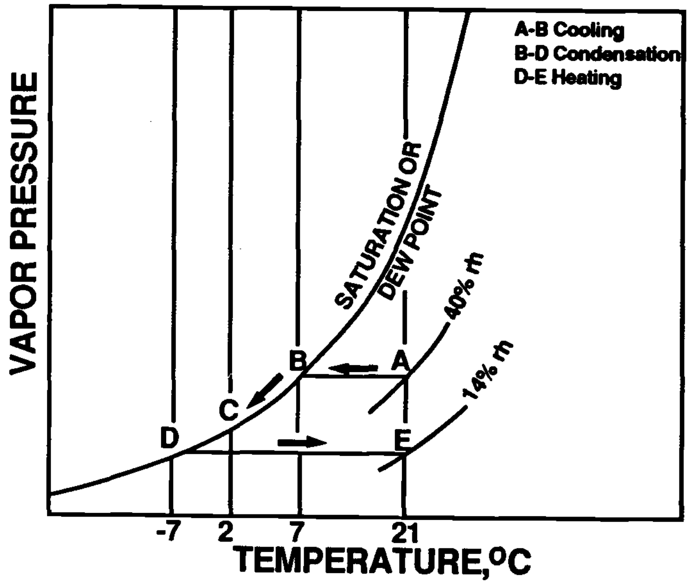


FIG. 1—Moisture processes within buildings. Reprinted with permission of the American Society of Heating, Refrigerating, and Air-Conditioning Engineers from the 1989 ASHRAE *Handbook—Fundamentals*.

chart the changes of humid air when heated and cooled. The saturation line or dew point represents the limiting concentration of water vapor that can exist as vapor at various temperatures. For example, air at 21°C and 40% relative humidity is at Point A at partial saturation. Cooling the air from Condition A on the figure to Condition B increases the relative humidity (to 100%), and the dew point is reached at about 7°C saturation. Further cooling of the air to 2°C causes condensation because the original amount of water vapor cannot be retained and is thus reduced to Condition C on the figure. If the air is further cooled, the condensation process continues as shown by Point D at −7°C on the figure. Note that dew point temperatures can be read directly from the psychrometric chart as Saturation Temperature, °C, for any known air dry-bulb temperature, wet-bulb temperature, or relative humidity. Heating the air from Point D (−7°C) to Point E (21°C) results in a relative humidity of 14%. A,B,C,D on the figure is typical of condensation forming on a cool window surface. Note that saturated outdoor air at −7°C heated to 21°C typical of indoor air results in a large decrease in relative humidity (100% to 14%) and is typical of winter heating of outdoor air to room conditions. Adding moisture at 21°C can increase the relative humidity back to Point A at 40%.

The wet-bulb temperature is a practical and useful variable as shown on the psychrometric charts. The wet-bulb temperature is determined using a psychrometer. The psychrometer consists of two matching calibrated thermometers; one thermometer bulb is covered by a wick that has been thoroughly wetted with distilled water. When the wick is placed in an air stream, water evaporates from the wick, cooling it, and eventually the thermometer reaches an equilibrium temperature called the wet-bulb temperature. The relationship between the dry-bulb temperature as read on the second thermometer and the wet-bulb temperature can define the relative humidity as shown on the psychrometric chart.

Pertinent thermodynamic properties are given in Table 2 of the Appendix: Thermodynamic Properties of MOIST AIR, SI Units (Standard Atmospheric Pressure 101.325 kPa, Ref *1*). Note in particular that the column P_s is the saturated water vapor pressure in kPa over the range of temperature in °C. The following briefly describes each column in Table 2.

°C = Celsius temperature,
W_s = humidity ratio at saturation, kg_w/kg_a, kilograms of moisture per kilogram of dry air,
V_a = specific volume of dry air, m^3/kg of dry air,
V_s = volume of moist air at saturation per kg of dry air m^3/kg,
$V_{as} = V_s - V_a$,
h_a = specific enthalpy of dry air, kJ/kg; in Table 2, h_a is zero at 0°C,
h_s = specific enthalpy of moist air at saturation per kg of dry air,
$h_{as} = h_s - h_a$,
S_a = specific entropy of dry air, kJ/(kg dry air)·K; in Table 2, S_a is zero at 0°C,
S_s = entropy of moist air at saturation per kg of dry air, kJ/(kg dry air)·K,
$s_{as} = S_s - S_a$,
h_w = specific enthalpy of condensed water (liquid or solid) in equilibrium with saturated air at a specified temperature and pressure, kJ/kg,
S_w = specific entropy of condensed water (liquid or solid) in equilibrium with saturated air, kJ/kg of water, K, and
P_s = vapor pressure of water in saturated moist air, kPa.

The relative humidity, Φ, can be defined as the ratio of the partial water vapor pressure, p, of an air sample to the saturated pressure, p_s, of the sample at a given temperature and pressure: $\Phi = p/p_s$.

Note that the dew point can readily be obtained more precisely using this table when the dry-bulb temperature and relative humidity are known. For example, in the previous example at 21°C, the saturated water vapor pressure from the table, p_s, is 2.4878 kPa. The partial water vapor pressure at 40% relative humidity is $p = \Phi p_s = 0.4 \times 2.4878 = 0.995\,12$ kPa. Locating this pressure under the column p_s indicates 7°C = 1.0020 and 6°C = 0.9353. Interpolation yields the dew point to be 6.8965 °C, where reading by eye on the psychrometric chart yields about 7°C.

It may be convenient for an initial evaluation to know the mean dew point temperature for each month or as an annual average in a given city within a state. This type of data as well as maps by month that show national dew point temperature distribution are published in Ref *4*, pages 57–58. The tabular data from this reference is reproduced in the Appendix as Table 3.

WEATHER DATA

The climatic conditions selected for use in this chapter have been published by ASHRAE. Table 1 (see Appendix) lists climatic conditions for the United States, Canada, and other countries. In the tables, winter Design Dry Bulb Temperature, Column 5, is given at two frequency levels; 99 or 97.5%

are for the months of December, January, and February (for a total of 2160 h) in the Northern Hemisphere and the months of June, July, and August (for a total of 2208 h) in the Southern Hemisphere. In a normal winter, there would be approximately 22 h at or below the 99% value and 54 h at or below the 97.5% value. Column 9 gives the prevailing wind direction occurring most frequently and the mean wind speed in both winter and summer, which occurs coincidently with the 97.5% dry-bulb winter design temperature. Column 10 is the median of the annual extreme minimum temperature. For Canadian stations, the two design values are based only for the month of January. Recommended summer design dry-bulb and wet-bulb temperatures are given in Columns 6, 7, and 8. Column 6 provides dry-bulb temperatures and their corresponding coincident wet-bulb temperatures. The dry-bulb temperatures represent values that have been equaled or exceeded by 1, 2.5, and 5% of the total hours during the months of June through September (a total of 2928 h) in the Northern Hemisphere and the months of December through March in the Southern Hemisphere (a total of 2904 h). The coincident wet-bulb temperature listed with each design dry-bulb temperature is the mean of all wet-bulb temperatures occurring at the specific dry-bulb. The mean daily range in Column 7 is the difference between the average daily minimum and the average daily minimum temperatures in the warmest month. Column 8 lists wet-bulb temperatures that have been equaled or exceeded by 1, 2.5, and 5% of the hours during the summer months.

An issue that has no single answer is what data should be used for moisture calculations. Should weather extremes be used, monthly averages, or seasonal averages? For constructions with large moisture storage capacity, seasonal averages may be appropriate; for others, it may be daily averages that are significant. Also, requirements differ for hot climates and for cold climates or for dry and humid climates. Judgment and local experience usually must be relied upon.

Much weather data are available in many forms. Given in the references are some publications that may be useful in moisture evaluations. For example, it is often necessary to define the climate at a given geographic location using weather variables and parameters such as heating degree days, cooling degree days, and as summer criteria for air conditioning the number of hours the dry bulb exceeds a value and the number of hours the wet-bulb temperature is exceeded. Chapter 17 states that a heating climate as 4000 degree days heating or greater, a mixed climate has 4000 degree days heating or less combined with a significant number of cooling (air conditioning) hours, and a cooling climate is a warm, humid climate with a significant number of cooling (air conditioning) hours. ASHRAE defines a humid climate in the United States as 3500 h or more of wet-bulb temperatures at 67°F (19.4°C) or higher for the warmest six consecutive months of the year or 1750 h or more of wet-bulb temperatures at 73°F (22.7°C) or more during the warmest six consecutive months of the year. A fringe climate in the United States is defined as 3000 h at 67°F (19.4°C) wet bulb or more for six months or 1500 h at 73°F (22.7°C) or more wet bulb. Table 4 (see Appendix) is excerpted from Ref 3 to provide a more precise means of defining the climate in respect to geographical location, heating degree days, summer air conditioning criteria data, and cooling degree days.

STEADY-STATE/DYNAMIC CONDITIONS

Simple diffusion vapor flow theory assumes conditions of unidirectional steady state flow. When inflow equals outflow with no condensation and the resistance to vapor flow of all of the materials in the flow path are known, useful calculations can be made for the purpose of predicting imminent condensation. If continuity is not possible and condensation is indicated, the rate of condensation and the time for condensation must be given serious consideration. Weather conditions may cause a rise of outdoor temperature with less harmful wetting and absorption of and release of moisture from the building materials. It is obvious in the above description that the natural process of moisture migration is rarely a steady-state phenomena. Changing weather temperatures, relative humidities, rainfall, winds, and pressures all indicate that diffusion, air leakage, and liquid water (snow, ice) provide an environment which is truly dynamic. To analyze and evaluate the behavior of a building construction in a given changing environment, it is necessary to predict performance for as little as hour-by-hour increments for all seasons of a complete year (8760 h). Computer programs have been developed for this purpose and usually require much more detailed weather data than presented here. The American Society of Heating, Refrigerating and Air Conditioning Engineers (ASHRAE) can provide a computer tape with a text for use. Quantified weather data for a weather year for energy calculations (WYEC) gives 51 locations with 8760 h of data for each station in the test reference year (TRY) format.

A number of simplified energy calculation methods such as degree hour, modified degree hour, bin, modified bin, and variable degree day are available. A source of weather data for direct use in these methods is available (Ref 2). These data are available in sets of weather data for 60 U.S. continental cities using Test reference year (TRY) source weather data (Fig. 2) and 23 cities using weather year for energy calculations (WYEC) source weather data. The data are organized in five volumes. Four of these volumes contain weather summaries as given in Table 5 (see Appendix). Note that considerable overlap is present in cities (21) covered by both TRY and WYEC data. Each volume contains material about the derivation, extent, and limits of the data. Volume V contains example uses of the data with simplified methods, as well as a detailed description of computational algorithms for generalizing weather data summaries. Computer program listings are also given for the algorithms. Weather variables summarized include dry-bulb and wet-bulb temperatures, percent relative humidity, humidity ratio, wind speed, percent possible sunshine, percent diffuse solar radiation, total solar radiation on horizontal and vertical surfaces, and solar heat gain through standard DSA glass. An example of TRY data (1965) of dry-bulb temperature frequencies with mean coincident wet-bulb temperatures: first quarter [5°F (−15°C),/3-h bins] for each month of the year for Jacksonville, Florida, is shown in Table 6A (see Appendix). Note these example tables are in Fahrenheit degrees and must be converted to SI units for use with computational methods in SI units. ASTM has available conversion tables for IP units to SI units. Tables 6-B, 6-C, 6-D, 6-E, 6-F, 6-G, 6-H, and 6-I, respectively, list the data for the other variables mentioned above.

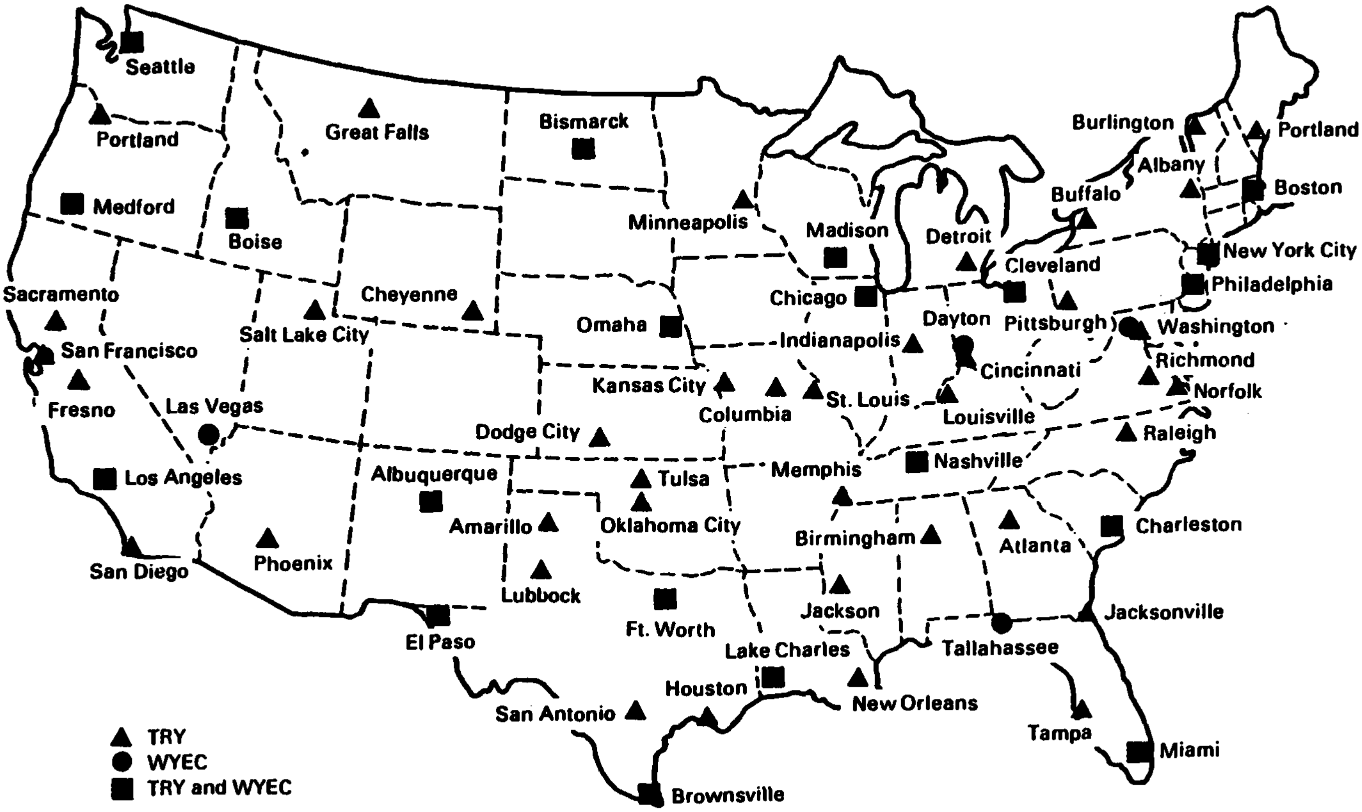


FIG. 2—Cities with TRY and WYEC data. Reprinted with permission of the American Society of Heating, Refrigerating, and Air-Conditioning Engineers from the 1989 ASHRAE *Handbook—Fundamentals*.

Another useful set of bin-1 type weather data is given in Ref *3*, a sample of which is shown in Table 7 (see Appendix) for Jacksonville, Florida.

Other sources of data tapes such as typical meteorological year (TMY) are available from the National Climatic Data Center, Asheville, NC, for the United States [*5*] and from the Canadian Climate Center Atmospheric Environment Service for Canada.

EXAMPLE USE OF A TABLE

An indoor design condition is specified as 21°C not to exceed 50% relative humidity. From Table 2, the saturated water vapor pressure, p_s, at 21°C is listed in the next-to-last column as 2.4878 kPa. Relative humidity (RH) as previously defined is the ratio of actual water vapor pressure to the saturated water vapor pressure or $\Phi = p/p_s$. Thus, the actual water vapor pressure, $p = \Phi p_s$, is $0.5 \times 2.4878 = 1.2439$ kPa. The dew point (saturated temperature) can be obtained directly from the psychrometric chart as 10°C. The outdoor design condition is -18°C and 80% relative humidity or the actual water vapor pressure $p_a = 0.8 \times 0.12494 = 0.099936$ kPa. From these data the difference in temperature and water vapor pressure across a building can be calculated and used in conjunction with the thermal and moisture resistance to evaluate heat and moisture flow and moisture condensation/evaporation potential of the construction.

REFERENCES

[*1*] American Society of Heating, Refrigerating and Air Conditioning Engineers, Inc. (ASHRAE), *1989 Handbook of Fundamentals*, SI edition, Atlanta, GA.

[*2*] "Weather Data for Simplified Energy Calculation Methods," A. R. Olsen, S. Moreno, S. Deringer, and C. R. Watson, Editors, August 1984, Pacific Northwest Laboratory, Richland, WA, prepared for the U.S. Department of Energy.

[*3*] "Facility Design and Planning Engineering Weather Data," Departments of the Air Force, the Army, and the Navy, 1 July 1978, AFM 88-29, TM 5-785, NAVPAC P-89, Department of Defense, Washington, DC.

[*4*] "Climatic Atlas of the United States," U.S. Department of Commerce, Environmental Science Services Administration, Environmental Data Service, June 1968, reprinted by the National Oceanic and Atmospheric Administration, 1983, available through the National Climatic Data Center, Federal Building, Asheville, NC, 28801.

[*5*] "Selective Guide to Climatic Data Sources," U.S. Department of Commerce, National Oceanic and Atmospheric Administration, National Environmental Satellite Data and Information Service, Warren L. Hatch, Ed., July 1983, Key to Meteorlogical Records Documentation No. 4.11, National Climatic Center, Asheville, NC.

Appendix*

TABLE 1—Climatic conditions for the United States.

				Winter,[b] °C		Summer,[c] °C							Prevailing Wind			Temp. °C	
Col. 1	Col. 2	Col. 3	Col. 4	Col. 5		Col. 6			Col. 7	Col. 8			Col. 9			Col. 10	
State and Station[a]	Lat.	Long.	Elev.	Design Dry-Bulb		Design Dry-Bulb and Mean Coincident Wet-Bulb			Mean Daily	Design Wet-Bulb			Winter		Summer	Median of Annual Extr.	
	° ′	° ′	m	99%	97.5%	1%	2.5%	5%	Range	1%	2.5%	5%		m/s[d]		Max.	Min.
ALABAMA																	
Alexander City	32 57	85 57	201	−8	−6	36/25	34/24	33/24	12	26	26	26					
Anniston AP	33 35	85 51	183	−8	−6	36/25	34/24	33/24	12	26	26	26	SW	3	SW	36.9	−10.9
Auburn	32 36	85 30	199	−8	−6	36/25	34/24	33/24	12	26	26	26				37.7	−9.7
Birmingham AP	33 34	86 45	189	−8	−6	36/23	34/24	33/23	12	26	25	24	NNW	4	WNW	36.9	−10.6
Decatur	34 37	86 59	177	−12	−9	35/24	34/23	33/23	12	26	25	24					
Dothan AP	31 19	85 27	114	−5	−3	34/24	33/24	33/24	11	27	26	26					
Florence AP	34 48	87 40	177	−8	−6	36/23	34/23	33/23	12	26	25	24	NW	4	NW		
Gadsden	34 01	86 00	169	−9	−7	36/24	34/24	33/23	12	26	25	24	NNW	4	WNW		
Huntsville AP	34 42	86 35	185	−12	−9	35/24	34/23	33/23	13	26	25	24	N	5	SW		
Mobile AP	30 41	88 15	64	−4	−2	35/25	34/25	33/24	10	27	26	26	N	5	N		
Mobile Co	30 40	88 15	64	−4	−2	35/25	34/25	33/24	9	27	26	26				36.6	−5.4
Montgomery AP	32 23	86 22	52	−6	−4	36/24	35/24	34/24	12	26	26	26	NW	4	W	37.2	−7.7
Selma-Craig AFB	32 20	87 59	51	−6	−3	36/26	35/25	34/25	12	27	27	26	N	5	SW	37.8	−8.0
Talladega	33 27	86 06	172	−8	−6	36/25	34/24	33/24	12	26	26	26				37.6	−11.6
Tuscaloosa AP	33 13	87 37	52	−7	−5	37/24	36/24	34/24	12	26	26	25	N	3	WNW		
ALASKA																	
Anchorage AP	61 10	150 01	35	−31	−28	22/15	20/14	19/13	8	16	15	14	SE	2	WNW		
Barrow (S)	71 18	156 47	9	−43	−41	14/12	12/10	9/8	7	12	10	8	SW	4	SE		
Fairbanks AP (S)	64 49	147 52	133	−46	−44	28/17	26/16	24/15	13	18	17	16	N	3	S		
Juneau AP	58 22	134 35	4	−20	−17	23/16	21/14	19/14	8	16	15	14	N	4	W		
Kodiak	57 45	152 29	22	−12	−11	21/14	18/13	17/13	6	16	14	13	WNW	7	NW		
Nome AP	64 30	165 26	4	−35	−33	19/14	17/13	15/12	6	14	13	13	N	2	W		
ARIZONA																	
Douglas AP	31 27	109 36	1249	−3	−1	37/17	35/17	34/17	17	21	21	20				40.2	−10.0
Flagstaff AP	35 08	111 40	2136	−19	−16	29/13	28/13	27/12	17	16	16	15	NE	3	SW	32.2	−24.2
Fort Huachuca AP (S)	31 35	110 20	1422	−4	−2	35/17	33/17	32/17	15	21	20	19	SW	3	W		
Kingman AP	35 12	114 01	1079	−8	−4	39/18	38/18	36/18	17	21	21	21					
Nogales	31 21	110 55	1159	−2	0	37/18	36/18	34/18	17	22	21	21	SW	3	W		
Phoenix AP (S)	33 26	112 01	339	−1	1	43/22	42/22	41/22	15	24	24	24	E	2	W	44.9	−2.9
Prescott AP	34 39	112 26	1528	−16	−13	36/16	34/16	33/16	17	19	18	18					
Tucson AP (S)	32 07	110 56	780	−2	0	40/19	39/19	38/19	14	22	22	22	SE	3	WNW	42.7	−7.1
Winslow AP	35 01	110 44	1492	−15	−12	36/16	35/16	34/16	18	19	18	18	SW	3	WSW	39.3	−18.0
Yuma AP	32 39	114 37	65	2	4	44/22	43/22	42/22	15	26	26	25	NNE	3	WSW	46.0	−.7

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[a] AP or AFB following the station name designates airport or Airforce base temperature observations. Co designates office locations within an urban area that are affected by the surrounding area. Undesignated stations are semirural and may be compared to airport data.

[b] Winter design data are based on the 3-month period, December through February.

[c] Summer design data are based on the 4-month period, June through September.

[d] Mean wind speeds occurring coincidentally with the 99.5% dry-bulb winter design temperature.

*Tables 1 and 2 in this appendix are reprinted with permission of the American Society of Heating, Refrigerating, and Air-Conditioning Engineers from the 1989 ASHRAE *Handbook—Fundamentals*. Table 3 is from Ref 4, Table 4 is from Ref 3, Tables 5 and 6 are from Ref 2, and Table 7 is from Ref 3.

TABLE 1—Climatic conditions for the United States (*continued*).

				Winter,[b] °C		Summer,[c] °C							Prevailing Wind		Temp. °C	
Col. 1	Col. 2	Col. 3	Col. 4	Col. 5		Col. 6			Col. 7	Col. 8			Col. 9		Col. 10	
State and Station[a]	Lat.	Long.	Elev.	Design Dry-Bulb		Design Dry-Bulb and Mean Coincident Wet-Bulb			Mean Daily Range	Design Wet-Bulb			Winter	Summer	Median of Annual Extr.	
	° ′	° ′	m	99%	97.5%	1%	2.5%	5%		1%	2.5%	5%	m/s[d]		Max.	Min.
ARKANSAS																
Blytheville AFB	35 57	89 57	80	−12	−9	36/26	34/25	33/24	12	27	27	26	N 4	SSW		
Camden	33 36	92 49	35	−8	−5	37/24	36/24	34/24	12	27	26	26				
El Dorado AP	33 13	92 49	84	−8	−5	37/24	36/24	34/24	12	27	26	26	S 3	SE	38.3	−10.1
Fayetteville AP	36 00	94 10	381	−14	−11	36/22	34/23	33/23	13	25	24	24	NE 5	SSW	37.4	−17.9
Fort Smith AP	35 20	94 22	141	−11	−8	38/24	37/24	35/24	13	27	26	26	NW 4	SW	38.8	−13.9
Hot Springs	34 29	93 06	163	−8	−5	38/25	36/25	34/25	12	27	26	26	N 4	SW	39.4	−11.9
Jonesboro	35 50	90 42	105	−12	−9	36/26	34/25	33/24	12	27	27	26			38.7	−13.7
Little Rock AP (S)	34 44	92 14	78	−9	−7	37/24	36/25	34/25	12	27	26	26	N 5	SSW	37.2	−11.6
Pine Bluff AP	34 18	92 05	73	−9	−6	38/26	36/25	35/26	12	27	27	27	N 4	SW	39.0	−10.5
Texarkana AP	33 27	93 59	119	−8	−5	37/24	36/25	34/24	12	27	26	26	WNW 5	SSW	40.4	−10.0
CALIFORNIA																
Bakersfield AP	35 25	119 03	145	−1	0	40/21	38/21	37/20	18	23	22	21	ENE 3	WNW	43.2	−3.7
Barstow AP	34 51	116 47	588	−3	−2	41/20	40/20	39/19	21	23	22	21	WNW 4	W	43.6	−8.1
Blythe AP	33 37	114 43	120	−1	1	44/22	43/22	42/21	16	24	24	23			47.1	−4.4
Burbank AP	34 12	118 21	236	3	4	35/20	33/20	31/19	14	22	21	21	NW 2	S		
Chico	39 48	121 51	73	−2	−1	39/21	38/20	37/19	20	22	21	20	NW 3	SSE	42.8	−5.2
Concord	37 58	121 59	61	−4	−3	38/21	36/20	34/19	18	22	21	20	WNW 3	NW		
Covina	34 05	117 52	175	0	2	37/21	35/20	33/19	17	23	22	21				
Crescent City AP	41 46	124 12	22	−1	1	20/16	18/15	17/14	10	17	16	15				
Downey	33 56	118 08	35	3	4	34/21	32/21	30/21	12	22	22	21				
El Cajon	32 49	116 58	112	6	7	28/21	27/21	26/20	17	22	21	20				
El Centro AP (S)	32 49	115 40	−13	2	3	44/23	43/23	42/23	19	27	27	26	W 3	SE		
Escondido	33 07	117 05	201	4	5	32/20	29/20	28/20	17	22	21	21				
Eureka/Arcata AP	40 59	124 06	66	−1	1	20/16	18/15	17/14	6	17	16	15	E 3	NW	24.3	−1.3
Fairfield-Travis AFB	38 16	121 56	19	−2	0	37/20	35/19	33/19	19	21	20	19	N 3	WSW		
Fresno AP (S)	36 46	119 43	100	−2	−1	39/21	38/21	36/20	19	22	22	21	E 2	WNW	42.6	−3.4
Hamilton AFB	38 04	122 30	1	−1	0	32/20	29/19	27/18	16	22	21	19	N 2	SE		
Laguna Beach	33 33	117 47	11	5	6	28/20	27/20	25/19	10	21	21	20				
Livermore	37 42	121 57	166	−4	−3	38/21	36/20	34/19	13	22	21	20	WNW 2	NW		
Lompoc, Vandenberg AFB	34 43	120 34	112	2	3	24/16	21/16	19/16	11	17	16	16	ESE 3	NW		
Long Beach AP	33 49	118 09	9	5	6	28/20	27/20	25/19	12	21	21	20	NW 2	WNW		
Los Angeles AP (S)	33 56	118 24	30	5	6	28/20	27/20	25/19	8	21	21	20	E 2	WSW		
Los Angeles Co (S)	34 03	118 14	82	3	4	34/21	32/21	30/21	11	22	22	21	NW 2	NW	36.7	2.2
Merced-Castle AFB	37 23	120 34	57	−2	−1	39/21	37/21	36/20	20	22	22	21	ESE 2	NW		
Modesto	37 39	121 00	28	−2	−1	38/21	37/20	35/19	20	22	21	21			41.0	−3.2
Monterey	36 36	121 54	12	2	3	24/17	22/16	20/16	11	18	17	16	SE 2	NW		
Napa	38 13	122 17	17	−1	0	38/21	36/20	33/19	17	22	21	20			39.5	−3.4
Needles AP	34 46	114 37	278	−1	1	44/22	43/22	42/21	15	24	24	23			46.9	−2.9
Oakland AP	37 49	122 19	2	1	2	29/18	27/17	24/17	11	19	18	17	E 3	WNW	33.9	−.1
Oceanside	33 14	117 25	8	5	6	28/20	27/20	25/19	7	21	21	20				
Ontario	34 03	117 36	290	−1	1	39/21	37/21	36/19	20	23	22	22	E 2	WSW		
Oxnard	34 12	119 11	15	1	2	28/19	27/18	25/17	11	21	20	19				
Palmdale AP	34 38	118 06	775	−8	−6	39/18	38/18	37/18	19	21	19	19	SW 3	WSW		
Palm Springs	33 49	116 32	125	1	2	44/22	43/21	42/21	19	24	23	23				
Pasadena	34 09	118 09	263	0	2	37/21	35/20	33/19	16	23	22	21			39.3	−.9
Petaluma	38 14	122 38	5	−3	−2	34/20	32/19	31/18	17	22	21	20			38.9	−4.3
Pomona Co	34 03	117 45	285	−2	−1	39/21	37/21	35/20	20	23	22	22	E 2	W	40.9	−3.2
Redding AP	40 31	122 18	151	−2	−1	41/20	39/19	38/19	18	22	21	20			42.9	−3.3
Redlands	34 03	117 11	402	−1	1	39/21	37/21	36/20	18	23	22	22			41.5	−2.7
Richmond	37 56	122 21	17	1	2	29/18	27/17	24/17	9	19	18	17				
Riverside-March AFB (S)	33 54	117 15	467	−2	0	38/20	37/20	35/19	21	22	22	21	N 2	NW	42.0	−3.0
Sacramento AP	38 31	121 30	5	−1	0	38/21	37/21	34/21	20	22	22	21	NNW 3	SW	40.6	−2.4
Salinas AP	36 40	121 36	23	−1	0	23/16	21/16	19/15	13	17	16	15				
San Bernardino, Norton AFB	34 08	117 16	343	−1	1	39/21	37/21	36/20	21	23	22	22	E 2	W	42.9	−3.7
San Diego AP	32 44	117 10	4	6	7	28/21	27/21	26/20	7	22	21	20	NE 2	WNW	32.9	3.0

TABLE 1—Climatic conditions for the United States (*continued*).

				Winter,[b] °C		Summer,[c] °C							Prevailing Wind		Temp. °C	
Col. 1	Col. 2	Col. 3	Col. 4	Col. 5		Col. 6			Col. 7	Col. 8			Col. 9		Col. 10	
State and Station[a]	Lat.	Long.	Elev.	Design Dry-Bulb		Design Dry-Bulb and Mean Coincident Wet-Bulb			Mean Daily	Design Wet-Bulb			Winter	Summer	Median of Annual Extr.	
	° ′	° ′	m	99%	97.5%	1%	2.5%	5%	Range	1%	2.5%	5%	m/s[d]		Max.	Min.
San Fernando	34 17	118 28	294	3	4	35/20	33/20	31/19	21	22	21	21				
San Francisco AP	37 37	122 23	2	2	3	28/18	25/17	23/17	11	18	18	17	S 3	NW		
San Francisco Co	37 46	122 26	22	3	4	23/17	22/17	21/16	8	18	17	16	W 3	W	32.9	2.2
San Jose AP	37 22	121 56	17	1	2	29/19	27/18	25/18	14	20	19	18	SE 2	NNW	37.0	– 2.1
San Luis Obispo	35 20	120 43	76	1	2	33/21	31/21	29/21	14	23	22	21	E 2	W	37.7	– 1.5
Santa Ana AP	33 45	117 52	35	3	4	32/21	29/20	28/20	16	22	21	21	E 2	SW	38.3	– 1.2
Santa Barbara MAP	34 26	119 50	3	1	2	27/19	25/19	24/18	13	20	19	19	NE 2	SW	36.2	– .2
Santa Cruz	36 59	122 01	38	2	3	24/17	22/16	20/16	16	18	17	16			36.4	– 2.9
Santa Maria AP (S)	34 54	120 27	72	– 1	1	27/18	24/17	23/17	13	18	18	17	E 2	WNW		
Santa Monica Co	34 01	118 29	20	5	6	28/20	27/20	25/19	9	21	21	20				
Santa Paula	34 21	119 05	80	1	2	32/20	30/19	29/19	20	22	21	20				
Santa Rosa	38 31	122 49	38	– 3	– 2	37/20	35/19	33/19	19	21	20	19	N 3	SE	39.2	– 4.8
Stockton AP	37 54	121 15	7	– 2	– 1	38/21	36/20	34/19	21	22	21	20	WNW 2	NW	40.1	– 4.2
Ukiah	39 09	123 12	190	– 3	– 2	37/21	35/20	33/19	22	21	20	19			42.3	– 5.8
Visalia	36 20	119 18	99	– 2	– 1	39/21	38/21	36/20	21	22	22	21			42.4	– 3.8
Yreka	41 43	122 38	800	– 11	– 8	35/18	33/18	32/17	21	19	18	18			39.3	– 13.8
Yuba City	39 08	121 36	24	– 2	– 1	40/20	38/19	37/19	20	22	21	20				
COLORADO																
Alamosa AP	37 27	105 52	2298	– 29	– 27	29/14	28/14	27/14	19	17	16	16				
Boulder	40 00	105 16	1660	– 17	– 13	34/15	33/15	32/15	15	18	17	17			35.6	– 22.4
Colorado Springs AP	38 49	104 43	1874	– 19	– 17	33/14	31/14	30/14	17	17	17	16	N 5	S	33.5	– 24.5
Denver AP	39 45	104 52	1611	– 21	– 17	34/15	33/15	32/15	16	18	17	17	S 4	SE	36.0	– 23.6
Durango	37 17	107 53	1997	– 18	– 16	32/15	31/15	29/15	17	18	17	17			33.6	– 24.0
Fort Collins	40 35	105 05	1524	– 23	– 20	34/15	33/15	32/15	16	18	17	17			35.1	– 27.8
Grand Junction AP (S)	39 07	108 32	1477	– 17	– 14	36/15	34/15	33/15	16	18	17	17	ESE 3	WNW	37.7	– 19.7
Greeley	40 26	104 38	1417	– 24	– 21	36/16	34/16	33/16	16	18	18	17				
Lajunta AP	38 03	103 30	1268	– 19	– 16	38/20	37/20	35/19	17	22	21	21	W 4	S		
Leadville	39 15	106 18	3096	– 22	– 20	29/11	27/11	26/10	17	13	13	12			26.5	– 27.7
Pueblo AP	38 18	104 29	1415	– 22	– 18	36/16	35/16	33/16	17	19	19	18	W 3	SE	38.1	– 24.6
Sterling	40 37	103 12	1201	– 22	– 19	35/17	34/17	32/17	17	19	19	18			37.9	– 26.3
Trinidad AP	37 15	104 20	1750	– 19	– 16	34/16	33/16	32/16	18	19	18	18	W 4	WSW	36.0	– 23.6
CONNECTICUT																
Bridgeport AP	41 11	73 11	8	– 14	– 13	30/23	29/22	27/21	10	24	23	23	NNW 7	WSW		
Hartford, Brainard Field	41 44	72 39	6	– 16	– 14	33/23	31/23	29/22	12	25	24	23	N 3	SSW	35.4	– 20.2
New Haven AP	41 19	73 55	2	– 16	– 14	31/24	29/23	28/22	9	24	24	23	NNE 4	SW	33.9	– 17.9
New London	41 21	72 06	18	– 15	– 13	31/23	29/22	28/22	9	24	24	23				
Norwalk	41 07	73 25	11	– 14	– 13	30/23	29/22	27/21	11	24	23	23				
Norwich	41 32	72 04	6	– 16	– 14	32/24	30/23	28/22	10	24	24	23				
Waterbury	41 35	73 04	257	– 20	– 17	31/23	29/22	28/21	12	24	23	22	N 4	SW		
Windsor Locks, Bradley Fld	41 56	72 41	52	– 18	– 16	33/23	31/22	29/22	12	24	24	23	N 4	SW		
DELAWARE																
Dover AFB	39 08	75 28	9	– 12	– 9	33/24	32/24	31/23	10	26	25	24	W 5	SW	36.1	– 13.9
Wilmington AP	39 40	75 36	23	– 12	– 10	33/23	32/23	31/23	11	25	24	24	WNW 5	WSW	35.2	– 15.1
DISTRICT OF COLUMBIA																
Andrews AFB	38 5	76 5	85	– 12	– 10	33/24	32/23	31/23	10	26	24	24				
Washington, National AP	38 51	77 02	4	– 10	– 8	34/24	33/23	32/23	10	26	25	24	WNW 6	S	36.4	– 13.7
FLORIDA																
Belle Glade	26 39	80 39	5	5	7	33/24	33/24	32/24	9	26	26	26			34.8	– .6
Cape Kennedy AP	28 29	80 34	5	2	3	32/26	31/26	31/26	8	27	26	26				
Daytona Beach AP	29 11	81 03	9	0	2	33/26	32/25	31/25	8	27	26	26	NW 4	E		
Fort Lauderdale	26 04	80 09	3	6	8	33/26	33/26	32/26	8	27	26	26	NW 5	ESE		
Fort Myers AP	26 35	81 52	5	5	7	34/26	33/26	33/25	10	27	26	26	NNE 4	W	34.9	1.6
Fort Pierce	27 28	80 21	8	3	6	33/26	32/26	32/26	8	27	26	26			35.6	1.1
Gainesville AP (S)	29 41	82 16	46	– 2	– 1	35/25	34/25	33/25	10	27	26	26	W 3	W	36.6	– 4.8

TABLE 1—Climatic conditions for the United States (*continued*).

				Winter,[b] °C		Summer,[c] °C							Prevailing Wind			Temp. °C	
Col. 1	Col. 2	Col. 3	Col. 4	Col. 5		Col. 6			Col. 7	Col. 8			Col. 9			Col. 10	
State and Station[a]	Lat.	Long.	Elev.	Design Dry-Bulb		Design Dry-Bulb and Mean Coincident Wet-Bulb			Mean Daily Range	Design Wet-Bulb			Winter		Summer	Median of Annual Extr.	
	° ′	° ′	m	99%	97.5%	1%	2.5%	5%		1%	2.5%	5%		m/s[d]		Max.	Min.
Jacksonville AP	30 30	81 42	8	-2	0	36/25	34/25	33/24	11	26	26	26	NW	4	SW	36.4	-3.7
Key West AP	24 33	81 45	1	13	14	32/26	32/26	32/26	5	27	26	26	NNE	6	SE	33.3	10.8
Lakeland Co (S)	28 02	81 57	65	4	5	34/24	33/24	32/24	9	26	26	26	NNW	5	SSW		
Miami AP (S)	25 48	80 16	2	7	8	33/25	32/25	32/25	8	26	26	26	NNW	4	SE	33.6	3.9
Miami Beach Co	25 47	80 17	3	7	9	32/25	32/25	31/25	6	26	26	26					
Ocala	29 11	82 08	27	-1	1	35/25	34/25	33/24	10	27	26	26				37.0	-4.0
Orlando AP	28 33	81 23	30	2	3	34/24	34/24	33/24	9	26	26	26	NNW	5	SSW		
Panama City, Tyndall AFB	30 04	85 35	5	-2	1	33/26	32/25	32/25	8	27	27	26	N	4	WSW		
Pensacola Co	30 25	87 13	17	-4	-2	34/25	34/25	33/25	8	27	26	26	NNE	4	SW	35.7	-4.8
St. Augustine	29 58	81 20	3	-1	2	33/26	32/26	31/26	9	27	26	26	NW	4	W	36.4	-3.4
St. Petersburg	27 46	82 80	11	2	4	33/25	33/25	32/24	9	26	26	26	N	4	W	34.9	2.0
Sanford	28 46	81 17	27	2	3	34/24	34/24	33/24	9	26	26	26					
Sarasota	27 23	82 33	8	4	6	34/25	33/25	32/24	9	26	26	26					
Tallahassee AP (S)	30 23	84 22	17	-3	-1	34/25	33/24	32/24	11	26	26	26	NW	3	NW	36.4	-6.2
Tampa AP (S)	27 58	82 32	6	2	4	33/25	33/25	32/24	9	26	26	26	N	4	W	35.0	-.3
West Palm Beach AP	26 41	80 06	5	5	7	33/26	33/26	32/26	9	27	26	26	NW	5	ESE		
GEORGIA																	
Albany, Turner AFB	31 36	84 05	68	-4	-2	36/25	35/24	34/24	11	27	26	26	N	4	W	1038.1	-6.7
Americus	32 03	84 14	139	-6	-4	36/25	34/24	33/24	11	26	26	25				38.0	-8.6
Athens	33 57	83 19	245	-8	-6	34/23	33/23	32/23	12	26	25	24	NW	5	WNW	37.1	-10.3
Atlanta AP (S)	33 39	84 26	308	-8	-6	34/23	33/23	32/23	11	25	24	24	NW	6	NW	35.4	-11.2
Augusta AP	33 22	81 58	44	-7	-5	36/25	35/24	34/24	11	27	26	26	W	2	WSW	37.2	-8.1
Brunswick	31 15	81 29	8	-2	0	33/26	32/26	31/26	10	27	26	26				37.4	-4.1
Columbus, Lawson AFB	32 31	84 56	74	-6	-4	35/24	34/24	33/24	12	26	26	25	NW	4	W		
Dalton	34 34	84 57	220	-8	-6	34/24	34/24	33/24	12	26	26	25					
Dublin	32 20	82 54	66	-6	-4	36/25	34/24	33/24	11	26	26	25				38.3	-8.5
Gainsville	34 11	83 41	387	-9	-6	34/23	33/23	32/23	12	25	24	24				36.2	-11.9
Griffin (S)	33 15	84 16	299	-8	-6	34/24	32/24	31/23	12	26	25	24					
La Grange	33 01	85 04	216	-7	-5	34/24	33/24	32/23	12	26	25	24				36.5	-11.2
Macon AP	32 42	83 39	108	-6	-4	36/25	34/24	33/24	12	26	26	25	NW	4	WNW	37.6	-8.4
Marietta, Dobbins AFB	33 55	84 31	326	-8	-6	34/23	33/23	32/23	12	26	25	24	NNW	6	NW		
Moultrie	31 08	83 42	89	-3	-1	36/25	35/25	33/24	11	27	26	26	NW	4	W	37.4	-6.8
Rome AP	34 21	85 10	194	-8	-6	34/24	34/24	33/24	13	26	26	25	N	4	N	37.3	-11.5
Savannah-Travis AP	32 08	81 12	15	-4	-3	36/25	34/25	33/25	11	27	26	26	WNW	4	SW	37.1	-5.6
Valdosta-Moody AFB	30 58	83 12	71	-2	-1	36/25	34/25	33/24	11	27	26	26	WNW	3	W		
Waycross	31 15	82 24	45	-3	-2	36/25	34/25	33/24	11	27	26	26				37.8	-6.9
HAWAII																	
Hilo AP (S)	19 43	155 05	11	16	17	29/23	28/22	28/22	8	24	23	23	SW	3	NE		
Honolulu AP	21 20	157 55	4	17	17	31/23	30/23	29/22	7	24	24	23	ENE	6	ENE		
Kaneohe Bay MCAS	21 27	157 46	5	18	19	29/24	29/23	28/23	7	24	24	24	NNE	5	NE		
Wahiawa	21 03	158 02	274	14	15	30/23	29/22	29/22	8	24	23	23	WNW	3	E		
IDAHO																	
Boise AP (S)	43 34	116 13	865	-16	-12	36/18	34/18	33/18	17	20	19	18	SE	3	NW	39.6	-17.4
Burley	42 32	113 46	1267	-19	-17	37/17	35/16	33/19	19	18	17	16				37.0	-22.4
Coeur D'Alene AP	47 46	116 49	906	-22	-18	32/17	30/16	28/16	17	18	17	16				37.7	-20.3
Idaho Falls AP	43 31	112 04	1446	-24	-21	32/16	31/16	29/15	21	18	17	16	N	5	S	35.7	-26.7
Lewiston AP	46 23	117 01	431	-18	-14	36/18	34/18	32/17	18	19	19	18	W	2	WNW	41.1	-16.3
Moscow	46 44	116 58	811	-22	-18	32/17	31/17	29/16	18	18	18	17				36.7	-21.1
Mountain Home AFB	43 02	115 54	913	-14	-11	37/18	36/17	34/17	20	19	18	17	ESE	4	NW	39.6	-21.4
Pocatello AP	42 55	112 36	1358	-22	-18	34/16	33/16	32/15	19	18	17	16	NE	3	W	36.6	-24.1
Twin Falls AP (S)	42 29	114 29	1265	-19	-17	37/17	35/16	33/16	19	18	17	16	SE	3	NW	38.3	-20.6
ILLINOIS																	
Aurora	41 45	88 20	227	-21	-18	34/24	33/24	31/24	11	26	26	24				35.9	-25.0
Belleville, Scott AFB	38 33	89 51	138	-17	-14	34/24	33/24	32/24	12	26	26	24	WNW	4	S		
Bloomington	40 29	88 57	267	-21	-19	33/24	32/23	31/23	12	26	24	24				36.9	-23.1

TABLE 1—Climatic conditions for the United States (*continued*).

				Winter,[b] °C		Summer,[c] °C							Prevailing Wind			Temp. °C	
Col. 1	Col. 2	Col. 3	Col. 4	Col. 5		Col. 6			Col. 7	Col. 8			Col. 9			Col. 10	
State and Station[a]	Lat.	Long.	Elev.	Design Dry-Bulb		Design Dry-Bulb and Mean Coincident Wet-Bulb			Mean Daily Range	Design Wet-Bulb			Winter		Summer	Median of Annual Extr.	
	° ′	° ′	m	99%	97.5%	1%	2.5%	5%		1%	2.5%	5%	m/s[d]			Max.	Min.
Carbondale	37 47	89 15	127	− 17	− 14	35/25	34/25	32/24	12	27	26	25				38.3	− 18.2
Champaign/Urbana	40 02	88 17	237	− 19	− 17	35/24	33/23	32/23	12	26	25	24					
Chicago, Midway AP	41 47	87 45	185	− 21	− 18	34/23	33/23	31/22	11	25	24	23	NW	6	SW		
Chicago, O'Hare AP	41 59	87 54	201	− 22	− 20	33/23	32/23	30/22	11	25	24	23	WNW	5	SW		
Chicago Co	41 53	87 38	180	− 19	− 17	34/24	33/23	31/23	8	26	25	24				35.6	− 22.4
Danville	40 12	87 36	212	− 20	− 17	34/24	32/23	31/23	12	26	25	24	W	5	SSW	36.8	− 22.4
Decatur	39 50	88 52	207	− 19	− 17	34/24	33/23	31/23	12	26	25	24	NW	5	SW	37.2	− 22.3
Dixon	41 50	89 29	212	− 22	− 19	34/24	32/23	31/23	13	26	25	24				36.4	− 25.3
Elgin	42 02	88 16	231	− 22	− 19	33/24	31/23	30/23	12	26	25	24					
Freeport	42 18	89 37	238	− 23	− 20	33/23	32/23	31/22	13	25	24	23					
Galesburg	40 56	90 26	233	− 22	− 19	34/24	33/24	31/23	12	26	25	24	WNW	4	SW		
Greenville	38 53	89 24	172	− 18	− 16	34/24	33/24	32/23	12	26	26	24					
Joliet	41 31	88 10	177	− 21	− 18	34/24	32/23	31/23	11	26	25	24	NW	6	SW		
Kankakee	41 05	87 55	191	− 20	− 17	34/24	32/23	31/23	12	26	25	24					
La Salle/Peru	41 19	89 06	159	− 22	− 19	34/24	33/24	31/23	12	26	25	24					
Macomb	40 28	90 40	214	− 21	− 18	35/24	33/24	32/24	12	26	26	24					
Moline AP	41 27	90 31	177	− 23	− 20	34/24	33/24	31/23	13	26	25	24	WNW	4	SW	36.0	− 24.8
Mt Vernon	38 19	88 52	146	− 18	− 15	35/24	33/24	32/23	12	26	26	24				38.1	− 19.4
Peoria AP	40 40	89 41	199	− 22	− 20	33/24	32/23	31/23	12	26	24	24	WNW	4	SW	36.7	− 23.8
Quincy AP	39 57	91 12	234	− 19	− 16	36/24	34/24	32/24	12	27	26	25	NW	6	SSW	38.4	− 21.5
Rantoul, Chanute AFB	40 18	88 08	230	− 20	− 17	34/24	33/23	32/23	12	26	25	24	W	5	SSW		
Rockford	42 21	89 03	226	− 23	− 20	33/23	32/23	31/22	13	25	24	23				36.3	− 25.4
Springfield AP	39 50	89 40	179	− 19	− 17	34/24	33/23	32/23	12	26	25	24	NW	5	SW	36.7	− 21.8
Waukegan	42 21	87 53	213	− 21	− 19	33/24	32/23	31/23	12	26	24	24				35.8	− 23.7
INDIANA																	
Anderson	40 06	85 37	280	− 18	− 14	35/24	33/24	32/23	12	26	26	24	W	5	SW	35.1	− 21.1
Bedford	38 51	86 30	204	− 18	− 15	35/24	33/24	32/23	12	26	26	24				36.4	− 20.2
Bloomington	39 08	86 37	258	− 18	− 15	35/24	33/24	32/23	12	26	26	24	W	5	SW	36.6	− 20.3
Columbus, Bakalar AFB	39 16	85 54	198	− 16	− 14	35/24	33/24	32/23	12	26	26	24	W	5	SW	36.8	− 21.3
Crawfordsville	40 03	86 54	207	− 19	− 16	34/24	33/23	31/23	12	26	25	24				36.9	− 22.0
Evansville AP	38 03	87 32	116	− 16	− 13	35/24	34/24	33/24	12	26	26	25	NW	5	SW	36.8	− 17.7
Fort Wayne AP	41 00	85 12	241	− 20	− 17	33/23	32/22	31/22	13	25	24	23	WSW	5	SW		
Goshen AP	41 32	85 48	252	− 19	− 17	33/23	32/23	30/22	13	25	24	23				36.0	− 23.6
Hobart	41 32	87 15	183	− 20	− 17	33/23	31/23	29/22	12	25	24	23				36.9	− 22.5
Huntington	40 53	85 30	245	− 20	− 17	33/23	32/22	31/22	13	25	24	23				36.1	− 22.3
Indianapolis AP (S)	39 44	86 17	241	− 19	− 17	33/23	32/23	31/23	12	26	24	24	WNW	5	SW	35.3	− 21.4
Jeffersonville	38 17	85 45	139	− 15	− 12	35/23	34/23	32/23	13	26	25	24				36.8	− 16.8
Kokomo	40 25	86 03	261	− 20	− 18	33/23	32/23	31/23	12	25	24	23				36.8	− 21.9
Lafayette	40 2	86 5	183	− 19	− 16	34/23	33/23	31/23	12	26	24	24					
La Porte	41 36	86 43	247	− 19	− 16	34/23	32/23	31/23	12	26	24	24				36.7	− 23.6
Marion	40 29	85 41	262	− 20	− 18	33/23	32/23	31/23	13	25	24	23				36.1	− 22.6
Muncie	40 11	85 21	292	− 19	− 17	33/23	32/23	31/23	12	24	24	24					
Peru, Grissom AFB	40 39	86 09	248	− 21	− 18	32/23	31/23	30/23	12	25	24	23	W	5	SW		
Richmond AP	39 46	84 50	348	− 19	− 17	33/23	32/23	31/23	12	26	24	24				34.9	− 22.5
Shelbyville	39 31	85 47	229	− 18	− 16	34/23	33/23	31/23	12	26	24	24				36.5	− 21.1
South Bend AP	41 42	86 19	236	− 19	− 17	33/23	32/23	30/22	12	25	24	23	SW	6	SSW	35.7	− 22.9
Terre Haute AP	39 27	87 18	178	− 19	− 16	35/24	33/23	32/23	12	26	25	24	NNW	4	SSW	36.8	− 20.5
Valparaiso	41 31	87 02	244	− 19	− 16	34/23	32/23	31/23	12	26	24	24				35.3	− 23.9
Vincennes	38 41	87 32	128	− 17	− 14	35/24	33/23	32/23	12	26	25	24				37.9	− 19.3
IOWA																	
Ames (S)	42 02	93 48	335	− 24	− 21	34/24	32/23	31/23	13	26	24	24				36.3	− 27.7
Burlington AP	40 47	91 07	211	− 22	− 19	34/23	33/24	31/23	12	26	25	24	NW	5	SSW	37.0	− 23.9
Cedar Rapids AP	41 53	91 42	263	− 23	− 21	33/24	31/24	30/23	13	26	25	24	NW	5	S	36.5	− 26.4
Clinton	41 50	90 13	181	− 22	− 19	33/24	32/24	31/23	13	26	25	24				36.4	− 25.4
Council Bluffs	41 20	95 49	369	− 22	− 19	34/24	33/24	31/23	12	26	25	24					

TABLE 1—Climatic conditions for the United States (*continued*).

				Winter,[b] °C		Summer,[c] °C							Prevailing Wind			Temp. °C	
Col. 1	Col. 2	Col. 3	Col. 4	Col. 5		Col. 6			Col. 7	Col. 8			Col. 9			Col. 10	
State and Station[a]	Lat.	Long.	Elev.	Design Dry-Bulb		Design Dry-Bulb and Mean Coincident Wet-Bulb			Mean Daily	Design Wet-Bulb			Winter		Summer	Median of Annual Extr.	
	° ′	° ′	m	99%	97.5%	1%	2.5%	5%	Range	1%	2.5%	5%	m/s[d]			Max.	Min.
Des Moines AP	41 32	93 39	286	-23	-21	34/24	33/23	31/23	13	26	25	24	NW	6	S	36.8	-25.7
Dubuque	42 24	90 42	322	-24	-22	32/23	31/23	30/22	12	25	24	23	N	5	SSW	35.1	-26.1
Fort Dodge	42 33	94 11	354	-24	-22	33/23	31/23	30/22	13	25	24	23	NW	6	S	36.9	-28.4
Iowa City	41 38	91 33	202	-24	-21	33/24	32/24	31/23	12	27	26	24	NW	5	SSW	36.3	-26.2
Keokuk	40 24	91 24	175	-21	-18	35/24	33/24	32/23	12	26	25	24				38.9	-22.7
Marshalltown	42 04	92 56	274	-24	-22	33/24	32/24	31/23	13	26	25	24				36.9	-25.2
Mason City AP	43 09	93 20	370	-26	-24	32/23	31/23	29/22	13	25	24	23	NW	6	S	35.8	-29.8
Newton	41 41	93 02	285	-23	-21	34/24	33/23	31/23	13	26	25	24				36.8	-25.9
Ottumwa AP	41 06	92 27	256	-22	-20	34/24	33/23	31/23	12	26	25	24				37.3	-24.4
Sioux City AP	42 24	96 23	334	-24	-22	35/23	33/23	32/23	13	26	25	24	NNW	5	S	37.7	-27.6
Waterloo	42 33	92 24	265	-26	-23	33/24	32/24	30/23	13	26	25	24	NW	5	S	36.5	-28.8
KANSAS																	
Atchison	39 34	95 07	288	-19	-17	36/25	34/24	33/24	13	27	26	25				38.1	-22.7
Chanute AP	37 40	95 29	299	-16	-14	38/23	36/23	34/23	13	26	25	24	NNW	6	SSW	39.3	-19.3
Dodge City AP (S)	37 46	99 58	787	-18	-15	38/21	36/21	35/21	14	23	23	22	N	6	SSW	39.4	-21.7
El Dorado	37 49	96 50	391	-16	-14	38/22	37/23	36/23	13	25	24	24				39.7	-20.6
Emporia	38 20	96 12	369	-17	-15	38/23	36/23	34/23	14	26	25	24				39.1	-21.3
Garden City AP	37 56	100 44	878	-18	-16	37/21	36/21	34/21	16	23	23	22					
Goodland AP	39 22	101 42	1114	-21	-18	37/19	36/18	34/19	17	22	21	20	WSW	5	S	39.6	-23.6
Great Bend	38 21	98 52	576	-18	-16	38/23	37/23	35/23	16	26	24	24					
Hutchinson AP	38 04	97 52	470	-16	-13	39/22	37/22	36/22	16	25	24	23	N	7	S	40.7	-21.2
Liberal	37 03	100 58	875	-17	-14	37/20	36/20	34/20	16	23	22	22				41.0	-19.9
Manhattan, Fort Riley (S)	39 03	96 46	325	-18	-16	37/24	35/24	33/23	13	26	25	24	NNE	4	S	40.3	-22.6
Parsons	37 20	95 31	274	-15	-13	38/23	36/23	34/23	13	26	25	24	NNW	6	SSW		
Russell AP	38 52	98 49	569	-18	-16	38/23	37/23	35/23	16	26	24	24					
Salina	38 48	97 39	388	-18	-15	39/23	38/23	36/23	14	26	25	24	N	4	SSW		
Topeka AP	39 04	95 38	267	-18	-16	37/24	36/24	34/23	13	26	26	24	NNW	5	S	38.8	-21.3
Wichita AP	37 39	97 25	403	-16	-14	38/22	37/23	36/23	13	25	24	24	NNW	6	SSW	39.2	-19.3
KENTUCKY																	
Ashland	38 33	82 44	166	-15	-12	34/24	33/23	32/23	12	26	25	24	W	3	SW	36.3	-17.3
Bowling Green AP	35 58	86 28	163	-16	-12	34/25	33/24	32/23	12	26	25	24				37.7	-17.1
Corbin AP	36 57	84 06	358	-16	-13	34/23	33/23	32/22	13	25	24	24					
Covington AP	39 03	84 40	265	-17	-14	33/23	32/22	31/22	12	25	24	23	W	5	SW		
Hopkinsville, Ft Campbell	36 40	87 29	174	-16	-12	34/25	33/24	32/23	12	26	25	24	N	3	W	37.8	-18.0
Lexington AP (S)	38 02	84 36	295	-16	-13	34/23	33/23	31/22	12	25	24	24	WNW	5	SW	35.2	-18.1
Louisville AP	38 11	85 44	145	-15	-12	35/23	34/23	32/23	13	26	25	24	NW	4	SW	36.3	-17.1
Madisonville	37 19	87 29	134	-15	-12	36/24	34/24	32/24	12	26	26	25					
Owensboro	37 45	87 10	124	-15	-12	36/24	34/24	33/24	13	26	26	25	NW	5	SW	36.7	-17.9
Paducah AP	37 04	88 46	126	-14	-11	37/24	35/24	33/24	11	26	26	25					
LOUISIANA																	
Alexandria AP	31 24	92 18	28	-5	-3	35/25	34/25	33/25	11	27	26	26	N	4	S	37.8	-9.1
Baton Rouge AP	30 32	91 09	20	-4	-2	35/25	34/25	33/25	11	27	27	26	ENE	4	W	36.7	-5.9
Bogalusa	30 47	89 52	31	-4	-2	35/25	34/25	33/25	11	27	27	26				37.4	-6.6
Houma	29 31	90 40	4	-1	2	35/26	34/26	33/25	8	27	27	26				36.2	-5.3
Lafayette AP	30 12	92 00	13	-3	-1	35/26	34/26	33/26	10	27	27	26	N	4	SW	36.8	-5.2
Lake Charles AP (S)	30 07	93 13	3	-3	-1	35/25	34/25	33/25	9	27	26	26	N	5	SSW	37.3	-6.4
Minden	32 36	93 18	76	-7	-4	37/25	36/24	34/24	11	26	26	26				38.7	-9.5
Monroe AP	32 31	92 02	24	-7	-4	37/25	36/24	34/24	11	26	26	26	N	5	S	38.4	-8.9
Natchitoches	31 46	93 05	40	-6	-3	36/25	35/25	34/25	11	27	26	26					
New Orleans AP	29 59	90 15	1	-2	1	34/26	33/26	32/25	9	27	27	26	NNE	5	SSW	35.7	-2.4
Shreveport AP (S)	32 28	93 49	77	-7	-4	37/25	36/24	34/24	11	26	26	26	N	5	S		
MAINE																	
Augusta AP	44 19	69 48	108	-22	-19	31/23	29/21	28/20	12	23	22	21	NNE	5	WNW		
Bangor, Dow AFB	44 48	68 50	59	-24	-21	30/21	28/20	27/19	12	23	22	21	WNW	4	S		
Caribou AP (S)	46 52	68 01	190	-28	-25	29/21	27/19	26/19	12	22	21	19	WSW	5	SW		
Lewiston	44 02	70 15	61	-22	-19	31/23	29/21	28/20	12	23	22	21				34.4	-25.4
Millinocket AP	45 39	68 42	126	-25	-23	31/21	28/20	27/19	12	22	21	20	WNW	6	WNW	33.6	-30.6
Portland (S)	43 39	70 19	13	-21	-18	31/22	29/22	27/21	12	23	22	21	W	4	S	34.2	-23.3
Waterville	44 32	69 40	92	-22	-20	31/22	29/21	27/20	12	23	22	21					

TABLE 1—Climatic conditions for the United States (*continued*).

				Winter,[b] °C		Summer,[c] °C							Prevailing Wind			Temp. °C	
Col. 1	Col. 2	Col. 3	Col. 4	Col. 5		Col. 6			Col. 7	Col. 8			Col. 9			Col. 10	
State and Station[a]	Lat.	Long.	Elev.	Design Dry-Bulb		Design Dry-Bulb and Mean Coincident Wet-Bulb			Mean Daily	Design Wet-Bulb			Winter		Summer	Median of Annual Extr.	
	° ′	° ′	m	99%	97.5%	1%	2.5%	5%	Range	1%	2.5%	5%	m/s[d]			Max.	Min.
MARYLAND																	
Baltimore AP	39 11	76 40	45	-12	-11	34/24	33/24	32/23	12	26	25	24	W	5	WSW		
Baltimore Co	39 20	76 25	6	-10	-8	33/25	32/24	31/24	9	27	26	24	WNW	5	S	36.6	-13.8
Cumberland	39 37	78 46	241	-14	-12	33/24	32/23	31/23	12	25	24	24	WNW	5	W		
Frederick AP	39 27	77 25	95	-13	-11	34/24	33/24	31/23	12	26	25	24	N	5	WNW		
Hagerstown	39 42	77 44	215	-13	-11	34/24	33/23	32/23	12	25	24	24	WNW	5	W		
Salisbury (S)	38 20	75 30	18	-11	-9	34/24	33/24	31/23	10	26	25	24				36.0	-13.7
MASSACHUSETTS																	
Boston AP (S)	42 22	71 02	5	-14	-13	33/23	31/22	29/21	9	24	23	22	WNW	8	SW	35.4	-18.4
Clinton	42 24	71 41	121	-19	-17	32/22	31/22	29/21	9	24	23	22				33.2	-22.5
Fall River	41 43	71 08	58	-15	-13	31/22	29/22	27/21	10	23	23	22	NW	5	SW	33.4	-18.3
Framingham	42 17	71 25	52	-16	-14	32/22	30/22	28/21	9	23	23	22				35.6	-22.1
Gloucester	42 35	70 41	3	-17	-15	32/23	30/22	28/21	8	24	23	22					
Greenfield	42 3	72 4	63	-22	-19	31/22	29/22	28/21	13	23	23	22					
Lawrence	42 42	71 10	17	-21	-18	32/23	31/22	29/21	12	24	23	23	NW	4	WSW	35.1	-22.8
Lowell	42 39	71 19	27	-20	-17	33/23	31/22	29/21	12	24	23	23				35.1	-22.5
New Bedford	41 41	70 58	24	-15	-13	29/22	28/22	27/21	11	23	23	22	NW	5	SW	33.0	-16.6
Pittsfield AP	42 26	73 18	364	-22	-19	31/22	29/21	27/20	13	23	22	21	NW	6	SW		
Springfield, Westover AFB	42 12	72 32	75	-21	-18	32/22	31/22	29/21	11	24	23	22	N	4	SSW	35.4	-20.4
Taunton	41 54	71 04	6	-15	-13	32/23	30/22	28/21	10	24	23	23				33.8	-23.2
Worcester AP	42 16	71 52	301	-18	-16	31/22	29/21	27/20	10	23	22	21	W	7	W		
MICHIGAN																	
Adrian	41 55	84 01	230	-18	-16	33/23	31/22	29/22	13	24	24	23				36.2	-21.7
Alpena AP	45 04	83 26	186	-24	-21	32/21	29/21	28/21	15	23	22	21	W	3	SW	34.4	-26.0
Battle Creek AP	42 19	85 15	287	-17	-15	33/23	31/22	29/21	13	24	23	23	SW	4	SW		
Benton Harbor AP	42 08	86 26	196	-17	-15	33/22	31/22	29/21	11	24	23	22	SSW	4	WSW		
Detroit	42 25	83 01	189	-16	-14	33/23	31/22	30/22	11	24	23	23	W	6	SW	35.1	-19.2
Escanaba	45 44	87 05	185	-24	-22	31/21	28/21	27/20	9	23	22	21				31.6	-26.7
Flint AP	42 58	83 44	235	-20	-17	32/23	31/22	29/22	14	24	23	22	SW	4	SW	35.2	-23.3
Grand Rapids AP	42 53	85 31	239	-17	-15	33/22	31/22	29/21	13	24	23	22	WNW	4	WSW	35.2	-20.9
Holland	42 42	86 06	207	-17	-14	31/22	30/22	28/21	12	24	23	22				34.5	-21.6
Jackson AP	42 16	84 28	311	-17	-15	33/23	31/22	29/21	13	24	23	23				35.8	-22.1
Kalamazoo	42 17	85 36	291	-17	-15	33/23	31/22	29/21	13	24	23	23				35.5	-21.5
Lansing AP	42 47	84 36	266	-19	-17	32/23	31/22	29/21	13	24	23	22	SW	6	W	34.8	-23.9
Marquette Co	46 34	87 24	224	-24	-22	29/21	27/21	25/19	10	22	21	20				34.7	-24.3
Mt Pleasant	43 35	84 46	243	-18	-16	33/23	31/22	29/22	13	24	23	22				35.2	-23.9
Muskegon AP	43 10	86 14	191	-17	-14	30/22	29/21	28/21	12	24	23	22	E	4	SW		
Pontiac	42 40	83 25	299	-18	-16	32/23	31/22	29/22	12	24	23	23				35.0	-21.6
Port Huron	42 59	82 25	179	-18	-16	32/23	31/22	28/22	12	24	23	23	W	4	S		
Saginaw AP	43 32	84 05	203	-18	-16	33/23	31/22	29/22	13	24	23	22	WSW	4	SW	35.6	-22.0
Sault Ste. Marie AP (S)	46 28	84 22	220	-24	-22	29/21	27/21	25/19	13	22	21	20	E	4	SW	32.1	-29.4
Traverse City AP	44 45	85 35	190	-19	-17	32/22	30/22	28/21	12	24	23	22	SSW	5	SW	35.2	-23.7
Ypsilanti	42 14	83 32	218	-17	-15	33/22	32/22	30/21	12	24	23	22	SW	5	SW		
MINNESOTA																	
Albert Lea	43 39	93 21	372	-27	-24	32/23	31/22	29/22	13	25	24	23					
Alexandria AP	45 52	95 23	436	-30	-27	33/22	31/22	29/21	13	24	23	22				35.1	-33.3
Bemidji AP	47 31	94 56	424	-35	-32	31/21	29/21	27/19	13	23	22	21	N	4	S	34.7	-38.3
Brainerd	46 24	94 08	374	-29	-27	32/23	31/22	29/21	13	24	23	22					
Duluth AP	46 50	92 11	435	-29	-27	29/21	28/20	26/19	12	22	21	20	WNW	6	WSW	32.7	-33.0
Fairbault	44 18	93 16	287	-27	-24	33/23	31/22	29/22	13	25	24	23				35.4	-31.3
Fergus Falls	46 16	96 04	369	-29	-27	33/22	31/22	29/21	13	24	23	22				36.1	-33.2
International Falls AP	48 34	93 23	359	-34	-32	29/20	28/20	27/19	14	22	21	20	N	5	S	34.1	-38.1
Mankato	44 09	93 59	306	-27	-24	33/22	31/22	29/21	13	25	24	23					
Minneapolis/St. Paul AP	44 53	93 13	254	-27	-24	33/24	32/23	30/22	12	25	24	23	NW	4	S	35.8	-30.0
Rochester AP	43 55	92 30	395	-27	-24	32/23	31/22	29/22	13	25	24	23	NW	5	SSW		
St. Cloud AP (S)	45 35	94 11	318	-26	-24	33/23	31/22	29/21	13	24	23	22					

TABLE 1—Climatic conditions for the United States (*continued*).

Col. 1	Col. 2	Col. 3	Col. 4	Col. 5		Col. 6			Col. 7	Col. 8			Col. 9			Col. 10	
				Winter,[b] °C		Summer,[c] °C							Prevailing Wind			Temp. °C	
State and Station[a]	Lat.	Long.	Elev.	Design Dry-Bulb		Design Dry-Bulb and Mean Coincident Wet-Bulb			Mean Daily	Design Wet-Bulb			Winter		Summer	Median of Annual Extr.	
	° ′	° ′	m	99%	97.5%	1%	2.5%	5%	Range	1%	2.5%	5%	m/s[d]			Max.	Min.
Virginia	47 30	92 33	438	-32	-29	29/21	28/20	27/19	13	22	21	20				33.7	-36.1
Willmar	45 07	95 05	344	-26	-24	33/23	31/22	29/22	13	24	23	22				36.0	-31.3
Winona	44 03	91 38	199	-26	-23	33/24	31/23	29/22	13	25	24	23					
MISSISSIPPI																	
Biloxi, Keesler AFB	30 25	88 55	8	-2	-1	34/26	33/26	32/26	9	28	27	27	N	4	S	36.7	-5.0
Clarksdale	34 12	90 34	54	-10	-7	36/25	34/25	33/24	12	27	26	26				38.3	-10.4
Columbus AFB	33 39	88 27	67	-9	-7	35/25	34/25	33/24	12	27	26	26	N	4	W	38.7	-10.7
Greenville AFB	33 29	90 59	42	-9	-7	35/25	34/25	33/24	12	27	26	26				37.5	-9.5
Greenwood	33 30	90 05	45	-9	-7	35/25	34/25	33/24	12	27	26	26				38.1	-9.3
Hattiesburg	31 16	89 15	45	-4	-3	36/26	34/25	33/25	12	27	27	26				37.7	-7.7
Jackson AP	32 19	90 05	95	-6	-4	36/24	35/24	34/24	12	26	26	26	NNW	3	NW	37.7	-8.9
Laurel	31 40	89 10	72	-4	-3	36/26	34/25	33/25	12	27	27	26				37.6	-7.9
Mccomb AP	31 15	90 28	143	-6	-3	36/25	34/24	33/24	10	27	26	26					
Meridian AP	32 20	88 45	88	-7	-5	36/25	35/24	34/24	12	27	26	26	N	3	WSW	36.8	-9.1
Natchez	31 33	91 23	59	-5	-3	36/26	34/26	33/25	12	27	27	26				36.9	-7.6
Tupelo	34 16	88 46	110	-10	-7	36/25	34/25	33/24	12	27	26	26				38.2	-11.2
Vicksburg Co	32 24	90 47	80	-6	-3	36/26	35/26	34/25	12	27	27	26				36.1	-7.8
MISSOURI																	
Cape Girardeau	37 14	89 35	107	-13	-11	37/24	35/24	33/24	12	26	26	25					
Columbia AP (S)	38 58	92 22	237	-18	-16	36/23	34/23	33/23	12	26	25	24	WNW	5	WSW	37.5	-21.2
Farmington AP	37 46	90 24	283	-16	-13	36/24	34/24	32/23	12	26	25	24				37.7	-18.9
Hannibal	39 42	91 21	149	-19	-16	36/24	34/24	32/24	12	27	26	25	NNW	6	SSW	36.9	-22.0
Jefferson City	38 34	92 11	195	-17	-14	37/24	35/23	33/23	13	26	25	24				38.4	-21.2
Joplin AP	37 09	94 30	299	-14	-12	38/23	36/23	34/23	13	26	25	24	NNW	6	SSW		
Kansas City AP	39 07	94 35	241	-17	-14	37/24	36/23	34/23	11	26	25	24	NW	5	S	37.9	-20.2
Kirksville AP	40 06	92 33	294	-21	-18	36/23	34/23	32/23	13	26	25	24				36.8	-23.8
Mexico	39 11	91 54	236	-18	-16	36/23	34/23	33/23	12	26	25	24				38.4	-22.2
Moberly	39 24	92 26	259	-19	-16	36/23	34/23	33/23	13	26	25	24					
Poplar Bluff	36 46	90 25	116	-12	-9	37/26	35/24	33/24	12	27	26	26					
Rolla	37 59	91 43	367	-16	-13	34/25	33/24	32/23	12	26	25	24				37.4	-19.5
St. Joseph AP	39 46	94 55	252	-19	-17	36/25	34/24	33/24	13	27	26	25	NNW	5	S	38.1	-22.2
St. Louis AP	38 45	90 23	163	-17	-14	36/24	34/24	33/23	12	26	25	24	NW	5	WSW		
St. Louis Co	38 39	90 38	141	-16	-13	37/24	34/24	33/23	10	26	25	24	NW	3	S	37.3	-19.3
Sikeston	36 53	89 36	99	-13	-9	37/25	35/24	33/24	12	27	26	25					
Sedalia, Whiteman AFB	38 43	93 33	265	-18	-16	35/24	33/24	32/24	12	26	26	24	NNW	4	SSW	37.8	-20.6
Springfield AP	37 14	93 23	387	-16	-13	36/23	34/23	33/23	13	26	25	24	NNW	5	S	36.2	-19.1
MONTANA																	
Billings AP	45 48	108 32	1088	-26	-23	34/18	33/18	31/17	17	19	19	18	NE	5	SW	38.1	-28.4
Bozeman	45 47	111 09	1356	-29	-26	32/16	31/16	29/15	18	17	17	16				33.4	-30.7
Butte AP	45 57	112 30	1693	-31	-27	30/14	28/13	27/13	19	16	14	14	S	3	NW	33.2	-32.4
Cut Bank AP	48 37	112 22	1170	-32	-29	31/16	29/16	28/16	19	18	17	16				34.8	-34.9
Glasgow AP (S)	48 25	106 32	842	-30	-28	33/18	32/17	29/17	16	20	19	18	E	4	S		
Glendive	47 08	104 48	755	-28	-25	35/19	33/18	32/17	16	21	19	18				39.6	-34.3
Great Falls AP (S)	47 29	111 22	1117	-29	-26	33/16	31/16	29/15	16	18	17	16	SW	4	WSW	36.7	-31.7
Havre	48 34	109 40	760	-28	[illegible]	34/18	32/18	31/17	18	20	19	18				37.6	-35.2
Helena AP	46 36	112 00	1167	-29	-27	33/16	31/16	29/15	18	18	17	16	N	6	WNW	35.3	-30.9
Kalispell AP	48 18	114 16	907	-26	-22	33/17	31/16	29/16	19	18	17	17				34.7	-27.1
Lewiston AP	47 04	109 27	1257	-30	-27	32/17	31/16	28/16	17	18	17	17	NW	5	NW	35.7	-33.2
Livingstown AP	45 42	110 26	1408	-29	-26	32/16	31/16	29/15	18	17	17	16				36.2	-29.6
Miles City AP	46 26	105 52	803	-29	-26	37/19	35/19	33/18	17	21	20	19	NW	4	SE	39.8	-33.2
Missoula AP	46 55	114 05	973	-25	-21	33/17	31/16	29/16	20	18	17	17	ESE	4	NW	37.0	-25.5
NEBRASKA																	
Beatrice	40 16	96 45	377	-21	-19	37/24	35/23	33/23	13	26	25	24				39.5	-24.1
Chadron AP	42 50	103 05	1010	-22	-19	36/19	34/18	33/18	17	22	21	20					
Columbus	41 28	97 20	442	-21	-19	37/23	35/23	33/23	14	25	24	24					
Fremont	41 26	96 29	366	-21	-19	37/24	35/23	33/23	12	26	25	24					

TABLE 1—Climatic conditions for the United States (*continued*).

				Winter,[b] °C		Summer,[c] °C							Prevailing Wind		Temp. °C	
Col. 1	Col. 2	Col. 3	Col. 4	Col. 5		Col. 6			Col. 7	Col. 8			Col. 9		Col. 10	
State and Station[a]	Lat.	Long.	Elev.	Design Dry-Bulb		Design Dry-Bulb and Mean Coincident Wet-Bulb			Mean Daily Range	Design Wet-Bulb			Winter	Summer	Median of Annual Extr.	
	° ′	° ′	m	99%	97.5%	1%	2.5%	5%		1%	2.5%	5%	m/s[d]		Max.	Min.
Grand Island AP	40 59	98 19	567	−22	−19	36/22	34/22	33/22	16	24	23	23	NNW 5	S	39.6	−25.7
Hastings	40 36	98 26	596	−22	−19	36/22	34/22	33/22	15	24	23	23	NNW 5	S	39.7	−23.7
Kearney	40 44	99 01	650	−23	−20	36/22	34/21	32/21	16	23	23	22			39.4	−25.4
Lincoln Co (S)	40 51	96 45	360	−21	−19	37/24	35/23	33/23	13	26	25	24	N 4	S	38.9	−24.7
Mccook	40 12	100 38	844	−21	−19	37/21	35/21	33/21	16	23	22	22				
Norfolk	41 59	97 26	473	−22	−20	36/23	34/23	32/23	17	26	25	24			38.9	−28.9
North Platte AP (S)	41 08	100 41	847	−22	−20	36/21	34/21	32/21	16	23	22	22	NW 5	SSE	38.2	−26.6
Omaha AP	41 18	95 54	298	−22	−19	34/24	33/24	31/23	12	26	25	24	NW 4	S	37.9	−25.1
Scottsbluff AP	41 52	103 36	1207	−22	−19	35/18	33/18	32/18	17	21	20	19	NW 5	SE	38.7	−28.3
Sidney AP	41 13	103 06	1341	−22	−19	35/18	33/18	32/18	17	21	20	19				
NEVADA																
Carson City	39 10	119 46	1425	−16	−13	34/16	33/15	32/14	23	17	16	16	SSW 2	WNW	37.3	−20.6
Elko AP	40 50	115 47	1540	−22	−19	34/15	33/15	32/14	23	17	17	16	E 2	SW		
Ely AP (S)	39 17	114 51	1907	−23	−20	32/14	31/13	29/13	22	16	15	14	S 5	SSW		
Las Vegas AP (S)	36 05	115 10	664	−4	−2	42/19	41/18	40/18	17	22	21	21	EME 4	SW		
Lovelock AP	40 04	118 33	1190	−13	−11	37/17	36/17	34/17	23	19	18	18			39.4	−18.3
Reno AP (S)	39 30	119 47	1343	−15	−12	35/16	33/16	32/15	25	18	17	16	SSW 2	WNW		
Reno Co	39 30	119 47	1344	−14	−12	36/16	34/16	33/15	25	18	17	16			37.2	−17.7
Tonopah AP	38 04	117 05	1654	−15	−12	34/16	33/15	32/14	22	18	17	16	N 4	S		
Winnemucca AP	40 54	117 48	1311	−18	−16	36/16	34/16	33/16	23	18	17	16	SE 5	W	37.8	−22.3
NEW HAMPSHIRE																
Berlin	44 3	71 1	338	−26	−23	31/22	29/21	27/20	12	23	22	21			34.0	−31.5
Claremont	43 2	72 2	128	−23	−20	32/22	30/21	28/21	13	23	23	22				
Concord AP	43 12	71 30	104	−22	−19	32/22	31/21	29/21	14	23	23	22	NW 4	SW	34.9	−26.7
Keene	42 55	72 17	149	−24	−22	32/22	31/21	28/21	13	23	23	22			34.8	−28.3
Laconia	43 03	71 3	154	−23	−21	32/22	30/21	28/21	14	23	23	22				
Manchester, Grenier AFB	42 56	71 26	71	−22	−19	33/22	31/22	29/21	13	24	23	22	N 6	SW	34.3	−24.8
Portsmouth, Pease AFB	43 04	70 49	31	−19	−17	32/23	29/22	28/21	12	24	23	22	W 4	W		
NEW JERSEY																
Atlantic City Co	39 23	74 26	3	−12	−11	33/23	32/23	30/22	10	26	25	24	NW 6	WSW	33.9	−13.6
Long Branch	40 19	74 01	5	−12	−11	34/23	32/23	31/22	10	26	25	24			35.5	−15.4
Newark AP	40 42	74 10	2	−12	−10	34/23	33/23	31/22	11	25	24	24	WNW 6	WSW		
New Brunswick	40 29	74 26	38	−14	−12	33/23	32/23	30/22	11	25	24	24				
Paterson	40 54	74 09	30	−14	−12	34/23	33/23	31/22	12	25	24	24				
Phillipsburg	40 41	75 11	55	−17	−14	33/23	32/22	30/22	12	24	24	23			36.3	−18.2
Trenton Co	40 13	74 46	17	−12	−10	33/24	31/23	29/23	11	26	24	24	W 5	SW	35.7	−15.4
Vineland	39 29	75 00	34	−13	−12	33/24	32/23	30/23	11	26	24	24				
NEW MEXICO																
Alamagordo, Holloman AFB	32 51	106 06	1248	−10	−7	37/18	36/18	34/18	17	21	20	19				
Albuquerque AP (S)	35 03	106 37	1619	−11	−9	36/16	34/16	33/16	15	19	18	18	N 4	W	36.7	−14.9
Artesia	32 46	104 23	1012	−11	−7	39/19	38/19	36/19	17	22	22	21			40.8	−15.7
Carlsbad AP	32 20	104 16	1004	−11	−7	39/19	38/19	36/19	16	22	22	21	N 3	SSE		
Clovis AP	34 23	103 19	1309	−13	−11	35/18	34/18	33/18	16	21	20	19			38.9	−16.4
Farmington AP	36 44	108 14	1678	−17	−14	35/17	34/17	33/16	17	19	18	18	ENE 3	SW		
Gallup	35 31	108 47	1971	−18	−15	32/15	32/14	30/14	18	18	17	16				
Grants	35 10	107 54	1989	−18	−16	32/15	31/14	29/14	18	18	17	16				
Hobbs AP	32 45	103 13	1125	−11	−8	38/19	37/19	36/19	16	22	21	21				
Las Cruces	32 18	106 55	1385	−9	−7	37/18	36/18	34/18	17	21	20	19	SE 3	SE		
Los Alamos	35 52	106 19	2259	−15	−13	32/16	31/16	29/16	18	17	16	16			32.1	−19.1
Raton AP	36 45	104 30	1943	−20	−17	33/16	32/16	31/16	19	18	18	17				
Roswell, Walker AFB	33 18	104 32	1121	−11	−8	38/19	37/19	36/19	18	22	21	21	N 3	SSE	39.4	−16.3
Santa Fe Co	35 37	106 05	1923	−14	−12	32/16	31/16	30/16	16	17	17	16			32.3	−18.4
Silver City AP	32 38	108 10	1659	−15	−12	35/16	34/16	33/16	17	19	18	17				
Socorro AP	34 03	106 53	1410	−11	−8	36/17	35/17	34/17	17	19	19	18				
Tucumcari AP	35 11	103 36	1231	−13	−11	37/19	36/19	35/18	16	21	21	20	NE 4	SW	39.3	−17.2
NEW YORK																
Albany AP (S)	42 45	73 48	84	−21	−18	33/23	31/22	29/21	13	24	23	22	WNW 4	S		
Albany Co	42 39	73 45	6	−20	−17	33/23	31/22	29/21	11	24	23	22			35.1	−24.1
Auburn	42 54	76 32	218	−19	−17	32/23	31/22	29/21	12	24	23	22			33.6	−23.1
Batavia	43 00	78 11	281	−17	−15	32/22	31/22	29/21	12	24	23	22			33.4	−21.9
Binghamton AP	42 13	75 59	485	−19	−17	30/22	28/21	27/20	11	23	22	21	WSW 5	WSW	33.8	−22.9
Buffalo AP	42 56	78 44	215	−17	−14	31/22	29/21	28/21	12	23	23	22	W 5	SW	32.2	−19.6
Cortland	42 36	76 11	344	−21	−18	31/22	29/22	28/21	13	23	23	22			34.3	−24.0
Dunkirk	42 29	79 16	211	−16	−13	31/23	29/22	28/22	10	24	23	22	SSW 5	WSW		

TABLE 1—Climatic conditions for the United States (*continued*).

Col. 1	Col. 2	Col. 3	Col. 4	Winter,[b] °C Col. 5		Summer,[c] °C Col. 6			Col. 7	Col. 8			Prevailing Wind Col. 9			Temp. °C Col. 10	
State and Station[a]	Lat.	Long.	Elev.	Design Dry-Bulb		Design Dry-Bulb and Mean Coincident Wet-Bulb			Mean Daily	Design Wet-Bulb			Winter		Summer	Median of Annual Extr.	
	° ′	° ′	m	99%	97.5%	1%	2.5%	5%	Range	1%	2.5%	5%		m/s[d]		Max.	Min.
Elmira AP	42 10	76 54	291	−20	−17	32/22	30/22	28/21	13	23	23	22				35.7	−21.5
Geneva (S)	42 45	76 54	187	−19	−17	32/23	31/22	29/21	12	24	23	22				35.6	−21.4
Glens Falls	43 20	73 37	100	−24	−21	31/22	29/22	28/21	13	23	23	22	NNW	3	S		
Gloversville	43 02	74 21	232	−22	−19	32/22	30/22	28/21	13	24	23	22				34.0	−25.9
Hornell	42 21	77 42	404	−20	−18	31/22	29/21	28/21	13	23	23	22					
Ithaca (S)	42 27	76 29	283	−21	−18	31/22	29/22	28/21	13	23	23	22	W	3	SW		
Jamestown	42 07	79 14	424	−18	−16	31/21	30/21	28/21	11	23	22	22	WSW	5	WSW		
Kingston	41 56	74 00	85	−19	−17	33/23	31/22	29/21	12	24	23	23					
Lockport	43 09	79 15	195	−16	−14	32/23	30/22	29/22	12	24	23	23	N	5	SW	33.4	−20.4
Massena AP	44 56	74 51	63	−25	−22	30/21	28/21	27/20	11	23	22	21					
Newburgh, Stewart AFB	41 30	74 06	144	−18	−16	32/23	31/22	29/21	12	24	23	23	W	5	W		
NYC-Central Park (S)	40 47	73 58	48	−12	−9	33/23	32/23	31/22	9	24	24	23				34.9	−15.7
NYC-Kennedy AP	40 39	73 47	4	−11	−9	32/23	31/22	29/22	9	24	24	23					
NYC-La Guardia AP	40 46	73 54	3	−12	−9	33/23	32/23	31/22	9	24	24	23					
Niagara Falls AP	43 06	79 57	180	−16	−14	32/23	30/22	29/22	11	24	23	23	W	5	SW		
Olean	42 14	78 22	646	−19	−17	31/22	29/22	27/21	13	23	23	22					
Oneonta	42 31	75 04	541	−22	−20	30/22	28/21	27/20	13	23	22	21					
Oswego Co	43 28	76 33	91	−17	−14	30/23	28/22	27/21	11	24	23	22	E	4	WSW	32.9	−21.9
Plattsburg AFB	44 39	73 28	72	−25	−22	30/21	28/21	27/20	12	23	22	21	NW	3	SE		
Poughkeepsie	41 38	73 55	50	−18	−14	33/23	32/23	30/22	12	25	24	23	NNE	3	SSW	36.7	−20.9
Rochester AP	43 07	77 40	167	−17	−15	33/23	31/22	29/21	12	24	23	22	WSW	6	WSW		
Rome, Griffiss AFB	43 14	75 25	157	−24	−21	31/22	29/21	28/21	12	24	23	22	NW	3	W		
Schenectady (S)	42 51	73 57	115	−20	−17	32/23	31/22	29/21	12	24	23	22	WNW	4	S		
Suffolk County AFB	40 51	72 38	20	−14	−12	30/22	28/22	27/21	9	24	23	23	NW	5	SW		
Syracuse AP	43 07	76 07	125	−19	−17	32/23	31/22	29/21	11	24	23	22	N	4	WNW	34.1	−23.3
Utica	43 09	75 23	218	−24	−21	31/23	29/22	28/21	12	24	23	22	NW	6	W		
Watertown	43 59	76 01	99	−24	−21	30/23	28/22	27/21	11	24	23	22	E	4	WSW	33.2	−28.7
NORTH CAROLINA																	
Asheville AP	35 26	82 32	652	−12	−10	32/23	31/22	29/22	12	24	23	22	NNW	6	NNW	33.3	−14.6
Charlotte AP	35 13	80 56	224	−8	−6	35/23	34/23	33/23	11	25	24	24	NNW	3	SW	36.6	−10.8
Durham	35 52	78 47	132	−9	−7	34/24	33/24	32/24	11	26	25	24				37.2	−12.4
Elizabeth City AP	36 16	76 11	4	−11	−7	34/26	33/25	32/24	10	27	26	26	NW	4	SW		
Fayetteville, Pope AFB	35 10	79 01	66	−8	−7	35/24	33/24	32/24	11	26	26	25	N	3	SSW	37.3	−10.5
Goldsboro, Seymour-Johnson	35 20	77 58	33	−8	−6	34/25	33/24	32/24	10	26	26	25	N	4	SW	37.7	−10.6
Greensboro AP (S)	36 05	79 57	273	−10	−8	34/23	33/23	32/23	12	25	24	24	NE	4	SW	36.5	−12.4
Greenville	35 37	77 25	23	−8	−6	34/25	33/24	32/24	11	26	26	25					
Henderson	36 22	78 25	146	−11	−9	35/25	33/24	32/24	11	26	26	25					
Hickory	35 45	81 23	362	−10	−8	33/23	32/22	31/22	12	24	23	23				35.8	−12.4
Jacksonville	34 50	77 37	29	−7	−4	33/26	32/26	31/25	10	27	26	26					
Lumberton	34 37	79 04	39	−8	−6	35/24	33/24	32/24	11	26	26	25					
New Bern AP	35 05	77 03	6	−7	−4	33/26	32/26	31/25	10	27	26	26				36.8	−9.4
Raleigh/Durham AP (S)	35 52	78 47	132	−9	−7	34/24	33/24	32/24	11	26	25	24	N	4	SW	36.5	−11.0
Rocky Mount	35 58	77 48	37	−8	−6	34/25	33/24	32/24	11	26	26	25					
Wilmington AP	34 16	77 55	9	−5	−3	34/26	33/26	32/25	10	27	27	26	N	4	SW	36.1	−7.7
Winston-Salem AP	36 08	80 13	295	−9	−7	34/23	33/23	32/23	11	24	24	23	NW	4	WSW		
NORTH DAKOTA																	
Bismarck AP (S)	46 46	100 45	502	−31	−28	35/20	33/20	31/19	15	23	22	21	WNW	4	S	37.9	−35.3
Devils Lake	48 07	98 54	442	−32	−29	33/21	31/20	29/19	14	23	22	21				36.4	−34.7
Dickinson AP	46 48	102 48	788	−29	−27	34/20	32/19	31/18	14	22	21	20	WNW	6	SSE	38.3	−35.2
Fargo AP	46 54	96 48	273	−30	−28	33/23	32/22	29/21	14	24	23	22	SSE	6	S	36.3	−34.3
Grand Forks AP	47 57	97 24	278	−32	−30	33/21	31/21	29/20	14	23	22	21	N	4	S	36.4	−33.9
Jamestown AP	46 55	98 41	455	−30	−28	34/21	32/21	31/20	14	23	23	22				38.5	−33.3
Minot AP	48 25	101 21	509	−31	−29	33/20	32/19	30/18	14	22	21	20	WSW	5	S		
Williston	48 09	103 35	572	−32	−29	33/20	31/19	29/18	14	22	21	20				37.6	−36.1
OHIO																	
Akron-Canton AP	40 55	81 26	368	−17	−14	32/22	30/22	29/21	12	24	23	22	SW	5	SW	34.7	−20.3
Ashtabula	41 51	80 48	210	−16	−13	31/23	29/22	28/22	10	24	23	22					
Athens	39 20	82 06	213	−18	−14	35/24	33/23	32/23	12	26	24	23					
Bowling Green	41 23	83 38	206	−19	−17	33/23	32/23	30/22	13	24	24	23				35.9	−21.8

TABLE 1—Climatic conditions for the United States (*continued*).

				Winter,[b] °C		Summer,[c] °C							Prevailing Wind			Temp. °C	
Col. 1	Col. 2	Col. 3	Col. 4	Col. 5		Col. 6			Col. 7	Col. 8			Col. 9			Col. 10	
State and Station[a]	Lat.	Long.	Elev.	Design Dry-Bulb		Design Dry-Bulb and Mean Coincident Wet-Bulb			Mean Daily Range	Design Wet-Bulb			Winter		Summer	Median of Annual Extr.	
	° ′	° ′	m	99%	97.5%	1%	2.5%	5%		1%	2.5%	5%	m/s[d]			Max.	Min.
Cambridge	40 04	81 35	246	− 17	− 14	34/24	32/23	31/23	13	26	24	24					
Chillicothe	39 21	83 00	195	− 18	− 14	35/24	33/23	32/23	12	26	24	23	W	4	WSW	36.8	− 18.9
Cincinnati Co	39 09	84 31	231	− 17	− 14	33/23	32/22	31/22	12	25	24	23	W	5	SW	36.2	− 17.9
Cleveland AP (S)	41 24	81 51	237	− 17	− 15	33/23	31/22	30/22	12	24	23	23	SW	6	N	34.8	− 19.5
Columbus AP (S)	40 00	82 53	248	− 18	− 15	33/23	32/23	31/22	13	25	24	23	W	4	SSW	35.6	− 19.7
Dayton AP	39 54	84 13	306	− 18	− 16	33/23	32/22	30/22	11	24	24	23	WNW	6	SW	35.9	− 20.3
Defiance	41 17	84 23	213	− 18	− 16	34/23	33/23	31/22	13	25	24	23					
Findlay AP	41 01	83 40	245	− 17	− 16	33/23	32/23	31/22	13	25	24	23				36.3	− 21.9
Fremont	41 20	83 07	183	− 19	− 17	32/23	31/23	29/22	13	24	24	23					
Hamilton	39 24	84 35	198	− 18	− 15	33/23	32/22	31/22	12	24	24	23				36.8	− 19.3
Lancaster	39 44	82 38	262	− 18	− 15	34/23	33/23	31/22	13	25	24	23					
Lima	40 42	84 02	297	− 18	− 16	34/23	33/23	31/22	13	25	24	23	WNW	6	SW	35.6	− 21.4
Mansfield AP	40 49	82 31	395	− 18	− 15	32/23	31/22	29/22	12	24	23	23	W	4	SW	34.3	− 23.7
Marion	40 36	83 10	281	− 18	− 15	34/23	33/23	31/22	13	25	24	23					
Middletown	39 31	84 25	194	− 18	− 15	33/23	32/22	31/22	12	24	24	23					
Newark	40 01	82 28	268	− 18	− 15	34/23	33/23	32/22	13	25	24	23	W	4	SSW	35.4	− 21.6
Norwalk	41 16	82 37	204	− 19	− 17	32/23	31/23	29/22	12	24	24	23				36.3	− 22.4
Portsmouth	38 45	82 55	165	− 15	− 12	35/24	33/23	32/23	12	26	25	24	W	4	SW	36.6	− 17.2
Sandusky Co	41 27	82 43	185	− 17	− 14	34/23	33/22	31/22	12	24	23	23				35.9	− 18.8
Springfield	39 50	83 50	321	− 18	− 16	33/23	32/23	31/22	12	25	24	23	W	4	W		
Steubenville	40 23	80 38	302	− 17	− 15	32/22	30/22	29/21	12	23	23	22					
Toledo AP	41 36	83 48	204	− 19	− 17	32/23	31/23	29/22	14	24	24	23	WSW	4	SW	35.2	− 20.7
Warren	41 20	80 51	283	− 18	− 15	32/22	31/22	29/21	13	23	23	22					
Wooster	40 47	81 55	311	− 17	− 14	32/22	30/22	29/21	12	24	23	22				34.4	− 22.1
Youngstown AP	41 16	80 40	359	− 18	− 16	31/22	30/22	29/21	13	23	23	22	SW	5	SW		
Zanesville AP	39 57	81 54	274	− 17	− 14	34/24	32/23	31/23	13	26	24	24	W	3	WSW		
OKLAHOMA																	
Ada	34 47	96 41	309	− 12	− 10	38/23	36/23	35/23	13	25	24	24					
Altus AFB	34 39	99 16	420	− 12	− 9	39/23	38/23	37/23	14	25	24	24	N	5	S		
Ardmore	34 18	97 01	235	− 11	− 8	38/23	37/23	35/23	13	25	25	24					
Bartlesville	36 45	96 00	218	− 14	− 12	38/23	37/23	35/23	13	25	25	24					
Chickasha	35 03	97 55	331	− 12	− 10	38/23	37/23	35/23	13	26	25	24					
Enid, Vance AFB	36 21	97 55	399	− 13	− 11	39/23	38/23	36/23	13	26	25	24					
Lawton AP	34 34	98 25	334	− 11	− 9	38/23	37/23	36/23	13	26	25	24					
McAlester	34 50	95 55	237	− 10	− 7	37/23	36/23	34/23	13	25	24	24	N	5	S		
Muskogee AP	35 40	95 22	186	− 12	− 9	38/23	37/24	35/24	13	26	26	25					
Norman	35 15	97 29	360	− 13	− 11	37/23	36/23	34/23	13	25	24	24	N	5	S		
Oklahoma City AP (S)	35 24	97 36	392	− 13	− 11	38/23	36/23	35/23	13	26	25	24	N	7	SSW		
Ponca City	36 44	97 06	304	− 15	− 13	38/23	36/23	34/23	13	25	24	24					
Seminole	35 14	96 40	264	− 12	− 9	37/23	36/23	34/23	13	25	24	24					
Stillwater (S)	36 10	97 05	300	− 13	− 11	38/23	36/23	34/23	13	25	24	24	N	6	SSW	39.8	− 16.9
Tulsa AP	36 12	95 54	198	− 13	− 11	38/23	37/24	35/24	12	26	26	25	N	6	SSW		
Woodward	36 36	99 31	660	− 14	− 12	38/23	36/23	34/23	14	26	24	24				41.7	− 18.5
OREGON																	
Albany	44 38	123 07	70	− 8	− 6	33/19	32/19	30/18	17	21	19	19				36.4	− 8.6
Astoria AP (S)	46 09	123 53	2	− 4	− 2	24/18	22/17	20/16	9	18	17	17	ESE	4	NNW		
Baker AP	44 50	117 49	1028	− 18	− 14	33/17	32/16	30/16	17	18	17	16				36.4	− 21.6
Bend	44 04	121 19	1096	− 19	− 16	32/17	31/16	29/15	18	18	17	16				35.8	− 21.0
Corvallis (S)	44 30	123 17	75	− 8	− 6	33/19	32/19	30/18	17	21	19	19	N	3	N	36.9	− 8.3
Eugene AP	44 07	123 13	109	− 8	− 6	33/19	32/19	30/18	17	21	19	19	N	4	N		
Grants Pass	42 26	123 19	282	− 7	− 4	37/21	36/20	34/19	18	22	21	20	N	3	N	39.8	− 8.7
Klamath Falls AP	42 09	121 44	1248	− 16	− 13	32/16	31/16	29/15	20	17	16	16	N	2	W	35.7	− 17.3
Medford AP (S)	42 22	122 52	396	− 7	− 5	37/20	34/19	33/19	19	21	20	19	S	2	WMW	39.9	− 9.4
Pendleton AP	45 41	118 51	452	− 19	− 15	36/18	34/18	32/17	16	19	18	17	NNW	3	WNW		
Portland AP	45 36	122 36	6	− 8	− 5	32/20	29/19	27/18	13	21	19	19	ESE	6	NW	35.9	− 7.6
Portland Co	45 32	122 40	23	− 8	− 4	32/20	30/19	28/18	12	21	19	19				36.4	− 6.4
Roseburg AP	43 14	123 22	160	− 8	− 5	34/19	32/19	31/18	17	21	19	19				37.6	− 6.9
Salem AP	44 55	123 01	60	− 8	− 5	33/20	31/19	29/18	17	21	20	19	N	3	N	37.2	− 8.9
The Dalles	45 36	121 12	30	− 11	− 7	34/21	32/20	29/19	16	21	20	19				40.6	− 13.4
PENNSYLVANIA																	
Allentown AP	40 39	75 26	118	− 16	− 13	33/23	31/22	30/22	12	24	24	23	W	6	SW		
Altoona Co	40 18	78 19	459	− 18	− 15	32/22	31/22	29/21	13	23	23	22	WMW	6	WSW	34.3	− 20.7
Butler	40 52	79 54	335	− 17	− 14	32/23	31/22	29/22	12	24	23	23					
Chambersburg	39 56	77 38	195	− 16	− 13	34/24	32/23	31/23	13	25	24	24				36.3	− 17.9
Erie AP	42 05	80 11	223	− 16	− 13	31/23	29/22	28/22	10	24	23	22	SSW	5	WSW	32.9	− 19.0

TABLE 1—Climatic conditions for the United States (*continued*).

				Winter,[b] °C		Summer,[c] °C							Prevailing Wind			Temp. °C	
Col. 1	Col. 2	Col. 3	Col. 4	Col. 5		Col. 6			Col. 7	Col. 8			Col. 9			Col. 10	
State and Station[a]	Lat.	Long.	Elev.	Design Dry-Bulb		Design Dry-Bulb and Mean Coincident Wet-Bulb			Mean Daily	Design Wet-Bulb			Winter		Summer	Median of Annual Extr.	
	° ′	° ′	m	99%	97.5%	1%	2.5%	5%	Range	1%	2.5%	5%	m/s[d]			Max.	Min.
Harrisburg AP	40 12	76 46	94	−14	−12	34/24	33/23	31/23	12	25	24	24	NW	6	WSW	35.8	−15.7
Johnstown	40 19	78 50	696	−19	−17	30/21	28/21	27/20	13	22	22	21	WNW	4	WSW	35.8	−18.8
Lancaster	40 07	76 18	123	−16	−13	34/24	32/23	31/23	12	25	24	24	NW	6	WSW		
Meadville	41 38	80 10	325	−18	−16	31/22	29/21	28/21	12	23	22	22				34.0	−22.5
New Castle	41 01	80 22	252	−17	−14	33/23	31/22	30/22	13	24	23	23	WSW	5	WSW	34.8	−21.3
Philadelphia AP	39 53	75 15	2	−12	−10	34/24	32/23	31/22	12	25	24	24	WNW	5	WSW	35.8	−14.5
Pittsburgh AP	40 30	80 13	347	−17	−15	32/22	30/22	29/21	12	23	23	22	WSW	5	WSW		
Pittsburgh Co	40 27	80 00	310	−16	−14	33/22	31/22	30/21	11	23	23	22				34.8	−18.4
Reading Co	40 20	75 38	81	−13	−11	33/23	32/22	30/22	11	24	24	23	W	6	SW	36.1	−15.8
Scranton/Wilkes-Barre	41 20	75 44	284	−17	−15	32/22	31/22	29/21	11	23	23	22	SW	4	WSW	34.9	−19.0
State College (S)	40 48	77 52	358	−16	−14	32/22	31/22	29/21	13	23	23	22	NNW	4	WSW	34.0	−19.8
Sunbury	40 53	76 46	136	−17	−14	33/23	32/22	30/21	12	24	23	23					
Uniontown	39 55	79 43	291	−15	−13	33/23	31/23	29/22	12	24	24	23				34.4	−19.2
Warren	41 51	79 08	390	−19	−16	32/22	30/22	28/21	13	23	23	22				34.1	−23.7
West Chester	39 58	75 38	137	−13	−11	33/24	32/23	30/22	11	25	24	24					
Williamsport AP	41 15	76 55	160	−17	−14	33/23	32/22	30/21	13	24	23	23	W	5	WSW	35.3	−20.3
York	39 55	76 45	119	−13	−11	34/24	33/23	31/23	12	25	24	24				36.1	−19.
RHODE ISLAND																	
Newport (S)	41 30	71 20	3	−15	−13	31/23	29/22	28/21	9	24	24	23	WNW	5	SW		
Providence AP	41 44	71 26	16	−15	−13	32/23	30/22	28/21	11	24	23	23	WNW	6	SW	34.8	−18.1
SOUTH CAROLINA																	
Anderson	34 30	82 43	236	−7	−5	34/23	33/23	32/23	12	25	24	24				37.5	−10.4
Charleston AFB (S)	32 54	80 02	14	−4	−3	34/26	33/26	32/25	10	27	27	26	NNE	4	SW		
Charleston Co	32 54	79 58	1	−4	−2	34/26	33/26	32/25	7	27	27	26				36.6	−5.9
Columbia AP	33 57	81 07	65	−7	−4	36/24	35/24	34/24	12	26	26	25	W	3	SW	38.1	−8.8
Florence AP	34 11	79 43	45	−6	−4	34/25	33/25	32/24	12	27	26	26	N	4	SW	37.5	−8.6
Georgetown	33 23	79 17	4	−5	−3	33/26	32/26	31/25	10	27	27	26	N	4	SSW	36.8	−7.2
Greenville AP	34 54	82 13	292	−8	−6	34/23	33/23	32/23	12	25	24	24	NW	4	SW	36.3	−10.8
Greenwood	34 10	82 07	189	−8	−6	35/24	34/23	33/23	12	26	25	24				37.5	−9.9
Orangeburg	33 30	80 52	79	−7	−4	36/24	35/24	34/24	11	26	26	25				38.4	−7.8
Rock Hill	34 59	80 58	143	−7	−5	36/24	34/23	33/23	11	26	25	24					
Spartanburg AP	34 58	82 00	251	−8	−6	34/23	33/23	32/23	11	25	24	24				37.5	−10.1
Sumter, Shaw AFB	33 54	80 22	52	−6	−4	35/25	33/24	32/24	12	26	26	25	NNE	3	W	37.8	−9.2
SOUTH DAKOTA																	
Aberdeen AP	45 27	98 26	395	−28	−26	34/23	33/22	31/21	15	25	24	23	NNW	4	S	39.1	−33.4
Brookings	44 18	96 48	499	−27	−25	35/23	33/22	32/22	14	25	24	23				36.6	−32.5
Huron AP	44 23	98 13	391	−28	−26	36/23	34/22	32/22	16	25	24	23	NNW	4	S	38.6	−32.1
Mitchell	43 41	98 01	410	−26	−23	36/22	34/22	32/21	16	24	24	23				39.4	−30.4
Pierre AP	44 23	100 17	531	−26	−23	37/22	35/22	33/21	16	24	23	22	NW	6	SSE	40.9	−29.2
Rapid City AP (S)	44 03	103 04	964	−24	−22	35/19	33/18	32/18	16	22	21	19	NNW	5	SSE	38.3	−28.3
Sioux Falls AP	43 34	96 44	432	−26	−24	34/23	33/22	31/22	13	24	24	23	NW	4	S		
Watertown AP	44 55	97 09	530	−28	−26	34/23	33/22	31/22	14	24	24	23				36.6	−32.5
Yankton	42 55	97 23	397	−25	−22	34/23	33/22	31/22	14	25	24	23				38.2	−28.4
TENNESSEE																	
Athens	35 26	84 35	287	−11	−8	35/23	33/23	32/23	12	25	24	24					
Bristol-Tri City AP	36 29	82 24	459	−13	−10	33/22	32/22	31/22	12	24	24	23	WNW	3	SW		
Chattanooga AP	35 02	85 12	203	−11	−8	36/24	34/23	33/23	12	26	25	24	NNW	4	WSW	36.2	−12.3
Clarksville	36 33	87 22	116	−14	−11	35/24	34/23	32/23	12	26	25	24				37.7	−15.7
Columbia	35 38	87 02	210	−12	−9	36/24	34/23	33/23	12	26	25	24					
Dyersburg	36 01	89 24	105	−12	−9	36/26	34/25	33/24	12	27	27	26					
Greenville	36 04	82 50	402	−12	−9	33/23	32/22	31/22	12	24	24	23				35.3	−17.3
Jackson AP	35 36	88 55	129	−12	−9	37/24	35/24	33/24	12	26	26	25				37.3	−14.1
Knoxville AP	35 49	83 59	299	−11	−7	34/23	33/23	32/23	12	25	24	24	NE	4	W	35.6	−13.9
Memphis AP	35 03	90 00	79	−11	−8	37/25	35/24	34/24	12	27	26	26	N	5	SW	36.6	−12.0
Murfreesboro	34 55	86 28	183	−13	−10	36/24	34/23	33/23	12	26	25	24				36.5	−15.3
Nashville AP (S)	36 07	86 41	180	−13	−10	36/24	34/23	33/23	12	26	25	24	NW	4	WSW		
Tullahoma	35 23	86 05	325	−13	−11	36/23	34/23	33/23	12	25	24	24	NW	5	WSW	35.9	−15.7
TEXAS																	
Abilene AP	32 25	99 41	544	−9	−7	38/22	37/22	36/22	12	24	23	23	N	6	SSE	39.8	−12.0
Alice AP	27 44	98 02	55	−1	1	38/26	37/25	35/25	11	28	27	26				40.5	−4.0
Amarillo AP	35 14	101 42	1099	−14	−12	37/19	35/19	34/19	14	22	21	21	N	6	S	38.2	−17.3
Austin AP	30 18	97 42	182	−4	−2	38/23	37/23	36/23	12	26	25	25	N	6	S	38.7	−6.8
Bay City	29 00	95 58	15	−2	1	36/25	34/25	33/25	9	27	26	26					
Beaumont	29 57	94 01	5	−3	−1	35/26	34/26	33/26	11	27	27	27				37.6	−4.7
Beeville	28 22	97 40	58	−1	1	37/26	36/25	35/25	10	28	27	26	N	5	SSE	39.5	−5.3
Big Spring AP (S)	32 18	101 27	792	−9	−7	38/21	36/21	35/21	14	23	23	22				40.7	−11.8
Brownsville AP (S)	25 54	97 26	6	2	4	34/25	34/25	33/25	10	27	26	26	NNW	7	SE	36.7	−1.1

TABLE 1—Climatic conditions for the United States (*continued*).

Col. 1	Col. 2	Col. 3	Col. 4	Winter,^{b} °C Col. 5		Summer,^{c} °C Col. 6			Col. 7	Col. 8			Prevailing Wind Col. 9			Temp. °C Col. 10	
State and Station^a	Lat.	Long.	Elev.	Design Dry-Bulb		Design Dry-Bulb and Mean Coincident Wet-Bulb			Mean Daily	Design Wet-Bulb			Winter		Summer	Median of Annual Extr.	
	° ′	° ′	m	99%	97.5%	1%	2.5%	5%	Range	1%	2.5%	5%	m/s^d			Max.	Min.
Brownwood	31 48	98 57	423	−8	−6	38/23	37/23	36/23	12	25	24	24	N	5	S	40.7	−10.6
Bryan AP	30 40	96 33	84	−4	−2	37/24	36/24	34/24	11	26	26	26					
Corpus Christi AP	27 46	97 30	13	−1	2	35/26	34/26	33/26	11	27	27	26	N	6	SSE	36.1	−2.7
Corsicana	32 05	96 28	130	−7	−4	38/24	37/24	36/24	12	26	26	25				40.1	
Port Arthur AP	29 57	94 01	5	−3	−1	35/26	34/26	33/26	11	27	27	27	N	5	S	36.5	−4.4
San Angelo, Goodfellow AFB	31 26	100 24	572	−8	−6	38/22	37/22	36/21	13	24	23	23	NNE	5	SSE		
San Antonio AP (S)	29 32	98 28	240	−4	−1	37/22	36/23	36/23	11	25	24	24	N	4	SSE	38.5	−6.1
Sherman, Perrin AFB	33 43	96 40	233	−9	−7	38/24	37/24	35/23	12	26	25	24	N	5	S	39.4	−11.2
Snyder	32 43	100 55	709	−11	−8	38/21	37/21	36/21	14	23	23	22					
Temple	31 06	97 21	213	−6	−3	38/23	37/23	36/23	12	26	25	25					
Tyler AP	32 21	95 16	162	−7	−4	37/24	36/24	35/24	12	27	26	26	NNE	12	S		
Vernon	34 10	99 18	370	−11	−8	39/23	38/23	36/23	13	25	24	24					
Victoria AP	28 51	96 55	32	−2	0	37/26	36/25	34/25	10	28	27	26				38.6	−4.8
Waco AP	31 37	97 13	152	−6	−3	38/24	37/24	36/24	12	26	26	25					
Wichita Falls AP	33 58	98 29	303	−10	−8	39/23	38/23	37/23	13	25	24	24	NNW	6	S		
UTAH																	
Cedar City AP	37 42	113 06	1713	−19	−15	34/16	33/16	32/15	18	18	17	17	SE	3	SW		
Logan	41 45	111 49	1459	−19	−17	34/17	33/16	31/16	18	18	18	17				35.3	−22.1
Moab	38 36	109 36	1209	−14	−12	38/16	37/16	36/16	17	18	18	17					
Ogden AP	41 12	112 01	1358	−17	−15	34/17	33/16	31/16	18	19	18	18	S	3	SW	37.5	−19.9
Price	39 37	110 50	1701	−19	−15	34/16	33/16	32/15	18	18	17	17					
Provo	40 13	111 43	1356	−17	−14	37/17	36/17	34/16	18	19	18	18	SE	3	SW		
Richfield	38 46	112 05	1607	−19	−15	34/16	33/16	32/15	19	18	17	17				36.7	−23.6
St George Co	37 02	113 31	884	−10	−6	39/18	38/18	37/18	18	21	20	19				42.9	−11.6
Salt Lake City AP (S)	40 46	111 58	1287	−16	−13	36/17	35/17	33/16	18	19	18	18	SSE	3	N	37.4	−17.8
Vernal AP	40 27	109 31	1610	−21	−18	33/16	32/16	30/15	18	18	17	17					
VERMONT																	
Barre	44 12	72 31	183	−27	−24	29/22	27/21	26/20	13	23	22	21					
Burlington AP (S)	44 28	73 09	101	−24	−22	31/22	29/21	28/21	13	23	22	22	E	4	SSW	33.6	−27.2
Rutland	43 36	72 58	189	−25	−22	31/22	29/21	27/21	13	23	22	22				33.6	−27.5
VIRGINIA																	
Charlottesville	38 02	78 31	265	−10	−8	34/23	33/23	31/23	13	25	24	24	NE	4	SW	36.3	−13.3
Danville AP	36 34	79 20	180	−10	−9	34/23	33/23	32/23	12	25	24	24				37.8	−12.7
Fredericksburg	38 18	77 28	30	−12	−10	36/24	34/24	32/23	12	26	25	24					
Harrisonburg	38 27	78 54	418	−11	−9	34/22	33/22	31/22	13	24	23	23					
Lynchburg AP	37 20	79 12	279	−11	−9	34/23	32/23	31/23	12	25	24	24	NE	4	SW	36.2	−13.6
Norfolk AP	36 54	76 12	7	−7	−6	34/25	33/24	32/24	10	26	26	25	NW	5	SW	36.2	−9.3
Petersburg	37 11	77 31	59	−10	−8	35/24	33/24	32/24	11	26	26	25					
Richmond AP	37 30	77 20	50	−10	−8	35/24	33/24	32/24	12	26	26	25	N	3	SW	36.6	−12.4
Roanoke AP	37 19	79 58	364	−11	−9	34/22	33/22	31/22	13	24	23	23	NW	5	SW		
Staunton	38 16	78 54	366	−11	−9	34/22	33/22	31/22	13	24	23	23	NW	5	SW	35.5	−16.4
Winchester	39 12	78 10	232	−14	−12	34/24	32/23	31/23	12	25	24	24				36.3	−15.7
WASHINGTON																	
Aberdeen	46 59	123 49	4	−4	−2	27/18	25/17	23/16	9	18	17	17	ESE	3	NNW	33.3	−7.1
Bellingham AP	48 48	122 32	48	−12	−9	27/19	25/18	23/17	11	20	18	17	NNE	8	WSW	30.8	−12.1
Bremerton	47 34	122 40	49	−6	−4	28/18	26/18	24/17	11	19	18	17	E	4	N		
Ellensburg AP	47 02	120 31	529	−17	−14	34/18	33/18	31/17	19	19	18	17					
Everett, Paine AFB	47 55	122 17	182	−6	−4	27/18	24/18	23/17	11	19	18	17	ESE	3	NNW	29.4	−9.3

TABLE 1—Climatic conditions for the United States.

				Winter,[b] °C		Summer,[c] °C							Prevailing Wind			Temp. °C	
Col. 1	Col. 2	Col. 3	Col. 4	Col. 5		Col. 6			Col. 7	Col. 8			Col. 9			Col. 10	
State and Station[a]	Lat.	Long.	Elev.	Design Dry-Bulb		Design Dry-Bulb and Mean Coincident Wet-Bulb			Mean Daily Range	Design Wet-Bulb			Winter		Summer	Median of Annual Extr.	
	° ′	° ′	m	99%	97.5%	1%	2.5%	5%		1%	2.5%	5%	m/s[d]			Max.	Min.
Kennewick	46 13	119 08	120	-15	-12	37/20	36/19	33/19	17	21	20	19				39.7	-16.7
Longview	46 10	122 56	4	-7	-4	31/20	29/19	27/18	17	21	19	19	ESE	5	NW	35.6	-9.6
Moses Lake, Larson AFB	47 12	119 19	361	-17	-14	36/19	34/18	32/17	18	19	19	18	N	4	SSW		
Olympia AP	46 58	122 54	66	-9	-6	31/19	28/18	26/18	18	19	19	18	NE	2	NE		
Port Angeles	48 07	123 26	30	-4	-3	22/17	21/16	19/16	10	18	17	16				28.6	-7.0
Seattle-Boeing Field	47 32	122 18	7	-6	-3	29/20	27/19	25/18	13	21	19	18					
Seattle Co (S)	47 39	122 18	6	-6	-3	29/20	28/19	26/18	11	21	19	18	N	4	N	32.3	-5.6
Seattle-Tacoma AP (S)	47 27	122 18	122	-6	-3	29/18	27/18	24/17	12	19	18	17	E	5	N	32.3	-6.7
Spokane AP (S)	47 38	117 31	719	-21	-17	34/18	32/17	31/17	16	18	18	17	NE	3	SW	37.1	-20.5
Tacoma, Mcchord AFB	47 15	122 30	30	-7	-4	30/19	28/18	26/17	12	20	19	18	S	3	NNE	31.9	-7.3
Walla Walla AP	60 61	181 7	368-	18-	14	6 /9	4 /9	2 /81	52	11	91	9	W	3	W	39.4	-15.7
Wenatchee	47 25	120 19	193	-14	-12	37/19	36/19	33/18	18	20	19	18				38.4	-17.2
Yakima AP	46 34	120 32	321	-19	-15	36/18	34/18	32/17	20	20	19	18	W	3	NW		
WEST VIRGINIA																	
Beckley	37 47	81 07	763	-19	-16	28/22	27/21	26/21	12	23	22	21	WNW	5	WNW		
Bluefield AP	37 18	81 13	874	-19	-16	28/22	27/21	26/21	12	23	22	21					
Charleston AP	38 22	81 36	286	-14	-12	33/23	32/23	31/22	11	24	24	23	SW	4	SW	36.2	-16.2
Clarksburg	39 16	80 21	298	-14	-12	33/23	32/23	31/22	12	24	24	23					
Elkins AP	38 53	79 51	594	-17	-14	30/22	29/21	28/21	12	23	22	22	WNW	5	WNW	32.6	-21.8
Huntington Co	38 25	82 30	172	-15	-12	34/24	33/23	32/23	12	26	25	24	W	3	SW	36.2	-16.6
Martinsburg AP	39 24	77 59	170	-14	-12	34/24	32/23	31/23	12	25	24	24	WNW	5	W	37.2	-17.2
Morgantown AP	39 39	79 55	378	-16	-13	32/23	31/23	29/23	12	24	24	23					
Parkersburg Co	39 16	81 34	188	-14	-12	34/24	32/23	31/23	12	25	24	24	WSW	4	WSW	35.5	-17.4
Wheeling	40 07	80 42	203	-17	-15	32/22	30/22	29/21	12	23	23	22	WSW	5	WSW	36.4	-18.1
WISCONSIN																	
Appleton	44 15	88 23	223	-26	-23	32/23	30/22	28/22	13	24	23	22				34.8	-26.8
Ashland	46 34	90 58	198	-29	-27	29/21	28/20	26/19	13	22	21	20				34.5	-32.7
Beloit	42 30	89 02	238	-22	-19	33/24	32/24	31/23	13	26	25	24					
Eau Claire AP	44 52	91 29	271	-26	-24	33/24	32/23	30/22	13	25	24	23					
Fond Du Lac	43 48	88 27	232	-24	-22	32/23	30/22	29/22	13	24	23	22				35.6	-27.6
Green Bay AP	44 29	88 08	208	-25	-23	31/23	29/22	28/22	13	24	23	22	W	4	SW	34.6	-27.7
La Crosse AP	43 52	91 15	198	-25	-23	33/24	31/23	29/22	12	25	24	23	NW	5	S	35.4	-29.6
Madison AP (S)	43 08	89 20	262	-24	-22	33/23	31/23	29/22	12	25	24	23	NW	4	SW	34.2	-27.1
Manitowoc	44 06	87 41	201	-24	-22	32/23	30/22	28/22	12	24	23	22				34.5	-25.4
Marinette	45 06	87 38	184	-26	-24	31/23	29/22	28/21	11	24	23	22				35.5	-26.6
Milwaukee AP	42 57	87 54	205	-22	-20	32/23	31/23	29/22	12	24	23	23	WNW	5	SSW		
Racine	42 43	87 51	223	-21	-19	33/24	31/23	29/22	12	25	24	23					
Sheboygan	43 45	87 43	198	-23	-21	32/24	30/23	28/22	11	25	24	23				36.1	-24.7
Stevens Point	44 30	89 34	329	-26	-24	33/24	32/23	30/22	13	25	24	23				35.2	-31.2
Waukesha	43 01	88 14	262	-23	-21	32/23	31/23	29/22	12	24	23	23				35.4	-25.7
Wausau AP	44 55	89 37	365	-27	-24	33/23	31/22	29/21	13	24	23	22					
WYOMING																	
Casper AP	42 55	106 28	1628	-24	-21	33/14	32/14	31/14	17	17	16	16	NE	5	SW	36.3	-29.4
Cheyenne	41 09	104 49	1868	-23	-18	32/14	30/14	29/14	17	17	17	16	N	6	WNW	33.6	-26.6
Cody AP	44 33	109 04	1521	-28	-25	32/16	30/16	28/15	18	18	17	16				36.3	-29.9
Evanston	41 16	110 57	2067	-23	-19	30/13	29/13	28/12	18	15	14	14				31.8	-29.6
Lander AP (S)	42 49	108 44	1696	-27	-24	33/16	31/16	29/16	18	18	17	16	E	3	NW	34.9	-30.3
Laramie AP (S)	41 19	105 41	2215	-26	-21	29/13	27/13	26/13	16	16	16	15					
Newcastle	43 51	104 13	1300	-27	-24	33/18	31/17	29/17	17	21	20	19				37.4	-28.3
Rawlins	41 48	107 12	2055	-24	-20	30/14	28/14	27/13	22	17	16	16					
Rock Springs AP	41 36	109 04	2057	-23	-19	30/13	29/13	28/12	18	15	14	14	WSW	5	W		
Sheridan AP	44 46	106 58	1209	-26	-22	34/17	33/17	31/16	18	19	18	17	NW	4	N	37.7	-30.9
Torrington	42 05	104 13	1249	-26	-22	34/17	33/17	31/16	17	19	18	17				38.4	-29.3

TABLE 1—Climatic conditions for Canada.

				Winter,[b] °C		Summer,[c] °C							Prevailing Wind		
Col. 1	Col. 2	Col. 3	Col. 4	Col. 5		Col. 6			Col. 7	Col. 8			Col. 9		
State and Station[a]	Lat.	Long.	Elev.	Design Dry-Bulb		Design Dry-Bulb and Mean Coincident Wet-Bulb			Mean Daily	Design Wet-Bulb			Winter		Summer
	° ′	° ′	m	99%	97.5%	1%	2.5%	5%	Range	1%	2.5%	5%		m/s[d]	
ALBERTA															
Calgary AP	51 06	114 01	1079	−33	−31	29/17	27/16	26/16	14	18	17	17	NNW	4	SE
Edmonton AP	53 34	113 31	677	−34	−32	29/19	28/18	26/17	13	20	19	18	E	5	SE
Grande Prairie AP	55 11	118 53	668	−39	−36	28/18	27/17	26/16	13	19	18	17			
Jasper	52 53	118 04	1061	−35	−32	28/18	27/17	25/16	16	19	18	17			
Lethbridge AP (S)	49 38	112 48	920	−33	−30	32/18	31/18	29/17	16	20	19	18			
Mcmurray AP	56 39	111 13	371	−41	−39	30/19	28/18	26/18	14	21	19	18			
Medicine Hat AP	50 01	110 43	721	−34	−31	34/19	32/18	31/18	16	21	20	19			
Red Deer AP	52 11	113 54	904	−35	−32	29/18	27/18	26/17	14	19	19	18			
BRITISH COLUMBIA															
Dawson Creek	55 44	120 11	660	−38	−36	28/18	26/17	24/16	14	19	18	17			
Fort Nelson AP (S)	58 50	122 35	375	−42	−40	29/18	27/17	26/17	13	19	18	18			
Kamloops Co	50 43	120 25	345	−29	−26	34/19	33/18	31/18	16	20	19	18			
Nanaimo (S)	49 11	123 58	70	−9	−7	28/19	27/18	25/18	12	20	19	18			
New Westminster	49 13	122 54	15	−10	−8	29/20	27/19	26/19	11	21	20	19			
Penticton AP	49 28	119 36	342	−18	−16	33/20	32/19	31/19	17	21	20	19			
Prince George AP (S)	53 53	122 41	676	−36	−33	29/18	27/17	25/16	14	19	18	17	N	6	N
Prince Rupert Co	54 17	130 23	52	−19	−17	18/15	17/14	16/13	7	16	14	14			
Trail	49 08	117 44	427	−21	−18	33/19	32/18	30/18	18	20	19	18			
Vancouver AP (S)	49 11	123 10	5	−9	−7	26/19	25/19	23/18	9	20	19	19	E	3	WNW
Victoria Co	48 25	123 19	70	−7	−5	25/18	23/17	21/16	9	18	17	16			
MANITOBA															
Brandon	49 52	99 59	366	−34	−33	32/22	30/21	28/20	14	23	22	21			
Churchill AP (S)	58 45	94 04	47	−41	−39	27/19	25/18	23/17	10	19	18	17	SE	6	S
Dauphin AP	51 06	100 03	305	−35	−33	31/22	29/21	27/20	13	23	22	21			
Flin Flon	54 46	101 51	335	−41	−38	29/20	27/19	26/18	11	21	20	19			
Portage La Prairie AP	49 54	98 16	264	−33	−31	31/23	30/22	28/21	12	24	23	22			
The Pas AP (S)	53 58	101 06	273	−38	−36	29/20	28/19	26/19	11	22	21	20	W	4	W
Winnipeg AP (S)	49 54	97 14	240	−34	−33	32/23	30/22	29/21	12	24	23	22	W	4	S
NEW BRUNSWICK															
Campbellton Co	48 00	66 40	8	−28	−26	29/20	28/19	26/19	12	22	21	20			
Chatham AP	47 01	65 27	34	−26	−23	32/21	29/20	28/19	12	22	22	21			
Edmundston Co	47 22	68 20	152	−29	−27	31/21	28/20	27/19	12	23	22	21			
Fredericton AP (S)	45 52	66 32	23	−27	−24	32/22	29/21	28/20	13	23	22	21			
Moncton AP (S)	46 07	64 41	76	−24	−22	29/21	28/21	26/19	13	22	22	21			
Saint John AP	45 19	65 53	107	−24	−22	27/19	25/18	24/18	11	21	20	19			
NEWFOUNDLAND															
Corner Brook	48 58	57 57	5	−21	−18	24/18	23/17	22/17	9	19	19	18			
Gander AP	48 57	54 34	147	−21	−18	28/19	26/18	25/18	11	21	19	19	WNW	6	SW
Goose Bay AP (S)	53 19	60 25	44	−33	−31	29/19	27/18	25/17	11	20	19	18	N	5	SW
St John's AP (S)	47 37	52 45	141	−16	−14	25/19	24/18	23/18	10	21	19	19	N	10	WSW
Stephenville AP	48 32	58 33	13	−19	−16	24/18	23/18	22/17	8	19	19	18	WNW	5	S
NORTHWEST TERRITORIES															
Fort Smith AP(S)	60 01	111 58	203	−45	−43	29/19	27/18	26/17	13	20	19	18	NW	2	S
Frobisher AP (S)	63 45	68 33	21	−42	−41	19/12	17/11	15/10	8	12	11	11	NNW	5	NW
Inuvik (S)	68 18	133 29	61	−49	−47	26/17	25/16	24/15	12	18	17	16			
Resolute AP (S)	74 43	94 59	64	−46	−44	14/9	12/8	11/7	6	10	9	8			
Yellowknife AP	62 28	114 27	208	−45	−43	26/17	25/16	23/16	9	18	17	17	SSE	4	S
NOVA SCOTIA															
Amherst	45 49	64 13	20	−24	−21	29/21	27/20	26/19	12	22	21	20			
Halifax AP (S)	44 39	63 34	25	−17	−15	26/19	24/18	23/18	9	21	19	19			
Kentville (S)	45 03	64 36	12	−19	−17	29/21	28/20	27/19	12	22	22	21			
New Glasgow	45 37	62 37	97	−23	−21	27/21	26/20	25/19	11	22	21	21			
Sydney AP	46 10	60 03	60	−18	−16	28/21	27/20	25/19	11	22	21	20			
Truro Co	45 22	63 16	40	−22	−21	28/21	27/21	26/20	12	23	22	21			
Yarmouth AP	43 50	66 05	41	−15	−13	23/18	22/18	21/17	8	20	19	18	NW	6	S

[a] AP following the station name designates airport temperature observations. Co designates office locations within an urban area that are affected by the surrounding area. Undesignated stations are semirural and may be compared to airport data.

[b] Winter design data are based on the month of January only.

[c] Summer design data are based on the month of July only. See also Boughner (1960).

[d] Mean wind speeds occurring coincidentally with the 99.5% dry-bulb winter design temperature.

TABLE 1—Climatic conditions for Canada (*continued*).

				Winter,[b] °C		Summer,[c] °C							Prevailing Wind		
Col. 1	Col. 2	Col. 3	Col. 4	Col. 5		Col. 6			Col. 7	Col. 8			Col. 9		
State and Station[a]	Lat.	Long.	Elev.	Design Dry-Bulb		Design Dry-Bulb and Mean Coincident Wet-Bulb			Mean Daily Range	Design Wet-Bulb			Winter		Summer
	° ′	° ′	m	99%	97.5%	1%	2.5%	5%		1%	2.5%	5%		m/s[d]	
ONTARIO															
Belleville	44 09	77 24	76	−24	−22	30/23	29/22	28/22	11	24	23	23			
Chatham	42 24	82 12	183	−18	−16	32/23	31/23	29/22	11	24	24	23			
Cornwall	45 01	74 45	64	−25	−23	32/23	31/22	29/22	12	24	23	22			
Hamilton	43 16	79 54	92	−19	−17	31/23	30/22	28/22	12	24	23	23			
Kapuskasing AP (S)	49 25	82 28	229	−35	−33	30/21	28/21	27/19	13	22	21	21			
Kenora AP	49 48	94 22	410	−36	−33	29/21	28/21	27/20	11	23	22	21			
Kingston	44 16	76 30	91	−24	−22	31/23	29/22	28/22	11	24	23	23			
Kitchener	43 26	80 30	343	−21	−19	31/23	29/22	28/22	13	24	23	22			
London AP	43 02	81 09	278	−20	−18	31/23	29/23	28/22	12	24	23	23			
North Bay AP	46 22	79 25	369	−30	−28	29/20	27/19	26/19	11	22	21	20			
Oshawa	43 54	78 52	113	−21	−19	31/23	30/22	29/22	11	24	23	23			
Ottawa AP (S)	45 19	75 40	126	−27	−25	32/22	31/22	29/21	12	24	23	22			
Owen Sound	44 34	80 55	182	−21	−19	29/22	28/21	27/21	12	23	22	21			
Peterborough	44 17	78 19	194	−25	−23	31/22	29/22	28/21	12	24	23	22			
St Catharines	43 11	79 14	99	−18	−16	31/23	29/22	28/22	11	24	23	23			
Sarnia	42 58	82 22	191	−18	−16	31/23	30/22	29/22	11	24	23	23			
Sault Ste Marie AP	46 32	84 30	206	−27	−25	29/22	28/21	26/20	12	23	22	21			
Sudbury AP	46 37	80 48	342	−30	−28	30/21	28/19	27/19	12	22	21	20			
Thunder Bay AP	48 22	89 19	196	−33	−31	29/21	28/20	27/19	13	22	21	20	W	4	W
Timmins AP	48 34	81 22	294	−36	−34	31/21	29/20	27/19	14	22	21	20			
Toronto AP (S)	43 41	79 38	176	−21	−18	32/23	31/22	29/22	11	24	23	23	N	5	SW
Windsor AP	42 16	82 58	194	−18	−16	32/23	31/23	30/22	11	25	24	23			
PRINCE EDWARD ISLAND															
Charlottetown AP (S)	46 17	63 08	57	−22	−20	27/21	26/20	24/19	9	22	21	20			
Summerside AP	46 26	63 50	24	−22	−20	27/21	26/20	25/19	9	22	21	20			
QUEBEC															
Bagotville AP	48 20	71 00	163	−33	−31	31/21	28/20	27/19	12	22	21	20			
Chicoutimi	48 25	71 05	46	−32	−30	30/21	28/20	27/19	11	22	21	20			
Drummondville	45 53	72 29	82	−28	−26	31/22	29/22	28/21	12	24	23	22			
Granby	45 23	72 42	168	−28	−26	31/22	29/22	28/21	12	24	23	22			
Hull	45 26	75 44	61	−28	−26	32/22	31/22	29/21	12	24	23	22			
Megantic AP	45 35	70 52	415	−29	−27	30/22	28/21	27/21	11	23	22	22			
Montreal AP (S)	45 28	73 45	30	−27	−23	31/23	29/22	28/22	9	24	23	22			
Quebec AP	46 48	71 23	75	−28	−26	31/22	29/21	27/20	11	23	22	21			
Rimouski	48 27	68 32	36	−27	−24	28/20	26/19	24/18	10	22	21	19			
St Jean	45 18	73 16	39	−26	−24	31/23	30/22	29/22	11	24	23	22			
St Jerome	45 48	74 01	170	−27	−25	31/22	30/22	28/21	13	24	23	22			
Sept. Iles AP (S)	50 13	66 16	58	−32	−29	24/17	23/16	21/16	9	19	18	17			
Shawinigan	46 34	72 43	93	−28	−26	30/22	29/21	28/21	12	23	22	22			
Sherbrooke Co	45 24	71 54	181	−32	−29	30/22	29/22	27/21	11	23	23	22			
Thetford Mines	46 04	71 19	311	−28	−26	31/22	29/21	27/21	12	23	22	22			
Trois Rivieres	46 21	72 35	15	−27	−25	31/22	29/21	28/21	13	23	22	22			
Val D'or AP	48 03	77 47	338	−36	−33	29/21	28/20	27/19	12	22	21	20			
Valleyfield	45 16	74 06	46	−26	−23	32/23	30/22	29/22	11	24	23	22			
SASKATCHEWAN															
Estevan AP	49 04	103 00	574	−34	−32	33/21	32/20	30/19	14	22	21	21			
Moose Jaw AP	50 20	105 33	566	−34	−32	34/21	32/19	30/19	15	22	21	20			
North Battleford AP	52 46	108 15	548	−36	−34	31/19	29/19	28/18	13	21	20	19			
Prince Albert AP	53 13	105 41	431	−41	−37	31/19	29/19	27/18	14	21	20	19			
Regina AP	50 26	104 40	574	−36	−34	33/21	31/20	29/19	14	22	21	20			
Saskatoon AP (S)	52 10	106 41	502	−37	−35	32/20	30/19	28/18	14	21	20	19			
Swift Current AP (S)	50 17	107 41	816	−33	−32	34/20	32/19	31/18	14	21	21	19			
Yorkton AP	51 16	102 28	504	−37	−34	31/21	29/20	27/19	13	22	21	20			
YUKON TERRITORY															
Whitehorse AP (S)	60 43	135 04	698	−43	−42	27/15	25/14	23/13	12	16	15	14	NW	3	SE

TABLE 1—Climatic conditions for other countries.

Col. 1	Col. 2		Col. 3	Winter, °C			Summer, °C							Prevailing Winds		
					Col. 4		Col. 5 Design Dry-Bulb			Col. 6	Col. 7 Design Wet-Bulb					
Country and Station	Lat. ° '	Long. ° '	Elevation, m	Mean of Annual Extremes	99%	97.5%	1%	2.5%	5%	Mean Daily Range, °C	1%	2.5%	5%	Winter	m/s	Summer
AFGHANISTAN																
Kabul	34 35N	69 12E	1816	−17	−14	−13	37	36	34	18	19	18	18	N	2	N
ALGERIA																
Algiers	36 46N	3 03E	59	3	6	7	35	33	32	8	25	24	24			
ARGENTINA																
Buenos Aires	34 35S	58 29W	27	−3	0	1	33	32	30	12	25	24	24	SW	5	NNE
Cordoba	31 22S	64 15W	423	−6	−2	0	38	36	34	15	24	24	23			
Tucuman	26 50S	65 10W	427	−4	0	2	39	37	36	13	24	24	23			
AUSTRALIA																
Adelaide	34 56S	138 35E	43	2	3	4	37	34	33	14	22	21	20	NE	3	NW
Alice Springs	23 48S	133 53E	547	−2	1	3	40	39	38	15	24	23	22	N	3	SE
Brisbane	27 28S	153 02E	42	4	7	8	33	31	30	10	25	24	24	N	4	NNE
Darwin	12 28S	130 51E	27	16	18	19	34	34	33	9	28	27	27	E	5	WNW
Melbourne	37 49S	144 58E	35	−1	2	3	35	33	30	12	22	21	20			
Perth	31 57S	115 51E	64	3	4	6	38	36	34	12	24	23	23	N	3	E
Sydney	33 52S	151 12E	42	3	4	6	32	29	27	7	23	23	22	N	4	NE
AUSTRIA																
Vienna	48 15N	16 22E	196	−19	−14	−12	31	30	28	9	22	21	19	W	7	SSE
AZORES																
Lajes (Terceira)	38 45N	27 05W	52	6	8	9	27	26	25	6	23	22	22	W	5	NW
BAHAMAS																
Nassau	25 05N	77 21W	3	13	16	17	32	32	31	7	27	27	26			
BANGLADESH																
Chittagong	22 21N	91 50E	27	9	11	12	34	33	32	11	28	27	27			
BELGIUM																
Brussels	50 48N	4 21E	100	−11	−9	−7	28	26	25	11	21	20	19	NE	4	ENE
BERMUDA																
Kindley AFB	33 22N	64 41W	9	8	12	13	31	30	29	7	26	26	26	NW	8	S
BOLIVIA																
La Paz	16 30S	68 09W	3659	−2	−1	1	22	21	20	13	14	14	13			
BRAZIL																
Belem	1 27S	48 29W	13	19	21	22	32	32	31	11	27	26	26	SE	3	E
Belo Horizonte	19 56S	43 57W	915	6	8	10	30	29	28	10	24	24	24			
Brasilia	5 52S	47 55W	1049	8	9	11	32	31	30	9	24	24	24	N	3	E
Curitiba	25 25S	49 17W	949	−2	1	3	30	29	28	12	24	23	23			
Fortaleza	3 46S	38 33W	27	19	21	21	33	32	32	9	26	26	26			
Porto Alegre	30 02S	51 13W	10	0	3	4	35	33	32	11	24	24	24			
Recife	8 04S	34 53W	30	19	21	21	31	31	30	6	26	25	25	S	4	ESE
Rio De Janeiro	22 55S	43 12W	61	13	14	16	34	33	32	6	27	26	26	N	3	S
Salvador	13 00S	38 30W	47	18	19	20	31	31	30	7	26	26	26			
Sao Paulo	23 33S	46 38W	795	2	6	8	30	29	28	10	24	23	23	N	3	W
BRITISH HONDURAS																
Belize	17 31N	88 11W	5	13	16	17	32	32	32	7	28	28	27			
BULGARIA																
Sofia	42 42N	23 20E	550	−19	−16	−13	32	30	29	14	22	21	21			
BURMA																
Mandalay	21 59N	96 06E	77	10	12	13	40	39	38	17	27	27	27			
Rangoon	16 47N	96 09E	5	15	17	17	38	37	35	14	28	28	28	W	3	W
CAMBODIA																
Phnom Penh	11 33N	104 51E	11	17	19	20	37	36	34	11	28	28	28	N	2	W
CHILE																
Punta Arenas	53 10S	70 54W	8	−6	−4	−3	20	19	18	8	13	13	12			
Santiago	33 27S	70 42W	520	−3	0	2	32	32	31	18	22	21	21	N	2	SW
Valparaiso	33 01S	71 38W	41	4	6	8	27	26	25	9	19	19	18			
CHINA																
Chongequing	29 33N	106 33E	230	1	3	4	37	36	35	10	27	27	26			
Shanghai	31 12N	121 26E	7	−9	−5	−3	34	33	32	9	27	27	27	WNW	3	S
COLOMBIA																
Baranquilla	10 59N	74 48W	13	19	21	22	35	34	34	9	28	28	28			
Bogota	4 36N	74 05W	2563	6	7	8	22	21	21	11	16	15	14	E	4	E
Cali	3 25N	76 30W	972	12	14	14	29	28	26	8	21	21	20			
Medellin	6 13N	75 36W	1418	9	12	13	31	29	29	14	23	22	22			
CONGO																
Brazzaville	4 15S	15 15E	318	12	16	17	34	33	33	12	27	27	27			
CUBA																
Guantanamo Bay	19 54N	75 09W	6	16	18	19	34	34	33	9	28	27	27	N	3	ESE
Havana	23 08N	82 21W	24	12	15	17	33	33	32	8	27	27	27	N	6	E
CZECHOSLOVAKIA																
Prague	50 05N	14 25E	202	−16	−16	−13	31	29	28	9	19	18	18			
DENMARK																
Copenhagen	55 41N	12 33E	13	−12	−9	−7	26	24	23	9	20	19	18	NE	6	N

TABLE 1—Climatic conditions for other countries (*continued*).

Col. 1	Col. 2		Col. 3	Winter, °C			Summer, °C							Prevailing Winds		
					Col. 4		Col. 5 Design Dry-Bulb			Col. 6 Mean Daily Range °C	Col. 7 Design Wet-Bulb					
Country and Station	Lat. ° ′	Long. ° ′	Elevation, m	Mean of Annual Extemes	99%	97.5%	1%	2.5%	5%		1%	2.5%	5%	Winter	m/s	Summer
DOMINICAN REPUBLIC																
Santo Domingo	18 29N	69 54W	17	16	17	18	33	32	31	9	27	27	27	NNE	3	SE
EQUADOR																
Guayaquil	2 10S	79 53W	6	16	18	18	33	33	32	11	27	27	26			
Quito	0 13S	78 32W	2880	−1	2	4	23	22	22	18	17	17	17	N	2	N
EGYPT																
Cairo	29 52N	31 20E	116	4	7	8	39	38	37	14	24	24	23	N	5	NNW
EL SALVADOR																
San Salvador	13 42N	89 13W	682	11	12	13	37	36	35	18	25	24	24	N	4	S
ETHIOPIA																
Addis Ababa	9 02N	38 45E	2364	2	4	5	29	28	27	16	19	18	18	E	5	S
Asmara	15 17N	38 55E	2326	2	4	6	28	27	27	15	18	18	17	E	5	WNW
FINLAND																
Helsinki	60 10N	24 57E	9	−24	−22	−18	25	23	22	8	19	18	17	E	2	S
FRANCE																
Lyon	45 42N	4 47E	286	−18	−12	−10	33	32	30	13	22	21	21	N	4	S
Marseilles	43 18N	5 23E	75	−5	−4	−2	32	31	29	12	22	22	21	SE	7	W
Nantes	47 15N	1 34W	37	−8	−6	−3	30	28	27	12	21	21	19	NNE	3	E
Nice	43 42N	7 16E	12	−1	1	3	31	29	28	8	23	22	22			
Paris	48 49N	2 29E	50	−9	−6	−4	32	30	28	12	21	20	19	NE	4	E
Strasbourg	48 35N	7 46E	142	−13	−12	−9	30	28	27	11	21	21	19			
FRENCH GUIANA																
Cayenne	4 56N	52 27W	6	21	22	22	33	33	32	9	28	28	28	ENE	3	E
FEDERAL REPUBLIC GERMANY																
Berlin (West)	52 27N	13 18E	57	−14	−14	−11	29	27	26	11	20	19	19	E	3	E
Hamburg	53 33N	9 58E	20	−12	−11	−9	27	24	23	7	20	19	18			
Hannover	52 24N	9 40E	171	−14	−9	−7	28	26	24	9	20	19	18	E	4	E
Mannheim	49 34N	8 28E	109	−17	−13	−12	31	29	28	10	22	21	20	N	3	S
Munich	48 09N	11 34E	527	−18	−15	−13	30	28	27	10	20	19	18	S	2	N
GHANA																
Accra	5 33N	0 12W	27	18	20	21	33	32	32	7	27	26	26	WSW	3	SW
GIBRALTAR																
Gibraltar	36 09N	5 22W	3	3	6	7	33	32	30	8	24	24	23			
GREECE																
Athens	37 58N	23 43E	107	−2	1	2	36	34	33	10	22	22	22	N	5	NNE
Thessaloniki	40 37N	22 57E	24	−5	−2	0	35	34	33	11	25	24	24			
GREENLAND																
Narsarssuaq	61 11N	45 25W	26	−31	−24	−22	19	17	16	11	13	12	11			
GUATEMALA																
Guatemala City	14 37N	90 31W	1480	7	9	11	28	28	27	13	21	20	19	N	5	S
GUYANA																
Georgetown	6 50N	58 12W	2	21	22	23	32	31	31	6	27	26	26			
HAITI																
Port-au-Prince	18 33N	72 20W	37	17	18	19	36	35	34	11	28	27	27	N	3	ESE
HONDURAS																
Tegucigalpa	14 06N	87 13W	943	7	8	10	32	31	29	16	23	22	22	N	4	E
HONG KONG																
Hong Kong	22 18N	114 10E	33	6	9	10	33	33	32	6	27	27	27	N	5	W
HUNGARY																
Budapest	47 31N	19 02E	120	−13	−12	−10	32	30	29	12	22	22	21	N	3	S
ICELAND																
Reykjavik	64 08N	21 56E	18	−13	−10	−8	15	14	13	9	12	12	12	E	6	E
INDIA																
Ahmenabad	23 02N	72 35E	50	9	12	13	43	42	41	16	27	26	26			
Bangalore	12 57N	77 37E	921	12	13	14	36	34	34	14	24	23	23			
Bombay	18 54N	72 49E	11	17	18	19	36	34	33	7	28	27	27	NW	3	NW
Calcutta	22 32N	88 20E	6	9	11	12	37	36	36	12	28	28	28	N	2	S
Madras	13 04N	80 15E	16	16	18	19	40	39	38	11	29	28	28	W	2	W
Nagpur	21 09N	79 07E	310	7	11	12	43	42	42	17	26	26	26			
New Delhi	28 35N	77 12E	214	2	4	5	43	42	41	14	28	28	28	N	3	NW
INDONESIA																
Djakarta	6 11S	106 50E	8	21	22	22	32	32	31	8	27	26	26	N	6	N
Kupang	10 10S	123 34E	45	17	19	20	34	34	33	11	27	27	27			
Makassar	5 08S	119 28E	19	18	19	20	32	32	31	9	27	27	26			
Medan	3 35N	98 41E	23	19	21	22	33	33	32	9	27	27	26			
Palembang	3 00S	104 46E	6	19	21	22	33	33	32	9	27	26	26			
Surabaya	7 13S	112 43E	3	18	19	20	33	32	32	10	27	26	26			
IRAN																
Abadan	30 21N	48 16E	2	0	4	5	47	45	43	18	28	27	27	W	3	WNW
Meshed	36 17N	59 36E	946	−16	−12	−10	37	36	34	16	20	19	19			
Tehran	35 41N	51 25E	1220	−9	−7	−4	39	38	37	15	24	23	23	W	3	SE

TABLE 1—Climatic conditions for other countries (*continued*).

Col. 1	Col. 2		Col. 3	Winter, °C Col. 4			Summer, °C Col. 5 Design Dry-Bulb			Col. 6	Col. 7 Design Wet-Bulb			Prevailing Winds		
Country and Station	Lat. ° ′	Long. ° ′	Elevation, m	Mean of Annual Extemes	99%	97.5%	1%	2.5%	5%	Mean Daily Range °C	1%	2.5%	5%	Winter	m/s	Summer
IRAQ																
Baghdad	33 20N	44 24E	34	−3	0	2	45	44	42	19	23	22	22	WNW	3	WNW
Mosul	36 19N	43 09E	223	−5	−2	0	46	44	43	22	23	22	22			
IRELAND																
Dublin	53 22N	6 21W	47	−7	−4	−3	23	22	21	9	18	18	17	W	5	SW
Shannon	52 41N	8 55W	2	−7	−4	−2	24	23	22	8	18	18	17	SE	2	W
IRIAN BARAT																
Manokwari	0 52S	134 05E	19	21	22	22	32	31	31	7	28	27	27			
ISRAEL																
Jerusalem	31 47N	35 13E	758	−1	2	3	35	34	33	13	21	21	21	W	6	NW
Tel Aviv	32 06N	34 47E	11	1	4	5	36	34	33	9	23	23	22	N	4	W
ITALY																
Milan	45 27N	9 17E	104	−11	−8	−6	32	31	29	11	24	24	23	W	2	SW
Naples	40 53N	14 18E	67	−2	1	2	33	31	30	11	23	23	22	N	3	SSW
Rome	41 48N	12 36E	115	−4	−1	1	34	33	32	13	23	23	22	E	3	WSW
IVORY COAST																
Abidjan	5 19N	4 01W	20	18	19	21	33	32	31	8	28	28	27	WSW	3	SW
JAPAN																
Fukuoka	33 35N	130 27E	7	−3	−2	−1	33	32	32	11	28	27	26			
Sapporo	43 04N	141 21E	17	−22	−17	−15	30	28	27	11	24	23	22	SE	2	SE
Tokyo	35 41N	139 46E	6	−6	−3	−2	33	32	31	8	27	27	26	SW	5	S
JORDAN																
Amman	31 57N	35 57E	777	−2	1	2	36	34	33	14	21	21	20	N	3	NNW
KENYA																
Nairobi	1 16S	36 48E	1821	7	9	10	27	27	26	13	19	18	18	E	7	ENE
KOREA																
Pyongyang	39 02N	125 41E	57	−23	−19	−16	32	31	29	12	25	24	24			
Seoul	37 34N	126 58E	87	−18	−14	−13	33	32	31	9	27	26	26	NW	4	W
LEBANON																
Beirut	33 54N	35 28E	34	4	6	7	34	33	32	8	26	25	24	N	4	SW
LIBERIA																
Monrovia	6 18N	10 48W	23	18	20	21	32	32	31	11	28	28	27	E	2	WSW
LIBYA																
Benghazi	32 06N	20 04E	25	5	8	9	36	34	33	7	25	24	24	SSE	4	S
MADAGASCAR																
Tananarive	18 55S	47 33E	1382	4	6	8	30	29	28	13	23	22	22			
MALAYSIA																
Kuala Lumpur	3 07N	101 42E	39	19	21	22	34	34	33	11	28	28	27	N	2	W
Penang	5 25N	100 19E	5	21	22	23	34	34	33	10	28	27	27			
MARTINIQUE																
Fort-de-France	14 37N	61 05W	4	17	18	19	32	32	31	8	27	27	27			
MEXICO																
Guadalajara	20 41N	103 20W	1557	2	4	6	34	33	32	16	20	19	19	N	4	W
Merida	20 58N	89 38W	22	13	15	16	36	35	34	12	27	26	25	E	6	E
Mexico City	19 24N	99 12W	2310	1	3	4	28	27	26	14	16	16	15	N	4	N
Monterrey	25 40N	100 18W	528	−1	3	5	37	35	34	11	26	26	25			
Vera Cruz	19 12N	96 08W	56	13	16	17	33	32	31	7	28	28	28			
MOROCCO																
Casablanca	33 35N	7 39W	50	2	4	6	34	32	30	28	23	22	21			
NEPAL																
Katmandu	27 42N	85 12E	1338	−1	1	2	32	31	30	14	26	25	24	W	2	NW
NETHERLANDS																
Amsterdam	52 23N	4 55E	2	−8	−7	−5	26	24	23	6	18	18	17	S	4	E
NEW ZEALAND																
Auckland	36 51S	174 46E	43	3	4	6	26	25	24	8	19	19	18			
Christchurch	43 32S	172 37E	10	−4	−2	−1	28	26	24	9	20	19	19	W	2	NNW
Wellington	41 17S	174 46E	120	0	2	3	24	23	22	8	19	18	18	NE	3	NNE
NICARAGUA																
Managua	12 10N	86 15W	41	17	18	19	34	34	33	12	27	27	26	E	5	E
NIGERIA																
Lagos	6 27N	3 24E	3	19	21	22	33	33	32	7	28	28	27	WSW	4	S
NORWAY																
Bergen	60 24N	5 19E	43	−10	−8	−7	24	23	23	12	19	19	18			
Oslo	59 56N	10 44E	94	−19	−18	−16	26	25	23	9	19	19	18	N	5	S
PAKISTAN																
Karachi	24 48N	66 59E	4	7	9	11	38	37	35	8	28	28	27	N	2	SSW
Lahore	31 35N	74 20E	214	0	2	3	43	42	41	15	28	28	27	NW	2	SE
Peshwar	34 01N	71 35E	355	−1	2	3	43	41	39	16	27	27	26	W	3	NE
PANAMA AND CANAL ZONE																
Panama City	8 58N	79 33W	6	21	22	23	34	33	33	10	27	27	27			

TABLE 1—Climatic conditions for other countries (*continued*).

				Winter, °C			Summer, °C									
Col. 1	Col. 2		Col. 3		Col. 4		Col. 5 Design Dry-Bulb			Col. 6	Col. 7 Design Wet-Bulb			Prevailing Winds		
Country and Station	Lat. ° ′	Long. ° ′	Elevation, m	Mean of Annual Extemes	99%	97.5%	1%	2.5%	5%	Mean Daily Range °C	1%	2.5%	5%	Winter	m/s	Summer
PAPUA NEW GUINEA																
Port Moresby	9 29S	147 09E	38	17	19	21	33	33	32	8	27	27	26			
PARAGUAY																
Asuncion	25 17S	57 30W	139	2	6	8	38	37	36	13	27	27	27	NE	4	NE
PERU																
Lima	12 05S	77 03W	120	11	12	13	30	29	29	9	24	24	23	N	5	S
PHILIPPINES																
Manila	14 35N	120 59E	14	21	23	23	34	33	33	11	28	27	27	N	2	ESE
POLAND																
Krakow	50 04N	19 57E	220	−19	−17	−14	29	27	26	11	20	19	19			
Warsaw	52 13N	21 02E	120	−19	−16	−13	29	27	26	11	22	21	20		4	SE
PORTUGAL																
Lisbon	38 43N	9 08W	95	0	3	4	32	30	28	9	21	20	19	ENE	3	N
PUERTO RICO																
San Juan	18 29N	66 07W	25	18	19	20	32	31	31	6	27	27	26	ENE	5	E
RUMANIA																
Bucharest	44 25N	26 06E	82	−19	−16	−13	34	33	32	14	22	22	21			
SAUDI ARABIA																
Dhahran	26 17N	50 09E	24	4	7	9	44	43	42	18	30	29	29	N	4	N
Jedda	21 28N	39 10E	6	11	14	16	41	39	38	12	29	29	28			
Riyadh	24 39N	46 42E	591	−2	3	4	43	42	41	18	26	25	24	N	4	N
SENEGAL																
Dakar	14 42N	17 29W	40	14	16	17	35	34	33	7	27	27	27	N	4	NW
SINGAPORE																
Singapore	1 18N	103 50E	10	21	22	22	33	33	32	8	28	27	27	N	2	SE
SOMALIA																
Mogadiscio	2 02N	49 19E	12	19	21	21	33	32	32	7	28	28	27	SSW	8	E
SOUTH AFRICA																
Cape Town	33 56S	18 29E	17	2	4	6	34	32	30	11	22	22	21			
Johannesburg	26 11S	78 03E	1666	−3	−1	1	29	28	27	13	21	21	21			
Pretoria	25 45S	28 14E	1369	−3	0	2	32	31	29	13	21	21	20	N	2	W
SOUTH YEMEN																
Aden	12 50N	45 02E	3	17	20	21	39	38	37	6	28	28	28			
SOVIET UNION																
Alma Ata	43 14N	76 53E	775	−28	−23	−21	31	30	28	12	21	20	19			
Archangel	64 33N	40 32E	7	−34	−31	−28	24	22	20	7	16	14	14			
Kaliningrad	54 43N	20 30E	7	−19	−17	−14	28	27	25	9	19	19	18			
Krasnoyarsk	56 01N	92 57E	152	−41	−31	−33	29	27	24	7	18	17	16			
Kiev	50 27N	30 30E	183	−24	−21	−17	31	29	27	12	21	20	19			
Kharkov	50 00N	36 14E	144	−28	−23	−19	31	29	28	13	21	20	19			
Kuibyshev	53 11N	50 06E	58	−31	−28	−25	32	29	27	11	21	19	19			
Leningrad	59 56N	30 16E	5	−26	−23	−21	26	24	22	8	18	18	17			
Minsk	53 54N	27 33E	225	−28	−24	−20	27	25	23	9	19	19	18			
Moscow	55 46N	37 40E	154	−28	−24	−21	29	27	26	12	21	19	18	SW	6	S
Odessa	46 29N	30 44E	65	−18	−16	−13	31	29	28	8	21	21	20			
Petropavlovsk	52 53N	158 42E	87	−23	−19	−18	21	20	18	7	14	14	13			
Rostov On Don	47 13N	39 43E	48	−23	−19	−16	32	31	29	11	21	21	20			
Sverdlovsk	56 49N	60 38E	273	−37	−32	−29	27	24	22	9	17	17	16			
Tashkent	41 20N	69 18E	478	−20	−16	−13	35	34	32	16	22	21	21			
Tbilisi	41 43N	44 48E	404	−11	−8	−6	31	29	28	10	20	19	19			
Vladivostok	43 07N	131 55E	29	−26	−23	−22	27	25	23	6	21	21	20			
Volgograd	48 42N	44 31E	41	−29	−25	−22	34	32	30	11	22	21	21			
SPAIN																
Barcelona	41 24N	2 09E	95	−1	1	2	31	30	29	7	24	23	23	N	5	S
Madrid	40 25N	3 41W	667	−6	−4	−2	34	33	32	14	22	21	19	NNE	3	W
Valencia	39 28N	0 23W	24	−1	1	3	33	32	31	8	24	23	23	W	4	ESE
SRI LANKA																
Colombo	6 54N	79 52E	7	18	21	21	32	32	31	8	27	27	27	W	3	W
SUDAN																
Khartoum	15 37N	32 33E	390	8	12	13	43	42	40	17	25	24	24	N	3	NW
SURINAM																
Paramaribo	5 49N	55 09W	4	19	20	21	34	33	32	10	28	28	27	NE	5	E
SWEDEN																
Stockholm	59 21N	18 04E	45	−16	−15	−13	26	23	22	8	18	17	16	W	2	S
SWITZERLAND																
Zurich	47 23N	8 33E	493	−16	−13	−10	29	27	26	12	20	19	19			
SYRIA																
Damascus	33 30N	36 20E	720	−4	−2	0	39	38	37	19	22	22	21			
TAIWAN																
Tainan	22 57N	120 12E	21	4	8	9	33	33	32	8	29	28	28	N	5	W
Taipei	25 02N	121 31E	9	5	7	8	34	33	32	9	28	28	27	E	4	E
TANZANIA																
Dar es Salaam	6 50S	39 18E	14	17	18	18	32	32	31	7	28	27	27			
THAILAND																
Bangkok	13 44N	100 30E	12	14	16	17	36	35	34	10	28	28	27	N	2	S

TABLE 1—Climatic conditions for other countries.

Col. 1	Col. 2		Col. 3	Winter, °C			Summer, °C							Prevailing Winds		
Country and Station	Lat.	Long.	Elevation,	Mean of Annual Extemes	Col. 4		Col. 5 Design Dry-Bulb			Col. 6 Mean Daily Range °C	Col. 7 Design Wet-Bulb			Winter		Summer
	° ′	° ′	m		99%	97.5%	1%	2.5%	5%		1%	2.5%	5%		m/s	
TRINIDAD																
Port of Spain	10 40N	61 31W	20	16	18	19	33	32	32	9	27	27	26			
TUNISIA																
Tunis	36 47N	10 12E	66	2	4	5	39	37	36	12	25	24	23	W	5	E
TURKEY																
Adana	36 59N	35 18E	25	−4	1	2	38	36	35	12	26	26	25			
Ankara	39 57N	32 53E	861	−17	−13	−11	34	33	32	16	20	19	19	N	4	W
Istanbul	40 58N	28 50E	18	−5	−2	−1	33	31	30	9	24	23	23	N	5	NE
Izmir	38 26N	27 10E	5	−4	−3	−2	37	36	34	13	24	23	23	NNE	4	N
UNITED KINGDOM																
Belfast	54 36N	5 55W	7	−7	−5	−3	23	22	21	9	18	18	17			
Birmingham	52 29N	1 56W	163	−6	−4	−3	26	24	23	8	19	18	17			
Cardiff	51 28N	3 10W	62	−6	−4	−3	26	24	23	8	18	17	17			
Edinburgh	55 55N	3 11W	134	−6	−4	−2	23	21	20	7	18	17	16	WSW	3	WSW
Glasgow	55 52N	4 17W	26	−8	−6	−4	23	22	20	7	18	17	16			
London	51 29N	0 00	45	−7	−4	−3	28	26	24	9	20	19	18	W	4	E
URUGUAY																
Montevideo	34 51S	56 13W	22	1	3	4	32	31	29	12	23	22	22	N	6	NNE
VENEZUELA																
Caracas	10 30N	66 56W	1042	9	11	12	29	28	27	12	21	21	21	E	4	ENE
Maracaibo	10 39N	71 36W	6	21	22	23	36	36	35	9	29	28	28			
VIETNAM																
Da Nang	16 04N	108 13E	7	13	16	17	36	35	34	8	30	30	29	NW	3	N
Hanoi	21 02N	105 52E	16	8	10	12	37	36	35	9	29	29	29			
Ho Chi Minh City (Saigon)	10 47N	106 42E	9	17	18	19	34	33	32	9	29	29	28			
YUGOSLAVIA																
Belgrade	44 48N	20 28E	138	−16	−13	−11	33	32	30	13	23	23	22	ESE	5	SE
ZAIRE																
Kinshasa (Leopoldville)	4 20S	15 18E	325	12	16	17	33	33	32	11	27	27	27	NNW	4	W
Kisangani (Stanleyville)	0 26S	15 14E	418	18	19	20	33	33	32	11	27	27	27			

TABLE 2—Thermodynamic properties of *MOIST AIR*, SI units (standard atmospheric pressure, 101.325 kPa).

Temp. °C	Humidity Ratio kg_w/kg_a	Volume m^3/kg dry air			Enthalpy kJ/kg dry air			Entropy kJ/(kg dry air)·K			Condensed Water			Temp °C
											Enthalpy kJ/kg	Entropy kJ/kg·K	Vapor Press. kPa	
	W_s	v_a	v_{as}	v_s	h_a	h_{as}	h_s	s_a	s_{as}	s_s	h_w	s_w	p_s	
−60	0.0000067	0.6027	0.0000	0.6027	−60.351	0.017	−60.334	−0.2495	0.0001	−0.2494	−446.29	−1.6854	0.00108	−60
−59	0.0000076	0.6056	0.0000	0.6056	−59.344	0.018	−59.326	−0.2448	0.0001	−0.2447	−444.63	−1.6776	0.00124	−59
−58	0.0000087	0.6084	0.0000	0.6084	−58.338	0.021	−58.317	−0.2401	0.0001	−0.2400	−442.95	−1.6698	0.00141	−58
−57	0.0000100	0.6113	0.0000	0.6113	−57.332	0.024	−57.308	−0.2354	0.0001	−0.2353	−441.27	−1.6620	0.00161	−57
−56	0.0000114	0.6141	0.0000	0.6141	−56.326	0.028	−56.298	−0.2308	0.0001	0.2306	−439.58	−1.6542	0.00184	−56
−55	0.0000129	0.6170	0.0000	0.6170	−55.319	0.031	−55.288	−0.2261	0.0002	−0.2260	−437.89	−1.6464	0.00209	−55
−54	0.0000147	0.6198	0.0000	0.6198	−54.313	0.036	−54.278	−0.2215	0.0002	−0.2214	−436.19	−1.6386	0.00238	−54
−53	0.0000167	0.6226	0.0000	0.6227	−53.307	0.041	−53.267	−0.2170	0.0002	−0.2168	−434.48	−1.6308	0.00271	−53
−52	0.0000190	0.6255	0.0000	0.6255	−52.301	0.046	−52.255	−0.2124	0.0002	−0.2122	−432.76	−1.6230	0.00307	−52
−51	0.0000215	0.6283	0.0000	0.6284	−51.295	0.052	−51.243	−0.2079	0.0002	−0.2076	−431.03	−1.6153	0.00348	−51
−50	0.0000243	0.6312	0.0000	0.6312	−50.289	0.059	−50.230	−0.2033	0.0003	−0.2031	−429.30	−1.6075	0.00394	−50
−49	0.0000275	0.6340	0.0000	0.6341	−49.283	0.067	−49.216	−0.1988	0.0003	−0.1985	−427.56	−1.5997	0.00445	−49
−48	0.0000311	0.6369	0.0000	0.6369	−48.277	0.075	−48.202	−0.1944	0.0004	−0.1940	−425.82	−1.5919	0.00503	−48
−47	0.0000350	0.6397	0.0000	0.6398	−47.271	0.085	−47.186	−0.1899	0.0004	−0.1895	−424.06	−1.5842	0.00568	−47
−46	0.0000395	0.6426	0.0000	0.6426	−46.265	0.095	−46.170	−0.1855	0.0004	−0.1850	−422.30	−1.5764	0.00640	−46
−45	0.0000445	0.6454	0.0000	0.6455	−45.259	0.108	−45.151	−0.1811	0.0005	−0.1805	−420.54	−1.5686	0.00721	−45
−44	0.0000500	0.6483	0.0001	0.6483	−44.253	0.121	−44.132	−0.1767	0.0006	−0.1761	−418.76	−1.5609	0.00811	−44
−43	0.0000562	0.6511	0.0001	0.6512	−43.247	0.137	−43.111	−0.1723	0.0006	−0.1716	−416.98	−1.5531	0.00911	−43
−42	0.0000631	0.6540	0.0001	0.6540	−42.241	0.153	−42.088	−0.1679	0.0007	−0.1672	−415.19	−1.5453	0.01022	−42
−41	0.0000708	0.6568	0.0001	0.6569	−41.235	0.172	−41.063	−0.1636	0.0008	−0.1628	−413.39	−1.5376	0.01147	−41
−40	0.0000793	0.6597	0.0001	0.6597	−40.229	0.192	−40.037	−0.1592	0.0009	−0.1584	−411.59	−1.5298	0.01285	−40
−39	0.0000887	0.6625	0.0001	0.6626	−39.224	0.216	−39.007	−0.1549	0.0010	−0.1540	−409.77	−1.5221	0.01438	−39
−38	0.0000992	0.6653	0.0001	0.6654	−38.218	0.241	−37.976	−0.1507	0.0011	−0.1496	−407.96	−1.5143	0.01608	−38
−37	0.0001108	0.6682	0.0001	0.6683	−37.212	0.270	−36.942	−0.1464	0.0012	−0.1452	−406.13	−1.5066	0.01796	−37
−36	0.0001237	0.6710	0.0001	0.6712	−36.206	0.302	−35.905	−0.1421	0.0014	−0.1408	−404.29	−1.4988	0.02005	−36
−35	0.0001379	0.6739	0.0001	0.6740	−35.200	0.336	−34.864	−0.1379	0.0015	−0.1364	−402.45	−1.4911	0.02235	−35
−34	0.0001536	0.6767	0.0002	0.6769	−34.195	0.375	−33.820	−0.1337	0.0017	−0.1320	−400.60	−1.4833	0.02490	−34
−33	0.0001710	0.6796	0.0002	0.6798	−33.189	0.417	−32.772	−0.1295	0.0018	−0.1276	−398.75	−1.4756	0.02772	−33
−32	0.0001902	0.6824	0.0002	0.6826	−32.183	0.464	−31.718	−0.1253	0.0020	−0.1233	−396.89	−1.4678	0.03082	−32
−31	0.0002113	0.6853	0.0002	0.6855	−31.178	0.517	−30.661	−0.1212	0.0023	−0.1189	−395.01	−1.4601	0.03425	−31
−30	0.0002346	0.6881	0.0003	0.6884	−30.171	0.574	−29.597	−0.1170	0.0025	−0.1145	−393.14	−1.4524	0.03802	−30
−29	0.0002602	0.6909	0.0003	0.6912	−29.166	0.636	−28.529	−0.1129	0.0028	−0.1101	−391.25	−1.4446	0.04217	−29
−28	0.0002883	0.6938	0.0003	0.6941	−28.160	0.707	−27.454	−0.1088	0.0031	−0.1057	−389.36	−1.4369	0.04673	−28
−27	0.0003193	0.6966	0.0004	0.6970	−27.154	0.782	−26.372	−0.1047	0.0034	−0.1013	−387.46	−1.4291	0.05175	−27
−26	0.0003533	0.6995	0.0004	0.6999	−26.149	0.867	−25.282	−0.1006	0.0037	−0.0969	−385.55	−1.4214	0.05725	−26
−25	0.0003905	0.7023	0.0004	0.7028	−25.143	0.959	−24.184	−0.0965	0.0041	−0.0924	−383.63	−1.4137	0.06329	−25
−24	0.0004314	0.7052	0.0005	0.7057	−24.137	1.059	−23.078	−0.0925	0.0045	−0.0880	−381.71	−1.4059	0.06991	−24
−23	0.0004762	0.7080	0.0005	0.7086	−23.132	1.171	−21.961	−0.0885	0.0050	−0.0835	−379.78	−1.3982	0.07716	−23
−22	0.0005251	0.7109	0.0006	0.7115	−22.126	1.292	−20.834	−0.0845	0.0054	−0.0790	−377.84	−1.3905	0.08510	−22
−21	0.0005787	0.7137	0.0007	0.7144	−21.120	1.425	−19.695	−0.0805	0.0060	−0.0745	−375.90	−1.3828	0.09378	−21
−20	0.0006373	0.7165	0.0007	0.7173	−20.115	1.570	−18.545	−0.0765	0.0066	−0.0699	−373.95	−1.3750	0.10326	−20
−19	0.0007013	0.7194	0.0008	0.7202	−19.109	1.729	−17.380	−0.0725	0.0072	−0.0653	−371.99	−1.3673	0.11362	−19
−18	0.0007711	0.7222	0.0009	0.7231	−18.103	1.902	−16.201	−0.0686	0.0079	−0.0607	−370.02	−1.3596	0.12492	−18
−17	0.0008473	0.7251	0.0010	0.7261	−17.098	2.092	−15.006	−0.0646	0.0086	−0.0560	−368.04	−1.3518	0.13725	−17
−16	0.0009303	0.7279	0.0011	0.7290	−16.092	2.299	−13.793	−0.0607	0.0094	−0.0513	−366.06	−1.3441	0.15068	−16
−15	0.0010207	0.7308	0.0012	0.7320	−15.086	2.524	−12.562	−0.0568	0.0103	−0.0465	−364.07	−1.3364	0.16530	−15
−14	0.0011191	0.7336	0.0013	0.7349	−14.080	2.769	−11.311	−0.0529	0.0113	−0.0416	−362.07	−1.3287	0.18122	−14
−13	0.0012262	0.7364	0.0014	0.7379	−13.075	3.036	−10.039	−0.0490	0.0123	−0.0367	−360.07	−1.3210	0.19852	−13
−12	0.0013425	0.7393	0.0016	0.7409	−12.069	3.327	−8.742	−0.0452	0.0134	−0.0318	−358.06	−1.3132	0.21732	−12
−11	0.0014690	0.7421	0.0017	0.7439	−11.063	3.642	−7.421	−0.0413	0.0146	−0.0267	−356.04	−1.3055	0.23775	−11
−10	0.0016062	0.7450	0.0019	0.7469	−10.057	3.986	−6.072	−0.0375	0.0160	−0.0215	−354.01	−1.2978	0.25991	−10
−9	0.0017551	0.7478	0.0021	0.7499	−9.052	4.358	−4.693	−0.0337	0.0174	−0.0163	−351.97	−1.2901	0.28395	−9
−8	0.0019166	0.7507	0.0023	0.7530	−8.046	4.764	−3.283	−0.0299	0.0189	−0.0110	−349.93	−1.2824	0.30999	−8
−7	0.0020916	0.7535	0.0025	0.7560	−7.040	5.202	−1.838	−0.0261	0.0206	−0.0055	−347.88	−1.2746	0.33821	−7
−6	0.0022811	0.7563	0.0028	0.7591	−6.035	5.677	−0.357	−0.0223	0.0224	0.0000	−345.82	−1.2669	0.36874	−6
−5	0.0024862	0.7592	0.0030	0.7622	−5.029	6.192	1.164	−0.0186	0.0243	0.0057	−343.76	−1.2592	0.40178	−5
−4	0.0027081	0.7620	0.0033	0.7653	−4.023	6.751	2.728	−0.0148	0.0264	0.0115	−341.69	−1.2515	0.43748	−4
−3	0.0029480	0.7649	0.0036	0.7685	−3.017	7.353	4.336	−0.0111	0.0286	0.0175	−339.61	−1.2438	0.47606	−3
−2	0.0032074	0.7677	0.0039	0.7717	−2.011	8.007	5.995	−0.0074	0.0310	0.0236	−337.52	−1.2361	0.51773	−2
−1	0.0034874	0.7705	0.0043	0.7749	−1.006	8.712	7.706	−0.0037	0.0336	0.0299	−335.42	−1.2284	0.56268	−1
0	0.0037895	0.7734	0.0047	0.7781	−0.000	9.473	9.473	0.0000	0.0364	0.0364	−333.32	−1.2206	0.61117	0
0	* 0.003789	0.7734	0.0047	0.7781	−0.000	9.473	9.473	0.0000	0.0364	0.0364	0.06	−0.0001	0.6112	0
1	0.004076	0.7762	0.0051	0.7813	1.006	10.197	11.203	0.0037	0.0391	0.0427	4.28	0.0153	0.6571	1
2	0.004381	0.7791	0.0055	0.7845	2.012	10.970	12.982	0.0073	0.0419	0.0492	8.49	0.0306	0.7060	2
3	0.004707	0.7819	0.0059	0.7878	3.018	11.793	14.811	0.0110	0.0449	0.0559	12.70	0.0459	0.7581	3
4	0.005054	0.7848	0.0064	0.7911	4.024	12.672	16.696	0.0146	0.0480	0.0627	16.91	0.0611	0.8135	4
5	0.005424	0.7876	0.0068	0.7944	5.029	13.610	18.639	0.0182	0.0514	0.0697	21.12	0.0762	0.8725	5
6	0.005818	0.7904	0.0074	0.7978	6.036	14.608	20.644	0.0219	0.0550	0.0769	25.32	0.0913	0.9353	6
7	0.006237	0.7933	0.0079	0.8012	7.041	15.671	22.713	0.0255	0.0588	0.0843	29.52	0.1064	1.0020	7
8	0.006683	0.7961	0.0085	0.8046	8.047	16.805	24.852	0.0290	0.0628	0.0919	33.72	0.1213	1.0729	8
9	0.007157	0.7990	0.0092	0.8081	9.053	18.010	27.064	0.0326	0.0671	0.0997	37.92	0.1362	1.1481	9
10	0.007661	0.8018	0.0098	0.8116	10.059	19.293	29.352	0.0362	0.0717	0.1078	42.11	0.1511	1.2280	10
11	0.008197	0.8046	0.0106	0.8152	11.065	20.658	31.724	0.0397	0.0765	0.1162	46.31	0.1659	1.3128	11
12	0.008766	0.8075	0.0113	0.8188	12.071	22.108	34.179	0.0433	0.0816	0.1248	50.50	0.1806	1.4026	12
13	0.009370	0.8103	0.0122	0.8225	13.077	23.649	36.726	0.0468	0.0870	0.1337	54.69	0.1953	1.4979	13
14	0.010012	0.8132	0.0131	0.8262	14.084	25.286	39.370	0.0503	0.0927	0.1430	58.88	0.2099	1.5987	14
15	0.010692	0.8160	0.0140	0.8300	15.090	27.023	42.113	0.0538	0.0987	0.1525	63.07	0.2244	1.7055	15

*Extrapolated to represent metasable equilibrium with undercooled liquid.

TABLE 2—Thermodynamic properties of *MOIST AIR*, SI units (standard atmospheric pressure, 101.325 kPa) (*continued*).

Temp. °C	Humidity Ratio kg_w/kg_a	Volume m^3/kg dry air			Enthalpy kJ/kg dry air			Entropy kJ/(kg dry air)·K			Condensed Water Enthalpy kJ/kg	Condensed Water Entropy kJ/kg·K	Condensed Water Vapor Press. kPa	Temp °C
	W_s	v_a	v_{as}	v_s	h_a	h_{as}	h_s	s_a	s_{as}	s_s	h_w	s_w	p_s	
16	0.011413	0.8188	0.0150	0.8338	16.096	28.867	44.963	0.0573	0.1051	0.1624	67.26	0.2389	1.8185	16
17	0.012178	0.8217	0.0160	0.8377	17.102	30.824	47.926	0.0607	0.1119	0.1726	71.44	0.2534	1.9380	17
18	0.012989	0.8245	0.0172	0.8417	18.108	32.900	51.008	0.0642	0.1190	0.1832	75.63	0.2678	2.0643	18
19	0.013848	0.8274	0.0184	0.8457	19.114	35.101	54.216	0.0677	0.1266	0.1942	79.81	0.2821	2.1979	19
20	0.014758	0.8302	0.0196	0.8498	20.121	37.434	57.555	0.0711	0.1346	0.2057	84.00	0.2965	2.3389	20
21	0.015721	0.8330	0.0210	0.8540	21.127	39.908	61.035	0.0745	0.1430	0.2175	88.18	0.3107	2.4878	21
22	0.016741	0.8359	0.0224	0.8583	22.133	42.527	64.660	0.0779	0.1519	0.2298	92.36	0.3249	2.6448	22
23	0.017821	0.8387	0.0240	0.8627	23.140	45.301	68.440	0.0813	0.1613	0.2426	96.55	0.3390	2.8105	23
24	0.018963	0.8416	0.0256	0.8671	24.146	48.239	72.385	0.0847	0.1712	0.2559	100.73	0.3531	2.9852	24
25	0.020170	0.8444	0.0273	0.8717	25.153	51.347	76.500	0.1881	0.1817	0.2698	104.91	0.3672	3.1693	25
26	0.021448	0.8472	0.0291	0.8764	26.159	54.638	80.798	0.0915	0.1927	0.2842	109.09	0.3812	3.3633	26
27	0.022798	0.8501	0.0311	0.8811	27.165	58.120	85.285	0.0948	0.2044	0.2992	113.27	0.3951	3.5674	27
28	0.024226	0.8529	0.0331	0.8860	28.172	61.804	89.976	0.0982	0.2166	0.3148	117.45	0.4090	3.7823	28
29	0.025735	0.8558	0.0353	0.8910	29.179	65.699	94.878	0.1015	0.2296	0.3311	121.63	0.4229	4.0084	29
30	0.027329	0.8586	0.0376	0.8962	30.185	69.820	100.006	0.1048	0.2432	0.3481	125.81	0.4367	4.2462	30
31	0.029014	0.8614	0.0400	0.9015	31.192	74.177	105.369	0.1082	0.2576	0.3658	129.99	0.4505	4.4961	31
32	0.030793	0.8643	0.0426	0.9069	32.198	78.780	110.979	0.1115	0.2728	0.3842	134.17	0.4642	4.7586	32
33	0.032674	0.8671	0.0454	0.9125	33.205	83.652	116.857	0.1148	0.2887	0.4035	138.35	0.4779	5.0345	33
34	0.034660	0.8700	0.0483	0.9183	34.212	88.799	123.011	0.1180	0.3056	0.4236	142.53	0.4915	5.3242	34
35	0.036756	0.8728	0.0514	0.9242	35.219	94.236	129.455	0.1213	0.3233	0.4446	146.71	0.5051	5.6280	35
36	0.038971	0.8756	0.0546	0.9303	36.226	99.983	136.209	0.1246	0.3420	0.4666	150.89	0.5186	5.9468	36
37	0.041309	0.8785	0.0581	0.9366	37.233	106.058	143.290	0.1278	0.3617	0.4895	155.07	0.5321	6.2812	37
28	0.043778	0.8813	0.0618	0.9431	38.239	112.474	150.713	0.1311	0.3824	0.5135	159.25	0.5456	6.6315	38
39	0.046386	0.8842	0.0657	0.9498	39.246	119.258	158.504	0.1343	0.4043	0.5386	163.43	0.5590	6.9988	39
40	0.049141	0.8870	0.0698	0.9568	40.253	126.430	166.683	0.1375	0.4273	0.5649	167.61	0.5724	7.3838	40
41	0.052049	0.8898	0.0741	0.9640	41.261	134.005	175.265	0.1407	0.4516	0.5923	171.79	0.5857	7.7866	41
42	0.055119	0.8927	0.0788	0.9714	42.268	142.007	184.275	0.1439	0.4771	0.6211	175.97	0.5990	8.2081	42
43	0.058365	0.8955	0.0837	0.9792	43.275	150.475	193.749	0.1471	0.5041	0.6512	180.15	0.6122	8.6495	43
44	0.061791	0.8983	0.0888	0.9872	44.282	159.417	203.699	0.1503	0.5325	0.6828	184.33	0.6254	9.1110	44
45	0.065411	0.9012	0.0943	0.9955	45.289	168.874	214.164	0.1535	0.5624	0.7159	188.51	0.6386	9.5935	45
46	0.069239	0.9040	0.1002	1.0042	46.296	178.882	225.179	0.1566	0.5940	0.7507	192.69	0.6517	10.0982	46
47	0.073282	0.9069	0.1063	1.0132	47.304	189.455	236.759	0.1598	0.6273	0.7871	196.88	0.6648	10.6250	47
48	0.077556	0.9097	0.1129	1.0226	48.311	200.644	248.955	0.1629	0.6624	0.8253	201.06	0.6778	11.1754	48
49	0.082077	0.9125	0.1198	1.0323	49.319	212.485	261.803	0.1661	0.6994	0.8655	205.24	0.6908	11.7502	49
50	0.086858	0.9154	0.1272	1.0425	50.326	225.019	275.345	0.1692	0.7385	0.9077	209.42	0.7038	12.3503	50
51	0.091918	0.9182	0.1350	1.0532	51.334	238.290	289.624	0.1723	0.7798	0.9521	213.60	0.7167	12.9764	51
52	0.097272	0.9211	0.1433	1.0643	52.341	252.340	304.682	0.1754	0.8234	0.9988	217.78	0.7296	13.6293	52
53	0.102948	0.9239	0.1521	1.0760	53.349	267.247	320.596	0.1785	0.8695	1.0480	221.97	0.7424	14.3108	53
54	0.108954	0.9267	0.1614	1.0882	54.357	283.031	337.388	0.1816	0.9182	1.0998	226.15	0.7552	15.0205	54
55	0.115321	0.9296	0.1713	1.1009	55.365	299.772	355.137	0.1847	0.9698	1.1544	230.33	0.7680	15.7601	55
56	0.122077	0.9324	0.1819	1.1143	56.373	317.549	373.922	0.1877	1.0243	1.2120	234.52	0.7807	16.5311	56
57	0.129243	0.9353	0.1932	1.1284	57.381	336.417	393.798	0.1908	1.0820	1.2728	238.70	0.7934	17.3337	57
58	0.136851	0.9381	0.2051	1.1432	58.389	356.461	414.850	0.1938	1.1432	1.3370	242.88	0.8061	18.1691	58
59	0.144942	0.9409	0.2179	1.1588	59.397	377.788	437.185	0.1969	1.2081	1.4050	247.07	0.8187	19.0393	59
60	0.15354	0.9438	0.2315	1.1752	60.405	400.458	460.863	0.1999	1.2769	1.4768	251.25	0.8313	19.9439	60
61	0.16269	0.9466	0.2460	1.1926	61.413	424.624	486.036	0.2029	1.3500	1.5530	255.44	0.8438	20.8858	61
62	0.17244	0.9494	0.2614	1.2109	62.421	450.377	512.798	0.2059	1.4278	1.6337	259.62	0.8563	21.8651	62
63	0.18284	0.9523	0.2780	1.2303	63.429	477.837	541.266	0.2089	1.5104	1.7194	263.81	0.8688	22.8826	63
64	0.19393	0.9551	0.2957	1.2508	64.438	507.177	571.615	0.2119	1.5985	1.8105	268.00	0.8812	23.9405	64
65	0.20579	0.9580	0.3147	1.2726	65.446	538.548	603.995	0.2149	1.6925	1.9074	272.18	0.8936	25.0397	65
66	0.21848	0.9608	0.3350	1.2958	66.455	572.116	638.571	0.2179	1.7927	2.0106	276.37	0.9060	26.1810	66
67	0.23207	0.9636	0.3568	1.3204	67.463	608.103	675.566	0.2209	1.8999	2.1208	280.56	0.9183	27.3664	67
68	0.24664	0.9665	0.3803	1.3467	68.472	646.724	715.196	0.2238	2.0147	2.2385	284.75	0.9306	28.5967	68
69	0.26231	0.9693	0.4055	1.3749	69.481	688.261	757.742	0.2268	2.1378	2.3646	288.94	0.9429	29.8741	69
70	0.27916	0.9721	0.4328	1.4049	70.489	732.959	803.448	0.2297	2.2699	2.4996	293.13	0.9551	31.1986	70
71	0.29734	0.9750	0.4622	1.4372	71.498	781.208	852.706	0.2327	2.4122	2.6448	297.32	0.9673	32.5734	71
72	0.31698	0.9778	0.4941	1.4719	72.507	833.335	905.842	0.2356	2.5655	2.8010	301.51	0.9794	33.9983	72
73	0.33824	0.9807	0.5287	1.5093	73.516	889.807	963.323	0.2385	2.7311	2.9696	305.70	0.9916	35.4759	73
74	0.36130	0.9835	0.5662	1.5497	74.525	951.077	1025.603	0.2414	2.9104	3.1518	309.89	1.0037	37.0063	74
75	0.38641	0.9863	0.6072	1.5935	75.535	1017.841	1093.375	0.2443	3.1052	3.3496	314.08	1.0157	38.5940	75
76	0.41377	0.9892	0.6519	1.6411	76.543	1090.628	1167.172	0.2472	3.3171	3.5644	318.28	1.0278	40.2369	76
77	0.44372	0.9920	0.7010	1.6930	77.553	1170.328	1247.881	0.2501	3.5486	3.7987	322.47	1.0398	41.9388	77
78	0.47663	0.9948	0.7550	1.7498	78.562	1257.921	1336.483	0.2530	3.8023	4.0553	326.67	1.0517	43.7020	78
79	0.51284	0.9977	0.8145	1.8121	79.572	1354.347	1433.918	0.2559	4.0810	4.3368	330.86	1.0636	45.5248	79
80	0.55295	1.0005	0.8805	1.8810	80.581	1461.200	1541.781	0.2587	4.3890	4.6477	335.06	1.0755	47.4135	80
81	0.59751	1.0034	0.9539	1.9572	81.591	1579.961	1661.552	0.2616	4.7305	4.9921	339.25	1.0874	49.3670	81
82	0.64724	1.0062	1.0360	2.0422	82.600	1712.547	1795.148	0.2644	5.1108	5.3753	343.45	1.0993	51.3860	82
83	0.70311	1.0090	1.1283	2.1373	83.610	1861.548	1945.158	0.2673	5.5372	5.8045	347.65	1.1111	53.4746	83
84	0.76624	1.0119	1.2328	2.2446	84.620	2029.983	2114.603	0.2701	6.0181	6.2882	351.85	1.1228	55.6337	84
85	0.83812	1.0147	1.3518	2.3666	85.630	2221.806	2307.436	0.2729	6.5644	6.8373	356.05	1.1346	57.8658	85
86	0.92062	1.0175	1.4887	2.5062	86.640	2442.036	2528.677	0.2757	7.1901	7.4658	360.25	1.1463	60.1727	86
87	1.01611	1.0204	1.6473	2.6676	87.650	2697.016	2784.666	0.2785	7.9128	8.1914	364.45	1.1580	62.5544	87
88	1.12800	1.0232	1.8333	2.8565	88.661	2995.890	3084.551	0.2813	8.7580	9.0393	368.65	1.1696	65.0166	88
89	1.26064	1.0261	2.0540	3.0800	89.671	3350.254	3439.925	0.2841	9.7577	10.0419	372.86	1.1812	67.5581	89
90	1.42031	1.0289	2.3199	3.3488	90.681	3776.918	3867.599	0.2869	10.9586	11.2455	377.06	1.1928	70.1817	90

TABLE 3—Mean dew point temperature (°F).

STATE AND STATION	YRS	JAN	FEB	MAR	APR	MAY	JUN	JUL	AUG	SEP	OCT	NOV	DEC	YEAR
ALA. BIRMINGHAM	20	36	37	41	49	58	66	69	68	62	52	41	36	51
MOBILE	20	44	45	48	57	64	70	72	72	68	57	48	44	57
MONTGOMERY	20	39	40	44	53	61	68	71	70	65	54	43	39	54
ALASKA ANCHORAGE	10	8	11	12	24	33	43	48	48	41	25	14	7	26
ANNETTE	10	29	29	30	35	40	47	51	52	48	41	34	31	39
BARROW	10	-23	-27	-26	-9	16	30	35	35	28	11	-8	-22	3
BARTER ISLAND	9	-23	-26	-26	-7	18	31	36	37	29	12	-8	-20	4
BETHEL	10	1	2	4	14	33	43	48	48	41	25	11	-5	22
COLD BAY	10	25	24	24	28	35	41	46	47	44	35	30	25	34
CORDOVA	9	21	24	22	31	38	45	49	49	43	34	27	23	34
FAIRBANKS	10	-15	-9	-2	19	32	44	49	48	36	18	-4	-18	17
JUNEAU	10	20	23	23	32	38	45	49	49	45	38	30	23	35
KING SALMON	10	9	11	13	24	34	42	47	48	42	27	16	5	27
KOTZEBUE	10	-8	-11	-7	7	27	39	47	47	36	16	1	-12	15
MCGRATH	10	-12	-8	-2	16	30	42	47	46	37	18	-3	-17	16
NOME	10	0	-2	2	13	29	39	45	45	37	21	9	-5	19
ST. PAUL ISLAND	10	23	19	21	25	32	38	44	45	42	34	29	24	31
SHEMYA	7	28	27	29	31	35	40	45	46	44	36	30	28	34
YAKUTAT	10	23	25	25	32	38	46	50	50	46	37	29	24	35
ARIZ. FLAGSTAFF	14	14	16	17	20	22	25	43	43	35	25	20	15	25
PHOENIX	20	33	33	33	35	36	42	58	60	53	44	36	33	41
PRESCOTT	15	19	21	21	23	25	29	48	50	41	31	24	21	29
TUCSON	20	28	26	27	26	27	35	56	59	48	39	30	28	36
WINSLOW	20	19	19	18	21	24	29	47	49	45	30	22	19	29
YUMA	20	27	28	29	33	36	42	57	61	54	43	32	29	39
ARK. FORT SMITH	20	30	33	37	48	59	67	69	67	61	51	38	32	49
LITTLE ROCK	20	32	34	39	49	60	67	70	69	62	52	40	34	51
TEXARKANA	11	35	38	43	52	63	69	70	70	64	53	43	36	53
CALIF. BAKERSFIELD	17	38	40	40	43	43	47	50	51	50	45	42	39	45
BLUE CANYON	7	23	24	25	30	34	36	36	35	35	31	30	27	31
BURBANK	17	36	38	40	45	49	53	57	57	54	49	41	36	46
EUREKA	10	41	40	40	44	48	50	52	53	53	49	48	43	47
FRESNO	20	38	41	41	44	45	48	51	52	51	46	42	40	45
LONG BEACH	7	38	42	44	48	50	55	58	60	58	53	46	42	50
LOS ANGELES	20	40	43	45	49	52	55	59	59	58	53	46	42	50
MT. SHASTA	7	25	28	26	30	35	40	41	38	38	34	34	30	33
OAKLAND	18	40	42	42	45	47	51	53	54	54	50	45	41	47
RED BLUFF	20	34	36	36	39	43	45	47	47	43	41	38	36	40
SACRAMENTO	20	39	41	41	45	47	50	53	53	50	47	42	40	46
SANDBERG	10	24	24	27	33	35	36	37	37	36	33	27	27	31
SAN DIEGO	20	42	44	46	50	52	56	60	61	60	55	46	43	51
SAN FRANCISCO	10	41	42	43	46	47	50	52	53	53	50	46	43	47
SANTA MARIA	16	40	42	42	46	48	51	54	54	53	49	43	40	47
COLO. COLORADO SPRINGS	15	10	14	15	22	33	40	47	47	37	26	17	12	27
DENVER	20	12	16	17	24	35	42	47	46	37	27	19	14	28
GRAND JUNCTION	20	17	20	21	25	29	31	39	43	35	29	24	19	28
PUEBLO	20	12	17	19	27	37	44	51	51	42	30	22	16	31
CONN. BRIDGEPORT	16	22	22	27	37	47	57	66	62	56	46	35	24	42
HARTFORD	20	18	19	25	35	46	57	62	61	54	44	37	22	40
NEW HAVEN	10	24	22	27	37	48	57	63	63	55	47	44	25	43
DEL. WILMINGTON	20	24	24	29	40	50	60	64	64	58	47	35	26	43
D.C. WASHINGTON	20	25	25	29	40	52	61	65	64	59	48	36	26	44
FLA. APALACHICOLA	10	47	48	54	60	66	72	73	74	71	62	50	50	61
DAYTONA BEACH	17	50	52	54	59	65	70	73	73	72	65	56	56	62
FT. MYERS	6	55	55	59	61	67	72	73	74	74	68	59	56	64
JACKSONVILLE	20	46	47	50	56	64	70	72	72	71	62	53	47	58
KEY WEST	16	61	63	65	66	69	73	74	75	74	71	67	64	69
MIAMI	16	57	59	61	63	68	72	73	74	74	69	63	58	66
ORLANDO	17	52	52	55	59	65	70	73	73	72	65	57	51	62
PENSACOLA	10	48	47	51	59	65	70	73	73	68	59	49	46	59
TALLAHASSEE	17	44	46	49	55	62	69	72	72	69	58	49	43	57
TAMPA	20	52	53	56	60	66	70	73	73	72	65	58	52	63
WEST PALM BEACH	17	57	58	61	63	68	72	74	74	74	68	62	57	66
GA. ATHENS	10	32	34	19	48	59	65	69	68	63	52	42	34	50
ATLANTA	20	34	34	39	48	57	65	68	67	62	51	40	34	50
AUGUSTA	20	37	37	42	50	60	66	70	70	65	54	43	36	53
MACON	20	37	38	42	51	59	66	70	69	64	53	43	37	52
SAVANNAH	20	42	43	46	54	63	69	72	72	68	58	48	41	56
HAWAII HILO	10	63	62	63	65	66	66	68	68	68	67	66	64	66
HONOLULU	10	63	61	62	63	64	65	66	66	67	66	65	63	64
KAHULUI	10	64	63	63	64	65	66	67	67	68	67	65	64	65
LIHUE	10	64	61	63	64	66	68	69	69	69	68	67	64	66
IDAHO BOISE	20	21	27	27	32	38	42	44	43	38	34	29	26	33
LEWISTON	10	21	28	28	32	40	45	44	44	42	39	33	28	35
POCATELLO	20	17	21	24	28	35	39	41	40	34	30	26	21	30
ILL. CHICAGO	20	18	20	26	36	46	56	61	61	53	43	31	21	39
MOLINE	20	15	19	26	37	48	59	64	63	54	43	30	21	40
PEORIA	20	18	21	28	38	49	59	64	63	54	44	31	22	41
ROCKFORD	7	12	17	24	35	48	56	61	61	54	43	31	24	39
SPRINGFIELD	20	20	23	30	41	49	61	65	64	55	44	32	24	42
IND. EVANSVILLE	20	26	27	34	44	53	63	67	66	58	47	35	28	46
FT. WAYNE	20	20	22	28	36	48	58	62	61	54	44	33	23	41
INDIANAPOLIS	20	22	23	30	40	50	60	64	63	55	45	32	23	42
SOUTH BEND	20	20	22	27	37	48	57	62	61	53	44	33	24	41
TERRE HAUTE	10	26	25	32	42	49	61	65	64	55	45	33	26	44
IOWA BURLINGTON	20	17	21	27	39	49	60	65	64	54	43	30	21	41
DES MOINES	20	14	18	25	37	48	60	64	63	53	42	29	19	39
DUBUQUE	10	15	18	25	35	45	59	64	62	52	42	27	19	39
SIOUX CITY	20	10	16	24	35	47	58	63	62	51	40	26	17	37
KANS. CONCORDIA	15	17	22	27	39	50	61	64	62	54	44	30	21	41
DODGE CITY	20	18	23	25	36	49	57	61	59	51	41	29	22	39
GOODLAND	20	15	21	21	30	42	52	56	55	45	34	23	18	34
TOPEKA	20	19	23	29	41	53	63	66	65	56	45	31	23	43
WICHITA	20	21	25	30	41	53	62	65	63	55	45	33	25	43
KY. LEXINGTON	20	27	27	32	42	53	61	65	64	56	46	34	28	45
LOUISVILLE	20	27	28	33	43	54	63	66	65	57	47	35	27	45
LA. ALEXANDRIA	6	37	40	46	56	62	68	72	71	67	56	49	40	55
BATON ROUGE	20	44	46	49	57	64	70	73	72	68	57	48	44	58
LAKE CHARLES	20	46	48	51	58	66	71	73	73	69	58	50	46	59
NEW ORLEANS	20	46	48	52	59	66	72	73	73	70	60	52	47	60
SHREVEPORT	20	38	40	44	54	62	69	71	70	65	55	45	39	54
MAINE CARIBOU	18	7	5	15	28	38	50	56	54	47	36	27	12	31
EASTPORT	10	18	20	25	33	40	47	55	57	52	42	33	22	37
PORTLAND	20	16	16	23	33	43	53	59	58	49	39	32	19	37
MD. BALTIMORE	20	24	24	29	40	51	61	65	64	58	47	35	25	44
MASS. BLUE HILL	10	20	20	26	35	46	56	62	61	53	45	34	23	40
BOSTON	20	19	19	25	34	44	55	60	60	53	44	34	22	39
NANTUCKET	20	26	25	29	37	46	56	63	62	57	49	39	29	43
WORCESTER	6	14	15	20	29	42	52	56	56	51	39	30	18	35

TABLE 3—Mean dew point temperature (°F) (*continued*).

STATE AND STATION	YRS	JAN	FEB	MAR	APR	MAY	JUN	JUL	AUG	SEP	OCT	NOV	DEC	YEAR
MICH. ALPENA	10	16	16	21	32	41	53	58	58	50	42	30	20	36
DETROIT	20	19	19	25	35	45	56	60	59	53	43	32	23	39
ESCANABA	10	12	14	20	32	41	52	59	58	50	41	28	17	35
FLINT	10	15	16	23	34	45	54	58	58	52	42	32	21	38
GRAND RAPIDS	20	19	19	25	34	44	55	59	59	52	43	32	23	39
LANSING	17	18	19	24	34	46	56	59	59	52	41	31	22	38
MARQUETTE	10	12	13	19	29	38	50	56	56	49	40	27	17	34
MUSKEGON	20	20	20	24	34	44	55	60	60	52	43	32	24	39
SAULT STE. MARIE	20	9	10	18	29	39	50	55	55	49	40	29	17	33
MINN. DULUTH	20	2	5	15	27	37	49	56	55	46	36	22	9	30
INTERNATL FALLS	20	-5	2	11	26	37	50	56	54	45	35	20	4	28
MINN.-ST. PAUL	20	6	10	20	32	43	55	60	59	50	40	25	13	34
ROCHESTER	20	7	12	19	32	44	56	61	59	49	39	25	14	35
ST. CLOUD	16	2	8	17	30	40	53	58	58	48	37	22	12	32
ST. PAUL	5	6	10	19	31	41	56	60	58	50	38	23	12	34
MISS. JACKSON	20	40	41	44	53	58	68	71	70	65	53	42	38	54
MERIDIAN	16	39	40	45	54	61	68	71	71	66	55	45	39	55
VICKSBURG	10	40	41	46	55	63	70	73	71	65	54	43	36	55
MO. COLUMBIA	20	21	24	29	40	52	62	66	64	55	45	32	25	43
KANSAS CITY	20	20	24	29	40	53	62	65	·64	55	45	33	24	43
ST. JOSEPH	10	19	24	29	40	51	63	65	65	53	44	30	23	42
ST. LOUIS	20	22	25	30	42	52	62	66	64	56	46	33	26	44
SPRINGFIELD	20	24	27	32	43	55	64	67	64	57	47	34	27	45
MONT. BILLINGS	20	11	16	20	28	38	46	48	46	38	31	22	15	30
BUTTE	10	6	12	16	23	32	38	39	39	33	27	18	13	25
GLASGOW	13	5	10	17	25	37	45	49	44	38	29	22	10	28
GREAT FALLS	20	10	15	18	26	34	42	44	42	36	29	21	15	28
HAVRE	12	6	12	16	26	33	42	45	43	37	29	21	13	27
HELENA	20	10	16	19	26	35	42	45	43	37	30	21	15	28
KALISPELL	9	14	20	23	29	36	43	47	46	39	34	27	20	32
MILES CITY	19	10	15	20	29	39	47	51	48	39	32	23	15	31
MISSOULA	20	15	21	23	29	37	43	45	43	39	34	26	20	31
NEBR. GRAND ISLAND	16	13	19	23	34	45	57	61	60	49	38	25	18	37
LINCOLN	8	16	21	28	37	46	60	63	62	51	41	28	20	39
NORFOLK	8	11	18	23	34	44	58	62	61	49	38	24	16	37
NORTH PLATTE	20	13	18	22	32	44	55	59	58	48	36	24	17	36
OMAHA	20	14	19	26	37	48	60	64	63	54	43	29	20	40
SCOTTSBLUFF	16	13	17	19	28	40	49	54	53	43	32	21	17	32
VALENTINE	10	13	15	22	31	39	51	56	55	43	34	22	16	33
NEV. ELKO	17	15	20	22	26	32	35	36	34	29	25	23	18	26
ELY	20	12	18	19	24	26	29	33	34	27	24	19	16	23
LAS VEGAS	20	21	22	20	24	26	28	39	41	33	29	25	23	28
RENO	20	20	24	23	26	32	37	40	38	35	31	25	22	29
WINNEMUCCA	18	20	23	23	26	31	34	34	33	30	28	24	22	27
N. H. CONCORD	20	14	14	22	32	43	53	58	58	51	39	30	18	36
MT. WASHINGTON	10	4	5	7	20	29	41	45	45	36	28	17	7	24
N. J. ATLANTIC CITY	18	27	26	30	40	50	60	66	65	59	49	39	28	45
NEWARK	20	23	23	27	37	47	57	62	62	56	46	34	25	42
TRENTON	10	25	23	29	38	50	59	64	64	56	48	35	25	43
N. MEX. ALBUQUERQUE	20	19	19	19	23	29	35	49	50	42	33	23	20	30
CLAYTON	10	18	20	22	31	42	50	54	57	47	35	24	19	35
ROSWELL	17	20	22	22	28	37	48	56	55	48	39	26	22	35
N. Y. ALBANY	20	16	16	24	34	44	55	60	59	53	42	32	20	38
BINGHAMTON	15	17	18	23	34	44	54	58	58	51	41	30	20	37
BUFFALO	20	19	19	25	35	45	55	59	59	52	43	33	23	39
CANTON	5	16	14	21	30	43	53	57	57	50	42	30	17	36
NEW YORK	15	22	23	27	38	47	57	62	62	56	48	35	26	42
OSWEGO	7	20	18	25	33	42	54	60	60	52	44	32	21	38
ROCHESTER	20	19	19	25	35	45	55	59	59	53	43	33	23	39
SYRACUSE	20	18	18	25	35	45	55	59	59	53	42	32	22	39
N. C. ASHEVILLE	10	30	29	33	43	53	63	65	64	56	47	32	29	45
CAPE HATTERAS	20	40	40	44	52	61	68	72	72	68	59	50	41	56
CHARLOTTE	20	32	32	36	46	56	64	67	67	61	50	39	32	49
GREENSBORO	20	29	29	34	44	55	63	67	66	60	48	37	29	47
RALEIGH	20	32	31	35	45	56	64	68	67	61	50	38	30	48
WILMINGTON	16	39	39	44	52	60	68	71	70	67	56	46	37	54
WINSTON SALEM	19	29	29	32	42	54	59	66	68	59	51	36	28	46
N. DAK. BISMARCK	20	1	7	17	29	38	51	56	53	42	33	20	9	30
DEVILS LAKE	10	-4	3	14	30	40	51	57	56	45	35	19	5	29
FARGO	20	-1	6	17	31	40	54	59	57	46	36	22	8	31
WILLISTON	16	3	7	17	27	37	48	53	51	42	32	21	11	29
OHIO AKRON-CANTON	17	22	22	27	37	47	56	60	60	53	42	32	24	40
CINCINNATI	12	26	26	29	39	51	60	63	62	55	43	31	26	43
CLEVELAND	20	23	22	28	37	47	57	61	61	54	44	33	24	41
COLUMBUS	20	23	24	30	40	50	59	63	62	55	44	33	25	42
DAYTON	20	23	24	29	39	50	58	62	61	54	44	33	24	42
TOLEDO	20	21	21	27	37	47	57	61	61	54	43	32	23	40
YOUNGSTOWN	17	22	22	26	37	46	56	60	59	53	42	32	22	40
OKLA. OKLAHOMA CITY	17	26	30	33	45	58	65	67	65	58	48	35	28	47
TULSA	20	26	30	34	46	58	66	68	66	59	49	36	29	47
ORE. ASTORIA	10	37	40	39	42	46	51	54	55	52	49	42	40	46
BAKER	7	15	23	27	30	37	42	44	42	37	32	26	23	32
BURNS	15	19	23	24	27	33	37	38	37	32	30	26	19	29
EUGENE	7	33	37	35	40	44	48	50	50	48	45	42	38	43
MEDFORD	20	32	34	35	38	42	46	49	49	45	43	37	34	40
PENDLETON	17	24	30	30	34	40	42	43	43	41	39	33	29	36
PORTLAND	20	33	36	37	41	46	50	53	54	51	47	40	36	44
ROSEBURG	10	35	37	36	36	41	46	48	48	47	45	41	38	42
SALEM	17	34	38	38	41	45	50	52	52	50	46	41	38	44
PA. ALLENTOWN	18	21	22	27	38	48	58	62	62	55	44	34	23	41
ERIE	13	22	21	27	36	46	56	60	60	54	44	34	24	40
HARRISBURG	20	21	21	26	37	48	58	62	62	55	44	33	23	41
PHILADELPHIA	16	24	24	28	39	49	59	64	63	57	46	35	25	43
PITTSBURGH	20	22	22	27	37	47	57	60	60	53	42	31	24	40
READING	10	24	23	28	37	49	58	63	63	55	45	34	24	42
SCRANTON	20	19	19	25	36	46	55	60	59	52	43	32	22	39
WILLIAMSPORT	13	20	19	25	36	47	58	61	60	54	43	32	21	40
R.I. BLOCK ISLAND	10	28	26	31	39	48	57	65	64	57	50	39	30	45
PROVIDENCE	20	20	19	25	34	45	55	62	61	54	44	34	23	40
S.C. CHARLESTON	20	40	41	44	53	62	69	72	71	68	57	47	39	55
COLUMBIA	20	36	36	41	49	58	66	69	69	64	53	43	35	52
FLORENCE	13	37	37	40	49	58	67	71	70	65	56	42	34	52
GREENVILLE	17	30	30	36	44	55	63	67	66	60	50	38	32	48
SPARTANBURG	10	37	36	38	45	55	63	67	67	61	50	37	31	49
S.DAK. HURON	20	6	12	21	32	43	58	60	58	47	37	23	13	34
RAPID CITY	20	12	15	20	28	39	50	53	50	39	31	22	16	31
SIOUX FALLS	17	5	12	20	31	43	56	60	59	47	37	23	12	34
TENN. BRISTOL	13	30	30	34	42	54	62	65	65	58	47	35	28	46
CHATTANOOGA	20	33	33	37	47	57	65	68	68	61	50	39	32	49

TABLE 3—Mean dew point temperature (°F) (*continued*).

STATE AND STATION	YRS	JAN	FEB	MAR	APR	MAY	JUN	JUL	AUG	SEP	OCT	NOV	DEC	YEAR
TENN. (Cont) KNOXVILLE	20	32	32	36	45	55	63	66	66	59	49	38	31	48
MEMPHIS	16	33	35	38	48	59	66	69	68	62	49	38	33	50
NASHVILLE	20	32	33	37	47	57	65	68	67	60	49	38	32	49
TEXAS ABILENE	20	29	32	33	45	56	62	63	61	58	50	37	31	46
AMARILLO	20	19	23	23	32	45	55	58	57	51	40	27	22	38
AUSTIN	20	38	42	45	55	64	68	69	68	65	56	46	41	55
BROWNSVILLE	20	53	55	59	65	70	73	74	74	72	66	60	54	65
CORPUS CHRISTI	20	48	52	55	63	70	73	74	74	71	64	55	50	62
DALLAS	20	34	37	41	52	62	67	68	67	63	53	42	36	52
DEL RIO	14	38	40	42	51	59	66	66	65	63	55	43	38	52
EL PASO	20	24	23	23	26	31	42	55	55	49	39	28	25	35
FORT WORTH	20	33	36	39	51	61	66	67	66	61	53	41	35	51
GALVESTON	18	47	50	54	62	69	73	75	74	71	64	54	50	62
HOUSTON	20	45	48	51	60	66	72	73	73	69	60	51	47	60
LAREDO	19	43	46	51	57	65	69	68	68	67	60	50	44	57
LUBBOCK	20	25	26	27	37	49	57	61	60	55	45	31	24	41
MIDLAND	10	25	29	29	37	49	58	60	58	56	47	36	30	43
PALESTINE	10	40	42	45	54	64	71	72	71	66	57	46	43	56
PORT ARTHUR	20	47	49	52	60	67	73	75	74	70	61	51	47	61
SAN ANGELO	20	30	34	35	45	56	62	62	61	59	50	38	32	47
SAN ANTONIO	20	39	42	45	55	64	68	68	67	65	56	46	41	55
VICTORIA	17	46	49	52	59	67	72	72	71	69	61	51	47	60
WACO	20	37	40	43	54	63	68	69	67	63	55	44	38	53
WICHITA FALLS	20	28	35	34	46	58	64	64	63	58	49	36	30	47
UTAH MILFORD	7	16	19	15	23	27	30	40	40	29	25	22	19	25
SALT LAKE CITY	20	20	23	26	31	36	40	44	45	38	34	28	24	32
VT. BURLINGTON	20	12	12	20	32	43	54	59	58	51	40	30	17	36
VA. LYNCHBURG	10	29	27	32	42	53	61	66	65	58	47	34	27	45
NORFOLK	20	32	32	36	45	56	64	68	68	63	53	42	33	49
RICHMOND	20	28	29	33	43	55	63	67	67	60	49	38	29	47
ROANOKE	17	26	26	29	39	52	60	64	63	57	45	33	25	43
CAPE HENRY	8	38	35	39	45	58	65	70	69	64	57	44	36	52
WASH. ELLENBURG	5	14	24	28	31	38	44	46	47	43	38	31	25	34
NORTH HEAD	7	34	39	40	42	47	51	54	55	53	48	43	40	46
OLYMPIA	17	33	36	35	38	43	48	51	52	49	45	40	37	42
SEATTLE AP	6	33	36	35	38	43	48	52	53	51	47	40	37	43
SEATTLE-TACOMA	16	34	35	35	39	43	48	52	53	50	46	39	36	43
SPOKANE	20	20	25	27	32	38	43	44	44	40	37	30	26	34
STAMPEDE PASS	7	18	24	24	28	34	39	42	44	41	35	29	25	32
TACOMA	7	32	36	37	40	46	50	52	53	52	46	40	37	43
TATOOSH ISLAND	20	36	38	38	41	46	50	52	54	51	47	42	39	45
WALLA WALLA	7	23	30	31	34	40	44	46	47	43	41	35	30	37
YAKIMA	19	21	26	27	31	37	43	44	46	42	37	30	26	34
W. VA. CHARLESTON	16	27	27	30	40	52	61	65	64	57	47	34	27	44
ELKINS	17	24	24	30	38	49	58	61	60	54	42	32	25	41
PARKERSBURG	10	28	26	31	40	51	60	64	63	56	46	34	27	44
WISC. GREEN BAY	20	10	12	21	33	43	55	60	59	51	41	27	15	36
LA CROSSE	20	9	13	21	33	45	56	61	61	52	41	27	15	36
MADISON	20	11	15	22	34	45	58	61	60	51	41	28	17	37
MILWAUKEE	20	14	17	24	34	44	55	61	61	52	43	29	19	38
WYO. CASPER	17	11	15	18	25	34	39	43	40	33	26	20	15	27
CHEYENNE	20	10	13	17	25	35	42	47	45	36	27	18	14	27
LANDER	20	8	13	17	24	33	39	42	40	35	28	18	12	26
SHERIDAN	20	11	16	20	28	38	46	48	45	38	30	22	16	30
ROCK SPRINGS	8	11	15	18	24	31	35	39	39	31	27	19	15	25
PUERTO RICO. SAN JUAN	20	68	67	67	69	71	73	73	73	73	73	71	69	71

Based on years of data indicated in table during 1946-65

TABLE 4A—Winter heating degree day data for heating and summer criteria data for air conditioning for sites in the United States.

	Location				Summer Criteria Data Air Conditioning			
					Dry Bulb		Wet Bulb	
STATE Station	Lat, °/min	Long, °/min	Elev, feet	Degree Days, heating, annual	≧ 93°F, h	≧ 80°F, h	≧ 73°F, h	≧ 67°F, h
ALABAMA	N	W						
Alabama Ordnance Works	33 20	86 21	430	2806	140	1251	1145	2620
Anniston Army Depot	33 37	85 58	765	2806	140	1251	1145	2620
Birmingham MAP	33 34	86 45	620	2844	116	1380	1033	2696
Brookley AFB/Mobile	30 38	88 04	26	1750	61	1697	2249	3505
Craig AFB/Selma	32 20	86 59	166	2155	196	1657	1821	3229
Dauphin Island AFS	30 15	88 06	5	1396	29	1833	2487	3600
Florence	34 48	87 40	581	3199	116	1380	1033	2696
Fort McClellan/Reilly AAF	33 43	85 47	790	2806	140	1251	1145	2620
Fort Rucker/Cairns AAF	31 16	85 43	305	1968	75	1406	1591	3180
Gadsden	34 01	86 00	554	3059	116	1380	1033	2696
Gunter AFS	32 24	86 15	221	2153	126	1522	1485	3079
Hall ANG Station	31 19	85 27	400	1968	75	1406	1591	3180
Hunter Loop Comm Facility	32 23	86 24	160	2153	126	1522	1485	3079
Huntsville	34 42	86 35	606	3302	100	1288	846	2541
Maxwell AFB/Montgomery	32 23	86 22	169	2153	126	1522	1485	3079
Mobile/Bates Field	30 41	88 15	211	1684	93	1514	2086	3441
Montgomery/Dannelly Field	32 18	86 24	183	2269	175	1579	1622	3128
Muscle Shoals	34 45	87 37	550	3199	116	1380	1033	2696
Redstone Arsenal	34 39	86 41	602	3302	100	1288	846	2541
Selma use Craig AFB								
Sheffield	34 46	87 42	480	3199	116	1380	1033	2696
Tuscaloosa MAP	33 13	87 37	169	2626	215	1436	1103	2549
ALASKA	N	W						
Adak NAVSTA/Mitchell Field	51 53	176 39	19	8825	0	0	0	1
Anchorage IAP	61 10	150 01	114	10911	0	0	0	0
Aniak	61 35	159 32	86	13412	0	10	0	1
Annette	55 02	131 34	110	7053	0	6	0	1
Anvil Mt	64 34	165 22	1100	14555	0	0	0	0
Attu/Casco Cove CGS	52 50	173E10	39	8339	0	0	0	0
Aurora	62 24	145 02	1900	13593	0	17	0	0
Barrow	71 18	156 47	31	20265	0	0	0	0
Barter Island	70 08	143 38	39	19994	0	0	0	0
Bear Creek	65 15	151 55	1650	13861	0	6	0	0
Beaver Creek	63 03	141 49	2433	14770	0	12	0	1
Bethel AFS	60 47	161 53	160	13203	0	4	0	2
Bethel Aprt	60 47	161 48	125	13203	0	4	0	2
Bettles	66 55	151 31	644	15925	0	20	0	5
Big Delta/Allen AAF	64 00	145 44	1268	13698	0	30	0	1
Big Mountain	59 23	155 13	2150	12144	0	0	0	0
Black Rapids	63 29	145 50	2703	12553	0	11	0	0
Blair Lake AF Range	64 23	147 41	725	14068	0	38	0	4
Boswell Bay AFS	60 25	146 09	800	9765	0	0	0	0
Campion AFS	64 42	156 44	363	14780	0	24	0	12
Canyon Creek	64 18	146 32	1779	13298	0	22	0	1
Cape Lisburne AFS	68 53	166 07	12	17063	0	0	0	0
Cape Newenham AFS	58 39	162 04	541	11481	0	0	0	0
Cape Romanzof AFS	61 47	166 02	457	13130	0	0	0	0
Cape Sarichef	54 36	164 55	560	9985	0	0	0	0
Cathedral	63 23	143 47	2010	15275	0	17	0	1
Clam Gulch	60 13	151 25	350	11375	0	1	0	1
Clear AFS	64 20	149 10	600	14060	0	32	0	10
Cold Bay AFS	55 12	162 43	98	9865	0	0	0	0
Cordova	60 30	145 29	42	9765	0	0	0	0
Diamond Ridge	59 41	151 37	1100	10394	0	0	0	0
Donnelly	63 47	145 51	2954	12683	0	0	0	0
Driftwood Bay	53 58	166 51	24	9197	0	0	0	4
Driftwood Bay AFS	53 58	166 53	1250	10637	0	0	0	0
Dutch Harbor	53 53	166 32	13	9197	0	0	0	4
Eielson AFB/Fairbanks	64 40	147 06	545	14498	0	38	0	4
Elmendorf AFB/Anchorage	61 15	149 48	212	10722	0	2	0	0
Fairbanks IAP	64 49	147 52	436	14345	0	53	0	5
Fort Greely	63 58	145 44	1314	13698	0	30	0	1
Fort Richardson/Bryant AAF	61 16	149 39	342	10722	0	2	0	0

TABLE 4A—Winter heating degree day data for heating and summer criteria data for air conditioning for sites in the United States. (*continued*)

STATE Station	Location			Degree Days, heating, annual	Summer Criteria Data Air Conditioning			
					Dry Bulb		Wet Bulb	
	Lat, °/min	Long, °/min	Elev, feet		≧ 93°F, h	≧ 80°F, h	≧ 73°F, h	≧ 67°F, h
Fort Wainwright	64 50	147 37	448	14345	0	53	0	5
Fort Yukon AFS	66 34	145 15	431	16084	1	29	1	23
Galena	64 44	156 56	152	15087	0	20	0	12
Gerstle River	63 48	145 00	1512	13398	0	30	0	1
Gold King Creek	64 12	149 55	1722	13364	0	13	0	2
Granite Mountain	65 26	161 14	2835	14986	0	0	0	0
Gulkana	62 09	145 27	1572	13938	0	22	0	0
Harding Lake	64 24	146 57	1445	13398	0	30	0	1
Homer	59 38	151 30	63	10364	0	0	0	0
Hoonah	58 07	135 25	1538	9552	0	0	0	0
Iliamna	59 45	154 55	190	12144	0	1	0	1
Indian Mountain AFS	66 00	153 42	1220	15169	0	12	0	3
Juneau MAP	58 22	134 35	12	9007	0	4	0	0
Kalakaket Creek	64 26	156 50	1598	13942	0	8	0	8
Kenai MAP	60 34	151 15	92	11615	0	1	0	1
King Salmon	58 42	156 40	65	11582	0	6	0	4
Knob Ridge	63 38	144 03	2170	15080	0	17	0	1
Kodiak	57 45	152 29	73	8860	0	1	0	1
Kotzebue	66 52	162 38	10	16039	0	1	0	1
Kotzebue AFS	66 53	162 36	11	16039	0	1	0	1
Kulis ANGB	61 10	149 59	96	10911	0	0	0	0
Lonely	70 55	153 15	23	20265	0	0	0	0
McCallum	63 14	145 38	3600	13343	0	0	0	0
McGrath MAP	62 58	155 37	344	14487	0	22	0	1
Middleton Island	59 27	146 18	79	8188	0	0	0	0
Moses Point	64 42	162 03	16	14505	0	3	0	3
Murphy Dome AFS	64 57	148 21	2914	13795	0	6	0	0
Naknek	58 45	157 00	70	11133	0	3	0	4
Naptowne	60 32	150 35	450	12054	0	8	0	1
Neklason Lake	61 37	149 15	460	11220	0	24	0	0
Nenana	64 33	149 05	356	14539	0	32	0	10
Nikolski AFS	52 58	168 51	712	9555	0	0	0	0
Nome MAP	64 30	165 26	13	14325	0	0	0	0
North River	63 53	160 31	490	14027	0	0	0	1
Northway Aprt	62 57	141 56	1713	15634	0	17	0	1
Ocean Cape	59 32	139 51	84	9533	0	1	0	0
Oliktok	70 31	149 53	10	20265	0	0	0	0
Paxson Lake	62 58	145 28	3786	13483	0	0	0	0
Pedro Dome	65 02	147 30	2588	13600	0	10	0	1
Pillar Mountain	57 47	152 26	1290	9925	0	0	0	0
Point Barrow	71 19	156 38	8	20265	0	0	0	0
Point Lay	69 44	163 01	20	19194	0	0	0	0
Port Heiden	56 59	158 38	105	10441	0	0	0	2
Port Moller	55 59	160 30	1050	10290	0	0	0	0
Rabbit Creek	61 05	149 44	1250	10814	0	0	0	0
St Paul Island	57 09	170 13	22	11119	0	0	0	0
Sawmill	61 48	148 19	2573	13531	0	0	0	0
Seward Rec Annex	60 07	149 24	15	9242	0	3	0	0
Shemya AFB	52 43	174E05	97	9573	0	0	0	0
Sitka	57 03	135 20	67	8132	0	1	0	0
Smuggler Cove	55 05	131 35	123	7053	0	6	0	1
Soldotna	60 32	151 05	212	11615	0	1	0	1
Sparrevohn AFS	61 06	155 35	1573	12982	0	2	0	3
Starisky Creek	59 53	151 47	300	10885	0	0	0	0
Tahneta Pass	61 50	149 19	3443	14361	0	0	0	0
Tanana	65 10	152 06	232	15116	0	31	0	11
Tatalina AFS	62 54	155 58	964	13453	0	17	0	0
Tin City AFS	65 34	167 55	269	16192	0	1	0	0
Tolsona	62 06	146 10	2974	12763	0	7	0	0
Unalakleet	63 53	160 48	15	14027	0	1	0	1

TABLE 4A—Winter heating degree day data for heating and summer criteria data for air conditioning for sites in the United States. (*continued*)

STATE Station	Location			Degree Days, heating, annual	Summer Criteria Data Air Conditioning			
					Dry Bulb		Wet Bulb	
	Lat, °/min	Long, °/min	Elev, feet		≧ 93°F, h	≧ 80°F, h	≧ 73°F, h	≧ 67°F, h
Wainwright	70 36	159 53	80	19991	0	0	0	0
Whittier	60 47	148 41	31	9444	0	3	0	0
Yakataga	60 04	142 25	39	9222	0	0	0	0
Yakutat	59 31	139 40	28	9533	0	1	0	0
ARIZONA	N	W						
Chandler use Williams AFB								
Davis-Monthan AFB/Tucson	32 11	110 54	2654	1574	595	2243	69	1268
Flagstaff	35 08	111 40	7006	7322	0	184	0	0
Fort Huachuca/Libby AAF	31 35	110 20	4664	2551	68	1154	0	209
Gila Bend	32 54	112 43	859	1348	1524	3096	438	1568
Holbrook	34 56	110 09	5264	4826	120	1050	0	15
Luke AFB/Glendale	33 33	112 22	1101	1410	1189	2815	492	1727
Navajo Army Depot	35 14	111 50	7125	7322	0	184	0	0
Nogales	31 21	110 55	3800	2150	220	1786	4	732
Phoenix/Sky Harbor IAP	33 26	112 01	1112	1552	1192	2819	506	1758
Tucson IAP	32 07	110 56	2558	1707	694	2297	18	1171
Williams AFB/Chandler	33 18	111 40	1385	1535	1211	2915	426	1762
Winslow MAP	35 01	110 44	4895	4733	172	1165	0	15
Yuma MCAS/IAP	32 39	114 37	213	1005	1394	3136	949	1891
Yuma Test Station	32 52	114 26	225	968	1493	3185	848	1838
ARKANSAS	N	W						
Blytheville AFB	35 57	89 57	264	3760	109	1242	1113	2423
El Dorado/Goodwin Field	33 13	92 49	277	2645	214	1405	1502	2908
Fayetteville/Drake Field	36 00	94 10	1251	3839	126	966	527	1845
Fort Chaffee	35 18	94 17	440	3336	291	1505	1265	2656
Fort Smith MAP	35 20	94 22	463	3336	291	1505	1265	2656
Harrison	36 14	93 07	1105	3884	126	966	527	1845
Hot Springs/Memorial Field	34 29	93 06	535	2729	231	1643	1408	2751
Little Rock/Adams Field	34 44	92 14	257	3354	206	1519	1408	2751
Little Rock AFB	34 55	92 09	311	3241	130	1402	1231	2619
Pine Bluff Arsenal	34 18	92 05	241	2588	285	1524	1630	2814
Texarkana/Webb Field MAP	33 27	93 59	389	2531	198	1639	1715	3097
Walnut Ridge MAP	36 08	90 56	275	3352	155	1376	615	1991
CALIFORNIA	N	W						
Alameda NAS/Nimitz Field	37 47	122 19	15	2507	3	90	0	24
Almaden AFS	37 10	121 54	3470	4468	14	542	0	0
Arcata	40 59	124 06	218	5029	0	3	0	1
Bakersfield/Meadows Field	35 25	119 03	475	2185	483	1691	33	607
Barstow-Daggett Aprt	34 51	116 47	1927	2203	809	2133	32	461
Beale AFB/Marysville	39 07	121 26	113	2835	329	1294	24	456
Berkeley	37 52	122 15	345	2973	2	91	0	14
Bishop	37 22	118 22	4108	4313	394	1196	0	4
Blue Canyon Aprt	39 17	120 42	5280	5704	0	189	0	1
Boron AFS	35 05	117 35	3015	3000	504	1505	6	216
Burbank	34 12	118 21	775	1701	67	711	10	392
Cambria AFS	35 32	121 04	690	3646	2	28	0	3
Camp Parks Comm Annex	37 44	121 53	684	3035	169	863	8	318
Camp Roberts	35 48	120 45	765	2890	275	928	29	296
Castle AFB/Merced	37 23	120 34	188	2590	320	1294	22	505
Centerville Beach	40 34	124 21	280	5029	0	3	0	1
Chico MAP	39 48	121 51	238	2835	404	1410	15	385
China Lake NAF/Armitage Fld	35 41	117 41	2283	2560	806	2116	20	301
Chula Vista	32 36	117 05	25	1839	4	34	6	426
Compton	33 53	118 13	65	1606	26	486	12	438
Concord NAD	38 01	122 00	23	3035	188	921	8	318
Corona	33 54	117 28	550	1875	214	1134	60	648
Coronado	32 40	117 10	10	1839	4	34	6	426
Costa Mesa ANG Station	33 40	117 53	49	1482	20	288	13	475
Crows Landing	37 25	121 06	140	2767	320	1294	22	505

TABLE 4A—Winter heating degree day data for heating and summer criteria data for air conditioning for sites in the United States. (*continued*)

STATE Station	Location			Degree Days, heating, annual	Summer Criteria Data Air Conditioning			
					Dry Bulb		Wet Bulb	
	Lat, °/min	Long, °/min	Elev, feet		≧ 93°F, h	≧ 80°F, h	≧ 73°F, h	≧ 67°F, h
Cuddeback Dry Lake Range	35 18	117 28	2300	3203	504	1505	6	216
Daggett Use Barstow-Daggett								
Dixon	38 26	121 51	100	2826	165	815	15	327
Donner Summit	39 19	120 20	7195	8290	0	13	0	3
Edwards AFB	34 54	117 52	2302	3077	504	1505	6	216
El Centro NAF	32 49	115 40	−43	925	1413	3067	904	1832
El Toro MCAS/Santa Ana	33 40	117 44	383	1573	38	502	37	609
Fallbrook Annex	33 21	117 15	703	2077	112	846	37	609
Fort Baker	37 50	122 28	15	3080	0	12	0	8
Fort Barry	37 49	122 32	267	3080	0	12	0	8
Fort Irwin	35 16	116 41	2500	2547	809	2133	32	461
Fort MacArthur	33 43	118 18	200	1819	3	109	3	291
Fort Mason	37 48	122 26	50	3080	0	12	0	8
Fort Ord/Fritzsche AAF	36 41	121 46	134	3818	1	23	0	2
Fresno/Air Terminal	36 46	119 43	328	2650	374	1399	27	524
George AFB/Victorville	34 35	117 23	2875	2885	433	1495	1	160
Hamilton AFB/San Rafael	38 04	122 30	3	3311	10	184	22	171
Hayward	37 39	122 07	47	2909	10	230	0	14
Hunter Liggett Mil Rsvn	36 01	121 14	1090	3332	358	1153	53	440
Imperial Beach NF/Ream Fld	32 34	117 07	23	1839	4	34	6	426
Klamath AFS	41 34	124 05	804	4445	0	3	0	1
Kramer	34 55	117 55	2315	3077	504	1505	6	216
Lemoore NAS/Reeves Field	36 20	119 57	237	2579	519	1577	40	555
Letterman Army Hospital	37 48	122 27	20	3080	0	12	0	8
Livermore	37 42	121 57	500	3035	169	863	8	318
Long Beach	33 45	118 14	12	1819	7	99	3	291
Long Beach/Daugherty Field	33 49	118 09	30	1606	19	299	12	438
Los Alamitos NAS	33 47	118 03	35	1482	20	288	13	475
Los Angeles City Office	34 03	118 14	270	1245	38	581	23	586
Los Angeles IAP	33 56	118 24	97	1819	7	99	3	291
March AFB/Riverside	33 53	117 15	1533	2162	269	1132	23	431
Mare Island NAVSHIPYD	38 05	122 16	25	3311	10	184	22	171
Mather AFB/Sacramento	38 34	121 18	96	2600	259	1052	12	376
McClellan AFB/Sacramento	38 40	121 24	76	2566	299	1124	16	413
McPherson Peak	34 53	119 48	5763	5200	3	345	0	0
Merced use Castle AFB								
Mill Valley AFS	37 55	122 35	2600	3400	107	701	3	72
Miramir NAS/Mitscher Field	32 52	117 08	477	1532	18	340	13	472
Moffett Field NAS	37 25	122 03	34	2511	3	117	1	85
Mojave	35 02	118 11	2735	3012	499	1649	6	216
Montague/Siskiyou Co Aprt	41 46	122 28	2648	5474	107	701	3	72
Monterey FWC	36 36	121 52	162	3556	1	18	0	6
Monterey/Presidio	36 36	121 54	100	3556	1	18	0	6
Mt Diablo	37 53	121 55	3849	4600	8	454	0	0
Mt Disappointment	34 18	118 02	5900	5200	0	293	0	0
Mt Laguna AFS	32 53	116 25	6199	5445	0	163	2	10
Mt Martell ANG	37 49	122 04	2022	2809	74	676	0	155
Mt Pinos	34 48	119 08	8831	7800	0	32	0	0
Muroc NAS use Edwards AFB								
North Highlands ANGB	38 38	121 25	76	2566	299	1124	16	413
Norton AFB/San Bernardino	34 06	117 14	1156	1978	345	1206	60	648
Oakland Army Base	37 49	122 19	5	2909	5	92	0	14
Oakland IAP	37 44	122 12	6	2909	5	92	0	14
Oakland Navy Hospital	37 46	122 09	500	2962	29	360	0	129
Oat Mountain	34 19	118 36	3000	3200	108	1016	1	160
Ontario IAP	34 03	117 36	952	2009	345	1200	60	648
Palmdale	34 38	118 06	2542	2929	449	1486	2	114
Pasadena	34 09	118 09	864	1694	133	935	41	498
Pendleton MCB	33 18	117 18	63	1532	18	340	13	472
Pendleton MCB Coast	33 13	117 24	24	1782	3	62	20	535

TABLE 4A—Winter heating degree day data for heating and summer criteria data for air conditioning for sites in the United States. *(continued)*

STATE Station	Location			Degree Days, heating, annual	Summer Criteria Data Air Conditioning			
					Dry Bulb		Wet Bulb	
	Lat, °/min	Long, °/min	Elev, feet		≧ 93°F, h	≧ 80°F, h	≧ 73°F, h	≧ 67°F, h
Pillar Point AFS	37 30	122 30	200	3859	0	13	0	6
Pinon Peak	36 05	117 28	7400	6800	0	75	0	0
Pt Arena AFS	38 57	123 44	200	4747	0	30	0	13
Pt Arguello	34 34	120 40	76	3826	1	15	0	2
Pt Mugu NAS/Port Hueneme	34 07	119 07	13	2334	3	45	1	129
Pt Sur NF	36 20	121 54	361	3556	1	18	0	6
Pomona	34 03	117 45	934	2166	267	1138	60	648
Port Hueneme	34 09	119 12	16	2334	3	45	1	129
Red Bluff MAP	40 09	122 15	342	2688	478	1515	6	314
Red Mountain Flight Annex	35 22	117 38	3551	2946	425	1479	6	216
Riverbank AAP	37 43	120 55	135	2767	320	1294	22	505
Sacramento	38 31	121 30	17	2843	208	955	25	452
Sacramento Army Depot	38 31	121 24	42	2843	259	1052	12	376
San Bernardino	34 07	117 19	1125	1891	345	1206	60	648
San Bruno	37 37	122 25	20	3042	2	63	0	13
San Clemente Is NALF	33 01	118 35	181	1645	1	22	0	59
Sandberg	34 45	118 44	4523	4427	32	631	0	5
San Diego FWF	32 43	117 09	48	1782	3	62	20	535
San Diego IAP	32 44	117 10	13	1507	6	110	4	435
San Francisco IAP	37 37	122 23	8	3042	2	63	0	13
San Francisco/Presidio	37 48	122 28	20	3080	0	12	0	8
San Jose MAP	37 22	121 56	56	2416	3	117	1	85
San Luis Obispo	35 20	120 43	250	2472	34	420	37	609
San Nicolas Island	33 14	119 28	504	2454	3	92	2	59
San Pedro	33 43	118 16	10	1819	3	109	3	291
San Rafael	37 58	122 33	31	3077	10	184	22	171
Santa Ana MCAS	33 42	117 50	54	1675	20	288	13	475
Santa Barbara MAP	34 26	119 50	10	2470	3	59	1	95
Santa Catalina	33 24	118 25	1568	2652	7	244	0	59
Santa Maria	34 54	120 27	236	3053	4	57	0	12
Santa Rosa/Sonoma Co Aprt	38 31	122 49	125	3065	132	770	4	203
Seal Beach NAD	33 44	118 05	20	1819	3	109	3	291
Shafter AFS	35 30	119 10	425	2185	483	1691	33	607
Sharpe Army Depot	37 51	121 17	16	2806	204	955	8	318
Sierra Army Depot	40 09	120 07	4110	5822	97	805	0	8
Skaggs Is NSGA	38 12	122 23	2	3311	10	184	22	171
Stockton	37 54	121 15	22	2806	204	955	8	318
Sunnyvale	37 23	122 02	30	2511	3	117	1	85
Travis AFB/Fairfield	38 16	121 56	62	2725	121	686	4	203
Treasure Is NAVSTA	37 49	122 22	10	2507	3	90	0	24
Twentynine Palms MCB	34 14	116 03	1781	2006	952	2240	32	461
Two Rock Ranch Station	38 15	122 48	200	2966	95	681	22	171
Vandenberg AFB/Lompoc	34 43	120 34	368	3451	2	28	0	3
Van Nuys/Los Angeles	34 13	118 29	800	1701	67	711	10	392
West Coast Radio Station	38 47	122 30	1380	3716	342	1122	26	513
COLORADO	N	W						
Buckley ANGB/Denver	39 42	104 45	5663	6239	23	540	0	9
Colorado Springs/Peterson	38 49	104 43	6145	6473	12	496	0	1
Denver/Stapleton IAP	39 45	104 52	5283	6016	35	667	0	3
Ent AFB/Colorado Springs	38 50	104 47	5980	6373	21	644	0	1
Fitzsimons AH/Denver	39 45	104 50	5375	6016	35	667	0	3
Fort Carson/Butts AAF	38 41	104 46	5840	6373	31	722	0	11
Grand Junction/Walker Field	39 07	108 32	4843	5605	113	975	0	1
La Junta	38 03	103 30	4160	5132	258	1139	22	415
Lamar	38 12	102 41	3703	5402	389	1435	41	586
Lowry AFB/Denver	39 43	104 53	5396	5978	29	639	0	13
Pueblo Army Depot	38 17	104 21	4700	5394	140	954	0	29
Pueblo Memorial Aprt	38 17	104 31	4684	5394	140	954	0	29
Rocky Mountain Arsenal	39 50	104 53	5184	6016	35	667	0	3
Trinidad	37 16	104 20	5761	5642	38	737	1	17
USAF Academy/Colorado Springs	39 00	104 53	7166	6973	0	193	0	0

TABLE 4A—Winter heating degree day data for heating and summer criteria data for air conditioning for sites in the United States. (*continued*)

	Location				Summer Criteria Data Air Conditioning			
					Dry Bulb		Wet Bulb	
STATE Station	Lat, °/min	Long, °/min	Elev, feet	Degree Days, heating, annual	≧ 93°F, h	≧ 80°F, h	≧ 73°F, h	≧ 67°F, h
CONNECTICUT	N	W						
Bradley IAP/Windsor Locks	41 56	72 41	169	6350	16	456	194	920
Bridgeport	41 11	73 11	25	5461	1	235	148	947
Groton	41 24	72 05	14	6150	0	338	254	1171
Hartford/Brainard Aprt	41 44	72 39	19	6105	18	476	253	1107
New Haven	41 19	72 55	6	5793	3	245	237	1186
Stamford	41 03	73 32	109	5461	1	235	148	947
Waterbury	41 35	73 04	843	6672	4	295	129	843
DELAWARE	N	W						
Dover AFB	39 08	75 28	28	4756	23	658	585	1689
Lewes	38 46	75 05	10	4333	11	477	585	1689
Wilmington	39 45	75 33	79	4940	26	643	458	1475
Wilmington Airport	39 40	75 36	78	4940	26	643	458	1475
DISTRICT OF COLUMBIA	N	W						
Army Map Service	38 57	77 07	250	4290	47	849	580	1744
Bolling-Anacostia Mil Cmplx	38 50	77 01	29	4153	59	967	620	1773
Fort McNair	38 52	77 01	15	4153	59	967	620	1773
Walter Reed Army Med Cen	38 58	77 02	285	4483	32	701	445	1573
Washington National Aprt	38 51	77 02	14	4211	41	910	580	1744
Washington Navy Yard	38 52	77 00	40	4153	59	967	620	1773
FLORIDA	N	W						
Apalachicola	29 43	85 01	20	1361	13	1908	2378	3630
Avon Park	27 38	81 20	65	493	86	2021	2679	3980
Big Coppitt Key	24 35	81 39	2	102	3	3360	3731	4327
Bowman Bayou	30 23	86 11	10	1535	13	1908	2378	3630
Brandon	27 54	82 18	40	678	20	1778	2555	3946
Cape Canaveral AFS	28 29	80 34	16	711	4	1626	2777	4046
Cap San Blas	29 41	85 21	10	1361	1	1908	2378	3630
Clausen	30 23	86 27	12	1782	16	1760	2151	3466
Cocoa Beach use Patrick AFB								
Daytona Beach	29 11	81 03	31	897	23	1553	2355	3877
Eglin AFB/Valparaiso	30 29	86 31	85	1658	30	1788	2209	3472
Fort Lauderdale	26 04	80 09	10	244	13	2342	3292	4207
Fort Myers/Page Fld	26 35	81 52	15	457	42	1890	3072	4131
Gainesville MAP	29 41	82 16	152	1081	112	1504	1916	3587
Homestead AFB	25 29	80 24	7	218	2	2290	3162	4212
Hurlburt Field/Eglin No 9	30 26	86 41	35	1782	16	1760	2151	3466
Jacksonville AFS	30 17	81 41	110	1212	61	1708	2220	3685
Jacksonville/Cecil Fld NAS	30 13	81 53	80	1379	112	1504	1916	3587
Jacksonville IAP	30 30	81 42	26	1327	126	1693	2269	3693
Jacksonville NAS/Towers Fld	30 14	81 41	22	1212	61	1708	2220	3685
Jupiter	26 57	80 04	26	299	17	2276	3272	4194
Key West IAP	24 33	81 45	4	64	1	3433	3778	4355
Key West NAS	24 34	81 41	6	102	3	3360	3731	4327
Lakeland	28 02	81 57	214	678	20	1778	2555	3946
Lynn Haven	30 15	85 37	69	1388	13	1908	2378	3630
MacDill AFB/Tampa	27 51	82 30	13	560	27	2031	2588	3976
Mayport NAVSTA	30 24	81 25	19	1322	20	1492	2502	3850
McCoy AFB/Orlando	28 27	81 20	96	709	28	1596	2195	3843
Melbourne Beach	28 03	80 33	15	611	5	2088	2886	4135
Miami IAP	25 48	80 16	7	206	8	2408	3313	4221
Milton/Whiting Field NAS	30 43	87 01	200	1743	99	1562	1718	3317
Orlando	28 33	81 23	100	704	81	1675	2555	3946
Panama City/Bay County	30 13	85 41	20	1388	13	1908	2378	3630
Patrick AFB/Cocoa Beach	28 14	80 36	9	452	5	2088	2886	4135
Pensacola/Ellyson Field NAS	30 31	87 12	115	1513	91	2030	2344	3583
Pensacola NAS/F Sherman Fld	30 21	87 19	30	1654	18	1923	2487	3600
Pensacola/Saufley Field NAS	30 28	87 21	85	1513	91	2030	2344	3583
Ponce de Leon	29 04	80 55	10	897	23	1553	2355	3877
Richmond AFS	25 37	80 24	83	218	2	2290	3162	4212
Rivera Beach	26 45	80 04	10	299	17	2276	3272	4194

TABLE 4A—Winter heating degree day data for heating and summer criteria data for air conditioning for sites in the United States. (*continued*)

	Location			Degree Days, heating, annual	Summer Criteria Data Air Conditioning			
					Dry Bulb		Wet Bulb	
STATE Station	Lat, °/min	Long, °/min	Elev, feet		≧ 93°F, h	≧ 80°F, h	≧ 73°F, h	≧ 67°F, h
St Augustine	29 58	81 20	10	1051	20	1492	2502	3850
St Petersburg/Clearwater IAP	27 55	82 41	11	665	30	1881	2669	3930
Tallahassee MAP	30 23	84 22	55	1563	66	1460	1925	3465
Tampa IAP	27 58	82 32	19	718	30	1881	2669	3930
Tyndall AFB/Panama City	30 04	85 35	18	1413	13	1908	2378	3630
Valkaria	27 57	80 33	15	598	20	1915	2813	4035
Vero Beach	27 40	80 20	13	503	17	2276	3272	4194
West Palm Beach	26 41	80 06	15	299	17	2276	3272	4194
GEORGIA	N	W						
Albany NAS/Turner AFB	31 36	84 05	223	1793	216	1644	1695	3249
Athens MAP	33 57	83 19	802	2975	62	1122	820	2547
Atlanta Army Depot	33 37	84 19	950	3095	52	1109	703	2454
Atlanta/Hartsfield IAP	33 39	84 26	1010	3095	52	1109	703	2454
Atlanta NAS/Dobbins AFB	33 55	84 31	1068	3273	64	1129	732	2430
Augusta/Bush Field	33 22	81 58	136	2547	169	1422	1403	2889
Augusta/Daniel Field	33 28	82 03	424	2547	169	1422	1403	2889
Columbus Metro Aprt	32 31	84 56	385	2378	140	1736	1472	3040
Dobbins AFB/Marietta	33 55	84 31	1068	3273	64	1129	732	2430
Fort Benning/Lawson AAF	32 21	85 00	232	2406	76	1296	1154	2843
Fort Gordon	33 26	82 11	465	2547	169	1422	1403	2889
Fort McPherson/Atlanta	33 42	84 26	1053	3095	52	1109	703	2454
Fort Stewart/Wright AAF	31 52	81 37	88	1713	83	1352	1772	3283
Glynco NAS/Brunswick	31 15	81 29	25	1765	39	1365	2110	3559
Hunter AAF/Savannah	32 01	81 08	42	2029	50	1308	1691	3295
Macon/L B Wilson Aprt ANG	32 42	83 39	354	2240	224	1536	1295	2961
McCollum Aprt ANG/Marietta	34 01	84 36	1030	3273	64	1129	732	2430
McKinnon Aprt ANG/Brunswick	31 08	81 23	20	1331	20	1492	2502	3850
Moody AFB/Valdosta	30 58	83 12	233	1549	133	1544	1895	3448
Moultrie/Spence AF Aux Fld	31 08	83 42	292	1640	157	1627	2143	3479
Robins AFB/Macon	32 38	83 36	294	2244	113	1365	1213	2884
Rome/Russell Field	34 21	85 10	637	3342	78	1086	922	2443
Savannah AFS	32 01	81 10	68	2029	50	1308	1691	3295
Savannah ANG Sta	32 00	81 06	42	2029	50	1308	1691	3295
Savannah MAP ANG	32 08	81 12	50	1952	109	1398	1772	3283
Statesboro Radar Bomb Site	32 29	81 45	180	1952	109	1398	1772	3283
Turner AFB/Albany NAS	31 36	84 05	223	1793	216	1644	1695	3249
HAWAII	N	W						
Barbers Point NAS	21 19	158 05	34	1	0	1562	874	4192
Barking Sands	22 01	159 47	14	0	1	1471	874	4192
Bellows AFB	21 22	157 43	15	0	0	1091	954	4246
Ford Island	21 22	157 58	15	0	0	1540	493	4136
Ft DeRussy	21 17	157 50	5	0	0	1540	493	4136
Ft Ruger	21 16	157 49	300	0	0	1414	493	4136
Ft Shafter	21 21	157 53	80	0	0	1540	493	4136
Helemano	21 32	158 02	1100	106	0	314	352	3835
Hickam AFB/Honolulu IAP	21 20	157 55	13	0	0	1540	493	4136
Hilo	19 43	155 05	36	0	0	728	468	3667
Kaala AFS	21 30	158 08	4000	1709	0	22	1	264
Kaena Point	21 34	158 15	1120	190	0	322	161	2255
Kahului	20 54	156 26	56	0	6	1414	741	3590
Kaneohe Bay MCAS	21 27	157 46	18	0	0	1186	1269	4370
Kokee AFS	22 09	159 38	4185	979	0	88	0	243
Kunia Comm Annex	21 28	158 03	800	8	0	854	352	3835
Lihue	21 59	159 21	148	2	0	1091	954	4246
Palehua AF Solar Obsy	21 23	158 06	1700	170	0	331	41	1493
Pearl Harbor	21 20	157 57	15	0	0	1540	493	4136
Punamano AFS	21 42	157 59	100	0	0	1091	954	4246
Schofield Barracks	21 30	158 02	850	8	0	854	352	3835
South Point AFS	18 56	155 41	310	0	0	615	468	3667
Tripler Army Hospital	21 22	157 54	220	0	0	1540	493	4136

TABLE 4A—Winter heating degree day data for heating and summer criteria data for air conditioning for sites in the United States. (*continued*)

	Location				Summer Criteria Data Air Conditioning			
					Dry Bulb		Wet Bulb	
STATE Station	Lat. °/min	Long. °/min	Elev, feet	Degree Days, heating, annual	≧ 93°F, h	≧ 80°F, h	≧ 73°F, h	≧ 67°F, h
Wahiawa	21 31	158 00	900	10	0	854	352	3835
Wheeler AFB	21 29	158 02	840	8	0	854	352	3835
IDAHO	N	W						
Boise	43 34	116 13	2838	5833	93	728	0	60
Idaho Falls/Fanning Fld	43 31	112 04	4741	7888	6	357	0	7
Lewiston	46 23	117 01	1413	5464	78	631	1	52
Mountain Home AFB	43 02	115 54	2996	5732	185	889	1	20
Pocatello	42 55	112 36	4454	7063	48	609	0	4
Saylor Creek	42 40	115 35	4000	6353	168	807	0	10
Twin Falls	42 29	114 29	4150	6731	133	682	0	10
Wilder	43 40	116 58	2449	5709	94	685	0	60
ILLINOIS	N	W						
Chanute AFB	40 18	88 08	753	5966	45	764	421	1386
Chicago/Midway Aprt	41 47	87 45	607	6127	46	700	275	1111
Chicago/O'Hare IAP	41 59	87 54	658	6497	18	549	265	1028
Danville/Vermilion Co	40 12	87 36	695	5538	36	714	421	1386
Decatur	39 50	88 52	679	5344	46	793	421	1386
Forest Park NOP	41 53	87 50	650	6127	46	700	275	1111
Fort Sheridan/Haley AAF	42 13	87 49	690	6068	18	549	290	1064
Galesburg MAP	40 56	90 26	764	6005	41	714	394	1306
Glenview NAS	42 05	87 49	659	6582	21	543	290	1064
Granite City Army Depot	38 41	90 11	415	4486	119	1223	645	1802
Great Lakes NTC	42 18	87 50	650	6068	18	549	290	1064
Joliet MAP	41 31	88 10	582	6180	35	632	335	1131
Moline/Quad City Aprt	41 27	90 31	582	6395	41	714	394	1306
Peoria	40 40	89 41	652	6098	13	669	384	1349
Quincy MAP	39 57	91 12	769	5267	75	829	608	1607
Rock Island Arsenal	41 31	90 33	575	5961	20	867	394	1306
Savanna Army Depot	42 11	90 15	640	6694	8	457	323	1181
Scott AFB/Belleville	38 33	89 51	453	4855	50	941	619	1764
Springfield/Capital	39 50	89 40	588	5558	60	904	539	1579
INDIANA	N	W						
Anderson MAP	40 06	85 37	919	5580	73	786	580	1687
Bakalar AFB/Columbus	39 16	85 54	651	5132	65	872	580	1687
Bloomington/Monroe County	39 08	86 37	847	4905	59	879	580	1687
Camp Atterbury	39 22	86 03	757	5132	65	872	580	1687
Crane	38 49	86 52	734	4637	62	925	580	1687
Evansville/Dress Rgnl Aprt	38 03	87 32	381	4624	86	1084	777	1942
Fort Benjamin Harrison	39 51	86 00	864	5577	24	682	400	1437
Fort Wayne/Baer Fld	41 00	85 12	791	6209	24	618	245	1120
Gary MAP	41 37	87 25	591	6165	18	519	234	1031
Grissom AFB/Bunker Hill	40 39	86 09	813	6278	12	563	261	1117
Indiana AAP	38 25	85 39	600	4640	80	1022	668	1886
Indianapolis/Weir Cook MAP	39 44	86 17	792	5577	24	682	400	1437
Jefferson Proving Ground	38 50	85 25	860	5132	90	932	668	1886
Newport AAP	39 52	87 26	640	5346	59	619	529	1576
South Bend/St Joseph Aprt	41 42	86 19	773	6462	15	534	234	1031
Terre Haute/Hulman Fld	39 27	87 18	585	5351	55	862	529	1576
IOWA	N	W						
Burlington MAP	40 47	91 07	692	6149	42	708	423	1370
Cedar Rapids MAP	41 53	91 42	863	6601	17	532	364	1248
Des Moines MAP	41 32	93 39	938	6710	43	691	400	1283
Dubuque MAP	42 24	90 42	1056	7277	11	605	252	1055
Fort Dodge MAP	42 33	94 11	1162	7072	16	524	233	891
Iowa Army Ammunition Plant	40 49	91 15	730	6149	42	708	423	1370
Iowa City MAP	41 38	91 33	661	6404	17	612	400	1251
Mason City MAP	43 09	93 20	1213	7901	11	444	233	891
Sioux City MAP	42 24	96 23	1095	6953	61	746	365	1188
Waterloo MAP	42 33	92 24	868	7415	18	580	364	1248

TABLE 4A—Winter heating degree day data for heating and summer criteria data for air conditioning for sites in the United States. ***(continued)***

	Location				Summer Criteria Data Air Conditioning			
					Dry Bulb		Wet Bulb	
STATE Station	Lat, °/min	Long, °/min	Elev, feet	Degree Days, heating, annual	≧ 93°F, h	≧ 80°F, h	≧ 73°F, h	≧ 67°F, h
KANSAS	N	W						
Chanute	37 40	95 29	981	4566	210	1234	746	2069
Dodge City	37 46	99 58	2582	5046	239	1144	72	1081
Forbes ANGB/Topeka	38 57	95 40	1064	5309	85	909	588	1674
Fort Leavenworth/Sherman AAF	39 22	94 55	770	4822	93	990	678	1749
Fort Riley/Marshall AAF	39 03	96 46	1065	5306	144	1094	510	1641
Goodland/Renner Fld	39 22	101 42	3654	6119	176	893	6	369
Hutchinson MAP	38 04	97 52	1542	4671	311	1301	412	1758
Kansas City/Fairfax MAP	39 09	94 36	745	4846	164	1278	654	1828
Kansas Ordnance Plant	37 20	95 13	925	4005	210	1234	746	2069
McConnell AFB/Wichita	37 38	97 16	1371	4695	168	1141	505	1840
Olathe NAS	38 50	94 53	1076	4483	110	1069	557	1711
Parsons/Tri City	37 20	95 31	899	4158	210	1234	746	2069
Salina MAP	38 48	97 39	1272	4992	311	1367	606	1873
Schilling Manor	38 48	97 39	1272	4992	311	1367	606	1873
Smoky Hill AF Range	38 42	97 50	1440	4841	311	1301	606	1873
Sunflower Ordnance Works	38 56	95 00	925	5030	137	1174	557	1711
Topeka/Philip Billard	39 04	95 38	877	5243	157	1100	668	1825
Wichita	37 39	97 25	1321	4687	270	1332	543	2005
KENTUCKY	N	W						
Ashland	38 33	82 44	546	4555	47	797	470	1671
Blue Grass Army Depot	37 41	84 14	1035	4729	37	822	401	1641
Covington	39 03	84 40	869	5070	24	748	316	1423
Fort Campbell/Campbell AAF	36 40	87 29	571	4290	56	998	664	1975
Fort Knox/Godman AAF	37 54	85 58	753	4616	20	847	543	1740
Lexington/Blue Grass Field	38 02	84 36	966	4729	37	822	401	1641
Louisville/Standiford Field	38 11	85 44	477	4640	80	1022	668	1886
Owensboro	37 45	87 10	407	4220	113	1106	777	1942
Richmond	37 40	84 15	1043	4729	37	822	401	1641
LOUISIANA	N	W						
Alexandria/Esler Field	31 24	92 18	92	2200	133	1599	1797	3264
Barksdale AFB/Shreveport	32 30	93 40	167	2337	156	1518	1558	2996
Baton Rouge/Ryan Aprt	30 32	91 09	64	1670	116	1667	2150	3482
Claibourne	31 07	92 35	200	1964	133	1599	1797	3264
England AFB/Alexandria	31 20	92 33	89	1964	133	1599	1797	3264
Fort Polk/Polk AAF	31 03	93 11	330	1889	133	1599	1797	3264
Hammond ANG Comm Sta	30 31	90 24	40	1591	116	1667	2150	3482
Lafayette	30 12	92 00	42	1551	142	1678	2476	3577
Lake Charles AFS	30 10	93 10	15	1498	92	1766	2475	3589
Lake Charles MAP	30 07	93 13	9	1498	92	1766	2475	3589
Louisiana Ordnance Plant	32 34	93 34	195	2337	156	1518	1558	2996
Monroe MAP	32 31	92 02	79	2311	244	1774	1853	3194
New Orleans Army Terminal	29 58	90 02	5	1465	44	1727	2572	3670
New Orleans/Moisant IAP	29 59	90 15	4	1465	44	1727	2572	3670
New Orleans NAS	29 50	90 01	3	1617	33	1639	2479	3618
Shreveport	32 28	93 49	254	2167	244	1774	1853	3194
MAINE	N	W						
Augusta	44 19	69 48	353	7826	5	246	63	442
Bangor IAP/Dow AFB	44 48	68 50	192	8034	2	181	34	321
Bar Harbor	44 27	68 22	84	7240	1	170	34	321
Brunswick NAS	43 54	69 56	75	7552	1	121	20	289
Bucks Harbor AFS	44 38	67 24	221	8056	1	171	34	321
Caribou MAP	46 52	68 01	624	9632	0	103	13	195
Caswell AFS	46 58	67 50	843	9500	0	85	9	155
Charleston AFS	45 05	69 05	930	9008	2	138	23	280
Loring AFB	46 57	67 53	746	9500	0	85	9	155
Millinocket	45 39	68 42	413	8533	5	188	23	279
Portland	43 39	70 19	43	7498	3	206	68	458
Searsport	44 27	68 55	7	7467	2	181	34	321
Winter Harbor	44 20	68 04	11	7240	1	170	34	321

TABLE 4A—Winter heating degree day data for heating and summer criteria data for air conditioning for sites in the United States. (*continued*)

STATE Station	Location			Degree Days, heating, annual	Summer Criteria Data Air Conditioning			
					Dry Bulb		Wet Bulb	
	Lat, °/min	Long, °/min	Elev, feet		≧ 93°F, h	≧ 80°F, h	≧ 73°F, h	≧ 67°F, h
MARYLAND	N	W						
Aberdeen PG/Phillips AAF	39 28	76 10	57	5184	42	713	601	1630
Andrews AFB	38 49	76 52	279	4551	16	729	445	1573
Annapolis USNA	38 59	76 29	40	4548	13	742	879	1990
Bainbridge NTC	39 37	76 04	50	5184	42	713	601	1630
Baltimore/Martin Aprt	39 20	76 25	24	4866	27	727	740	1810
Baltimore/Washington IAP	39 11	76 40	148	4729	43	790	533	1613
Bethesda NAVNATMEDCEN	39 00	77 06	310	4645	47	726	445	1573
Bethesda NSRDC	38 59	77 12	130	4290	41	809	580	1744
Cumberland MAP	39 37	78 46	790	5012	20	596	314	1254
Edgewood Arsenal	39 24	76 18	22	4866	28	713	700	1761
Fort Detrick	39 26	77 26	355	5059	35	647	472	1492
Fort Holabird	39 16	76 32	32	4101	23	813	800	1892
Fort Meade/Tipton AAF	39 05	76 46	150	4733	22	767	398	1393
Fort Richie	39 40	77 28	1320	5897	16	416	221	1078
Frederick	39 27	77 25	313	5059	41	693	469	1466
Hagerstown	39 42	77 44	704	5152	44	702	384	1383
Indian Head NOS	38 36	77 10	15	4498	37	892	710	1884
Patuxent River NAS	38 17	76 26	38	4307	20	772	682	1850
White Oak NAVSURFWPNCEN	39 02	76 59	200	4483	27	670	445	1573
MASSACHUSETTS	N	W						
Army Mat/Mech Res Cen	42 21	71 10	40	5621	16	394	125	762
Boston/Logan IAP	42 22	71 02	15	5621	16	394	125	762
Boston Navy Base	42 21	71 03	15	5621	16	394	125	762
Fall River	41 43	71 08	190	5774	5	230	90	780
Fort Devens/Devens AAF	42 34	71 36	268	6475	26	466	154	770
Hanscom AFB/Bedford	42 28	71 17	133	6474	10	394	154	770
Lawrence MAP	42 43	71 07	147	6195	15	358	154	770
Lynn	42 28	70 55	50	5621	16	394	125	762
Maynard	42 25	71 29	205	6539	10	394	165	803
Nantucket	41 15	70 10	12	5929	0	28	35	697
Natick Laboratories	42 17	71 22	160	6144	35	539	154	770
New Bedford MAP	41 41	70 58	79	5395	1	173	90	780
North Truro AFS	42 02	70 04	160	5393	1	142	90	780
Otis AFB/Falmouth	41 39	70 31	132	6132	1	137	90	780
Pittsfield MAP	42 26	73 18	1194	7580	1	185	38	451
Quincy	42 14	71 00	20	5621	16	394	125	762
Salem	42 32	70 52	40	5975	4	152	125	762
South Weymouth NAS	42 09	70 57	156	6332	9	433	177	840
Springfield	42 06	72 35	195	5844	23	500	123	743
Wellesly ANG Station	42 19	71 14	65	6144	35	539	154	770
Westfield/Barnes MAP	42 10	72 43	270	6794	9	402	123	743
Westover AFB	42 12	72 32	245	6794	9	402	123	743
Worcester	42 16	71 52	986	6848	2	212	40	476
MICHIGAN	N	W						
Alpena/Phelps Collins Field	45 04	83 34	689	8518	5	321	47	450
Ann Arbor	42 17	83 45	926	6306	19	522	147	843
Battle Creek Aprt	42 19	85 15	941	6720	21	477	168	833
Bayshore	45 21	85 06	678	7669	4	221	80	548
Benton Harbor/Ross Field	42 08	86 26	643	6296	14	465	142	800
Calumet AFS	47 22	88 10	1520	9700	0	62	20	173
Detroit Arsenal	42 30	83 02	618	6228	16	504	167	896
Detroit/City Aprt	42 25	83 01	619	6228	16	504	167	896
Empire AFS	44 48	86 03	1000	7617	1	156	80	548
Flint/Bishop Aprt	42 58	83 44	771	7041	9	407	137	763
Grand Rapids/Kent County	42 53	85 31	784	6801	12	467	142	800
Hancock/Houghton Co Mem	47 10	88 29	1091	9499	0	104	29	237
Houghton	47 10	88 30	1082	9499	0	104	29	237
Kincheloe AFB	46 15	84 28	799	9234	0	107	21	235
K I Sawyer AFB	46 21	87 24	1220	9498	3	151	25	250
Lansing/Capital City Aprt	42 47	84 36	841	6904	7	409	123	738
Michigan Army Missile Plant	42 34	83 01	615	6228	16	504	167	896

TABLE 4A—Winter heating degree day data for heating and summer criteria data for air conditioning for sites in the United States. (*continued*)

STATE Station	Location			Degree Days, heating, annual	Summer Criteria Data Air Conditioning			
					Dry Bulb		Wet Bulb	
	Lat, °/min	Long, °/min	Elev, feet		≧ 93°F, h	≧ 80°F, h	≧ 73°F, h	≧ 67°F, h
Mount Clemens NAF	42 36	82 50	583	6665	5	387	168	869
Muskegon/Muskegon Co Aprt	43 10	86 14	625	6890	2	262	105	712
Port Austin AFS	44 02	83 00	670	7638	4	240	65	465
Port Huron	42 59	82 25	586	6564	11	348	168	869
Saginaw/Tri City Aprt	43 32	84 05	667	7143	15	365	131	642
Sault Sainte Marie AFS	46 28	84 22	721	9193	0	96	25	243
Selfridge ANGB/Mt Clemens	42 36	82 50	583	6665	5	387	168	869
Traverse City Aprt	44 45	85 35	624	7698	10	305	80	548
Wurtsmith AFB/Oscoda	44 27	83 24	634	7929	6	227	65	465
Ypsilanti	42 14	83 32	716	6424	19	522	147	843
MINNESOTA	N	W						
Baudette AFS	48 40	94 37	1100	10098	1	153	16	226
Bemidji MAP	47 31	94 56	1389	10203	6	213	43	314
Duluth IAP	46 50	92 11	1428	9757	0	131	23	226
Finland AFS	47 27	91 14	1950	10407	0	76	13	177
International Falls IAP	48 34	93 23	1179	10547	2	168	16	226
Minneapolis-St Paul IAP	44 53	93 13	834	8310	19	475	178	772
Rochester MAP	43 55	92 30	1297	8227	11	389	168	749
Twin Cities Ordnance Plant	45 05	93 10	970	8310	19	475	178	772
MISSISSIPPI	N	W						
Biloxi use Keesler AFB								
Columbus AFB	33 39	88 27	219	2890	102	1333	1288	2825
Gulfport	30 22	89 06	33	1496	56	2096	2574	3644
Jackson/Allen Thompson Fld	32 19	90 05	310	2300	185	1576	1561	3091
Keesler AFB/Biloxi	30 25	88 55	26	1549	56	2096	2574	3644
Meridian/Key Field ANG	32 20	88 45	290	2388	188	1568	1120	2649
Meridian NAS/McCain Field	32 33	88 34	317	2712	105	1331	1120	2649
MISSOURI	N	W						
Columbia Regional Aprt	38 58	92 22	778	5078	105	1008	547	1723
Ft Leonard Wood/Forney AAF	37 45	92 09	1158	4707	45	825	474	1640
Gateway AAP	38 42	90 16	500	4557	103	1123	645	1802
Hannibal	39 43	91 22	712	5512	75	829	608	1607
Jefferson Barracks ANG	38 30	90 17	770	4486	119	1223	645	1802
Joplin MAP	37 09	94 30	980	4188	214	1171	699	2058
Kansas City MAP	39 07	94 35	791	4711	164	1278	654	1828
Lake City Arsenal	39 06	94 15	810	5218	37	796	490	1588
Malden MAP	36 36	89 59	295	3908	120	1375	1054	2310
Richards-Gebaur AFB/Grandview	38 51	94 33	1090	5218	37	796	490	1588
St Joseph/Rosecrans Aprt	39 46	94 55	825	5440	93	990	678	1749
St Louis AFS	38 45	90 22	570	4750	103	1123	645	1802
St Louis/Lambert IAP	38 45	90 23	535	4750	103	1123	645	1802
St Louis Ordnance Depot	38 41	90 16	580	4486	119	1223	645	1802
Springfield MAP	37 14	93 23	1268	4570	92	975	566	1888
Whiteman AFB/Knob Noster	38 43	93 33	869	5012	58	913	601	1738
MONTANA	N	W						
Billings/Logan IAP	45 48	108 32	3567	7265	50	537	1	42
Butte	45 57	112 30	5553	9719	1	177	0	0
Cut Bank	48 37	112 22	3838	9033	6	219	0	7
Dillon	45 15	112 33	5224	8354	7	310	0	4
Glasgow AFB	48 25	106 32	2760	9251	23	370	1	51
Great Falls IAP	47 29	111 22	3662	7652	18	364	0	6
Havre AFS	48 52	109 56	3200	9058	32	351	0	18
Helena	46 36	112 00	3828	8190	15	326	0	4
Kalispell AFS	48 01	114 22	6780	11024	0	205	0	0
Lewistown	47 04	109 27	4122	8586	10	288	0	13
Malmstrom AFB	47 30	111 11	3525	7671	26	403	0	3
Miles City	46 26	105 52	2634	7889	123	691	6	154
Missoula	46 55	114 05	3190	7931	20	346	0	8
Opheim AFS	48 52	106 28	3290	9251	21	278	0	32

TABLE 4A—Winter heating degree day data for heating and summer criteria data for air conditioning for sites in the United States. (*continued*)

STATE Station	Location			Degree Days, heating, annual	Summer Criteria Data Air Conditioning			
					Dry Bulb		Wet Bulb	
	Lat, °/min	Long, °/min	Elev, feet		≧ 93°F, h	≧ 80°F, h	≧ 73°F, h	≧ 67°F, h
NEBRASKA	N	W						
Cornhusker AAP	40 55	98 29	1915	6420	113	818	193	1037
Grand Island	40 58	98 19	1841	6420	113	818	193	1037
Hastings MAP	40 36	98 26	1954	6070	113	818	193	1037
Lincoln MAP	40 51	96 45	1180	6218	143	991	508	1548
North Platte/Lee Bird Fld	41 08	100 41	2775	6743	94	733	58	704
Offutt AFB	41 07	95 55	1048	6213	42	732	381	1292
Omaha/Eppley Airfield	41 18	95 54	977	6049	42	732	381	1292
Scottsbluff	41 52	103 36	3958	6774	69	673	1	176
NEVADA	N	W						
Bald Mountain	37 32	115 45	7200	8264	0	146	0	0
Beatty	37 05	116 49	4959	5383	82	594	0	29
Carson City	39 10	119 46	4675	5753	59	644	0	1
Cherry Creek	39 55	114 55	8250	8864	0	28	0	0
Desert Rock Camp	36 37	116 01	3315	3978	556	1991	2	185
Egan Range	38 41	115 02	5800	7614	10	586	0	0
Elko MAP	40 50	115 47	5050	7483	55	687	0	1
Ely	39 17	114 51	6253	7814	2	464	0	0
Fallon AFS	39 24	118 43	4053	5229	181	1006	0	20
Fallon NAS/Van Voorhis Fld	39 25	118 42	3934	5229	181	1006	0	20
Goshute	40 14	114 14	7053	8264	0	190	0	0
Hawthorne NAD	38 32	118 40	4186	5508	132	878	0	9
Indian Springs AF Aux Fld	36 35	115 40	3123	3778	659	2152	7	293
Las Vegas/McCarran IAP	36 05	115 10	2162	2601	943	2427	7	425
Nellis AFB/Las Vegas	36 15	115 02	1868	2377	1063	2516	29	672
Reno IAP	39 30	119 47	4404	6022	67	704	0	3
Stead AFB/Reno	39 40	119 52	5023	6398	15	542	0	0
Tonopah AFS	38 03	117 14	7100	6650	0	372	0	0
Tonopah MAP	38 04	117 05	5426	5900	62	865	0	4
Winnemucca AFS	41 00	117 46	6750	8100	0	299	0	0
Winnemucca MAP	40 54	117 48	4301	6629	128	771	0	2
Worthington Mountain	37 58	115 30	6093	7614	4	542	0	0
NEW HAMPSHIRE	N	W						
Concord MAP	43 12	71 30	342	7360	14	388	85	597
Grenier Fld/Manchester	42 56	71 26	233	7101	15	538	127	764
Hanover	43 40	72 16	800	7680	9	312	76	501
Manchester use Grenier	43 00	71 28	170					
NH Satellite Tracking	42 56	71 38	700	7831	5	249	41	483
Pease AFB/Portsmouth	43 04	70 49	101	6846	6	295	114	609
Portsmouth	43 05	70 44	100	6846	3	220	114	609
NEW JERSEY	N	W						
Atlantic City	39 27	74 34	64	4946	19	508	491	1543
Bayonne NSC	40 40	74 05	10	5034	42	663	337	1259
Burlington Ordnance Plant	40 05	74 52	10	4699	14	600	373	1306
Camden	39 55	75 04	20	4865	31	687	417	1424
Clifton	40 52	74 10	175	5231	42	663	337	1259
Coyle ANG	39 48	74 26	175	5139	14	600	373	1306
Dover	40 55	74 35	570	6245	23	508	309	1060
Earle NAD	40 20	74 03	100	5128	16	430	398	1398
Elizabeth	40 40	74 14	33	5017	42	663	337	1259
Fort Dix	40 01	74 38	172	5139	14	600	373	1306
Fort Hancock	40 28	74 00	19	4737	12	388	275	1222
Fort Monmouth	40 19	74 02	15	5128	16	430	398	1398
Gibbsboro AFS	39 50	74 58	200	5121	14	600	373	1306
Jersey City	40 44	74 03	135	5238	42	663	337	1259
Lakehurst NAS	40 02	74 21	103	5377	17	586	344	1313
McGuire AFB	40 01	74 36	133	5139	14	600	373	1306
Newark IAP	40 42	74 10	7	5034	42	663	337	1259
Perth Amboy	40 31	74 17	20	5034	42	663	337	1259
Picatinny Arsenal	40 56	74 34	706	6304	23	508	309	1060
Trenton	40 13	74 46	56	4947	14	526	373	1306

TABLE 4A—Winter heating degree day data for heating and summer criteria data for air conditioning for sites in the United States. (*continued*)

STATE Station	Location			Degree Days, heating, annual	Summer Criteria Data Air Conditioning			
					Dry Bulb		Wet Bulb	
	Lat, °/min	Long, °/min	Elev, feet		≧ 93°F, h	≧ 80°F, h	≧ 73°F, h	≧ 67°F, h
NEW MEXICO	N	W						
Albuquerque IAP/Kirtland AFB	35 03	106 37	5311	4337	119	1118	0	11
Cannon AFB/Clovis	34 23	103 19	4283	4046	84	982	2	235
Carlsbad	32 20	104 16	3293	2835	414	1864	19	878
Cloudcroft	32 57	105 44	9060	7619	0	126	0	0
Farmington MAP	36 44	108 14	5503	5713	81	943	0	30
Holloman AFB/Alamogordo	32 51	106 06	4093	3223	227	1473	2	176
Kirtland AFB/Albuquerque IAP	35 03	106 37	5311	4337	119	1118	0	11
Las Cruces	32 18	106 55	4544	3194	215	1157	10	198
Melrose Range	34 14	103 48	4500	3976	62	893	2	235
Roswell	33 18	104 32	3649	3697	350	1560	5	583
Sacramento Peak	32 47	105 49	9240	7968	0	59	0	0
Truth or Consequences	33 14	107 16	4858	3392	185	1374	0	65
Tucumcari	35 11	103 36	4039	4047	248	1232	1	418
Walker AFB/Roswell	33 18	104 32	3676	3697	350	1560	5	583
White Sands Missile Range	32 23	106 29	4330	2526	278	1781	10	198
Wingate Army Depot	35 31	108 35	6680	5915	4	512	0	1
Zuni	35 06	108 47	6440	5815	8	616	0	1
NEW YORK	N	W						
Albany	42 45	73 48	275	6888	16	417	132	775
Army Procurement Center	40 45	74 00	40	4909	25	602	309	1243
Binghampton/Broome Co Aprt	42 13	75 59	1590	7285	2	205	41	518
Brooklyn Navy Shipyard	40 42	73 58	15	4909	25	602	309	1243
Buffalo IAP	42 56	78 44	705	6927	2	346	92	731
Camp Drum	44 02	75 46	655	7601	2	168	77	552
Dunkirk MAP	42 29	79 16	692	6851	2	317	141	814
Fort Hamilton	40 36	74 02	21	5184	8	383	275	1222
Fort Tilden	40 34	73 54	10	5184	8	383	275	1222
Fort Totten	40 48	73 47	35	4812	25	602	309	1243
Fort Wadsworth	40 36	74 03	135	5184	8	383	275	1222
Freeport	40 38	73 35	15	5184	8	383	275	1222
Glen Falls/Warren Co Aprt	43 20	73 37	328	7270	6	277	80	591
Griffiss AFB/Rome	43 14	75 25	514	7331	3	306	84	611
Huntington	40 52	73 24	100	5084	21	476	331	1284
Ithaca/Tompkins Co Aprt	42 29	76 28	1099	7052	5	252	73	625
Jamestown/Chautauqua Co	42 09	79 15	1723	6849	1	305	50	627
Liverpool	43 07	76 13	400	6678	8	412	107	745
Lockport AFS	43 08	78 50	638	6724	4	350	162	814
Montauk AFS	41 04	71 52	110	5771	0	52	93	873
New Rochelle	40 50	73 47	70	5161	25	602	309	1243
New York/JFK IAP	40 39	73 47	13	5184	8	383	275	1222
New York/La Guardia Aprt	40 46	73 54	11	4909	25	602	309	1243
New York NB	40 45	74 00	40	4909	25	602	309	1243
Newburgh/Stewart Aprt	41 30	74 06	471	6336	14	460	175	886
Niagara Falls IAP	43 06	78 57	590	6688	4	350	162	814
Ogdensburg	44 41	75 28	297	7777	2	266	89	550
Oswego	43 28	76 33	300	6792	1	141	100	665
Plattsburg AFB	44 39	73 28	235	8044	3	171	43	432
Poughkeepsie/Dutchess Co	41 38	73 53	165	5824	26	490	249	1035
Rochester/Monroe Co Aprt	43 07	77 40	547	6719	15	414	112	738
Roslyn	40 47	73 36	100	5084	21	476	331	1284
Saint Albans NAVHOSP	40 41	73 46	50	5184	8	383	275	1222
Saratoga AFS	43 01	73 41	617	7180	18	470	88	662
Schenectady	42 51	73 56	378	6817	12	368	132	775
Seneca Army Depot	42 45	76 50	750	6359	20	463	107	745
Suffolk Co/Westhampton Bch	40 51	72 38	67	5951	2	174	172	991
Syracuse/Hancock IAP	43 07	76 07	410	6772	8	412	107	745
Troy	42 46	73 39	330	6888	16	417	132	775
Utica/Oneida Co Aprt	43 09	75 23	742	7299	7	251	87	604
Watertown IAP	43 59	76 01	325	7376	1	222	100	665
Watervliet Arsenal	42 43	73 42	35	6393	17	387	132	775

TABLE 4A—Winter heating degree day data for heating and summer criteria data for air conditioning for sites in the United States. (*continued*)

	Location				Summer Criteria Data Air Conditioning			
					Dry Bulb		Wet Bulb	
STATE Station	Lat, °/min	Long, °/min	Elev, feet	Degree Days, heating, annual	≧ 93°F, h	≧ 80°F, h	≧ 73°F, h	≧ 67°F, h
Westchester Co/White Plains	41 04	73 43	439	5802	13	376	265	1092
West Point USMA	41 23	73 57	160	5753	41	578	249	1035
Whitestone	40 47	73 50	10	4909	25	602	309	1243
Yonkers	40 56	73 53	50	5109	25	602	309	1243
Youngstown	43 14	79 02	300	6688	4	350	162	814
NORTH CAROLINA	N	W						
Asheville MAP	35 26	82 32	2140	4237	6	536	139	1143
Badin ANG	35 22	80 08	455	3218	87	1116	699	2288
Camp Lejeune MCS	34 40	77 21	25	2901	30	1020	1481	2870
Cape Hatteras	35 16	75 33	7	2731	0	832	1521	2771
Charlotte/Douglas MAP	35 13	80 56	736	3218	87	1116	699	2288
Cherry Point MCAS	34 54	76 53	29	2832	23	1055	1342	2760
Dare County	35 45	76 10	15	3207	30	957	1158	2461
Edenton Recovery Site	36 02	76 34	19	3082	30	957	1158	2461
Elizabeth City CGAS/MAP	36 16	76 11	12	3207	30	957	1158	2461
Fort Bragg/Simmons AF	35 08	78 56	242	3105	60	1080	846	2376
Fort Fisher AFS	33 59	77 55	13	2353	2	823	1521	2771
Greensboro	36 05	79 57	897	3825	37	878	488	1944
New River MCAS	34 43	77 26	24	2901	30	1020	1481	2870
Pope AFB/Fayetteville	35 10	79 01	218	3122	65	1131	931	2389
Raleigh/Raleigh-Durham Aprt	35 52	78 47	434	3514	57	977	748	2188
Roanoke Rapids AFS	36 26	77 43	294	3850	96	1066	804	2086
Seymour Johnson AFB	35 20	77 58	109	3124	47	1069	1044	2478
Sunnypoint Mil Ocean Trml	34 00	78 00	25	2353	2	823	1557	2915
Wadesboro ANG	34 57	80 04	455	3058	87	1116	699	2288
Wilmington/New Hanover Co	34 16	77 55	28	2433	42	1149	1557	2915
Winston-Salem	36 08	80 13	969	3679	44	917	417	1897
NORTH DAKOTA	N	W						
Bismarck MAP	46 46	100 45	1647	9044	50	504	45	347
Dickinson MAP	46 48	102 48	2585	8942	40	423	15	207
Fargo/Hector Field	46 54	96 48	896	9271	25	439	115	572
Finley AFS	47 30	97 52	1560	9752	10	296	41	284
Fortuna AFS	48 55	103 53	2380	9573	29	360	9	144
Grand Forks AFB	47 57	97 24	911	9963	15	338	68	389
Minot AFB	48 25	101 21	1668	9625	28	377	22	220
OHIO	N	W						
Akron/Akron-Canton Aprt	40 55	81 26	1208	6224	6	395	112	871
Blue Ash ANGB/Cincinnati	39 16	84 24	846	5070	24	748	316	1423
Camp Perry ANG	41 32	83 01	570	5857	11	438	176	997
Chillicothe	39 21	83 00	640	5075	68	884	272	1318
Cincinnati Aprt/Covington	39 03	84 40	869	5070	24	748	316	1423
Cleveland/Hopkins IAP	41 24	81 51	777	6154	13	488	176	997
Clinton County AFB/Wilmington	39 26	83 48	1065	5073	11	600	252	1288
Columbus IAP	40 00	82 53	812	5702	28	690	282	1301
Dayton MAP	39 54	84 13	1002	5641	16	627	222	1210
Fort Hayes	39 58	82 59	800	5702	28	690	282	1301
Gentile AFS	39 43	84 09	750	5455	12	686	297	1293
Lima/Allen Co Aprt	40 42	84 02	975	5838	44	660	381	1523
Lima Ordnance Mod Center	40 41	84 05	915	5838	44	660	381	1523
Lorain Co Rgnl Aprt	41 21	82 11	794	6094	38	681	176	997
Mansfield/Lahm MAP	40 49	82 31	1295	5818	9	431	183	989
Newark	40 01	82 28	880	5655	56	745	282	1301
Portsmouth	38 45	82 55	540	4547	66	942	470	1671
Ravenna AAP	41 11	81 06	1130	6262	38	563	176	1054
Rickenbacker AFB/Columbus	39 49	82 56	744	5567	11	575	223	1147
Ridgewood AAP	39 15	84 40	670	5070	24	748	316	1423
Springfield MAP	39 50	83 50	1052	5284	12	686	297	1293
Toledo/Toledo Express Aprt	41 36	83 48	669	6381	11	506	197	997
Wright-Patterson AFB/Dayton	39 49	84 03	824	5455	12	686	297	1293
Youngstown MAP	41 16	80 40	1178	6426	4	371	82	729
Zanesville MAP	39 57	81 54	900	5738	28	627	339	1314

TABLE 4A—Winter heating degree day data for heating and summer criteria data for air conditioning for sites in the United States. (*continued*)

	Location				Summer Criteria Data Air Conditioning			
					Dry Bulb		Wet Bulb	
STATE Station	Lat, °/min	Long, °/min	Elev, feet	Degree Days, heating, annual	≧ 93°F, h	≧ 80°F, h	≧ 73°F, h	≧ 67°F, h
OKLAHOMA	N	W						
Altus AFB	34 39	99 16	1378	3346	422	1684	633	2292
Clinton-Sherman AFB	35 20	99 12	1928	3931	243	1339	283	1821
Fort Sill/Post AAF	34 39	98 24	1187	3367	346	1601	797	2412
McAlester NAD	34 50	95 55	776	3255	181	1505	618	2211
Norman	35 15	97 29	1181	3247	193	1331	618	2211
Oklahoma City AFS	35 24	97 22	1262	3588	193	1331	618	2211
Oklahoma City Aprt	35 24	97 36	1285	3695	240	1392	799	2357
Stillwater/Searcy Field	36 10	97 05	984	3631	145	1410	618	2211
Tinker AFB/Oklahoma City	35 25	97 23	1291	3588	193	1331	618	2211
Tulsa IAP	36 12	95 54	650	3680	270	1543	1089	2478
Vance AFB/Enid	36 21	97 55	1307	3971	373	1521	836	2234
OREGON	N	W						
Astoria	46 09	123 53	8	5295	1	16	0	14
Burns	43 35	119 03	4151	7212	19	462	0	1
Corvallis MAP	44 30	123 17	246	4854	27	372	4	100
Eugene	44 07	123 13	359	4739	28	393	4	100
Grants Pass	42 26	123 19	925	4375	160	700	9	255
Keno AFS	42 04	121 58	6400	7687	0	70	0	0
Kingsley Field	42 09	121 44	4092	6987	6	354	0	1
Klamath Falls	42 09	121 44	4092	6987	6	354	0	1
Medford	42 22	122 52	1298	4930	111	673	3	156
MT Hebo AFS	45 13	123 45	3155	6293	0	94	0	3
North Bend AFS	43 32	124 10	748	4688	0	2	0	1
Pendleton	45 41	118 51	1482	5240	88	620	0	28
Portland IAP	45 36	122 36	21	4792	11	210	4	101
Redmond	44 16	121 08	3084	6643	25	404	0	7
Salem/McNary Field	44 55	123 01	196	4852	27	295	4	113
Umatilla Army Depot	45 48	119 25	590	5123	155	849	1	85
PENNSYLVANIA	N	W						
Allentown	40 39	75 26	387	5827	21	523	227	1091
Altoona/Blair Co Aprt	40 18	78 19	1504	6192	8	353	88	763
Benton AFS	41 20	76 17	2389	8257	2	80	20	336
Brookville	41 09	79 06	1422	6870	4	333	87	731
Carlisle Barracks	40 12	77 11	475	5269	61	758	235	1191
Columbia	40 02	76 30	300	5315	40	700	366	1326
Connellsville	39 57	79 39	1258	5305	18	488	258	1221
Erie IAP	42 05	80 11	731	6851	2	317	141	814
Folsom	39 54	75 19	100	4865	31	687	417	1424
Fort Indiantown Gap	40 26	76 34	475	5609	36	627	366	1326
Frankford Arsenal	40 00	75 04	10	4865	31	687	417	1424
Freemansburg	40 37	75 20	225	5597	28	609	227	1091
Harrisburg IAP/Olmsted	40 12	76 46	308	5315	40	700	366	1326
Hazleton MAP	40 59	76 00	1604	6471	7	302	71	720
Johnstown/Cambria Co Aprt	40 19	78 50	2284	7804	0	170	32	515
Lancaster	40 07	76 18	403	5583	36	631	366	1326
Letterkenny Army Depot	40 00	77 39	670	5519	37	674	366	1326
Mechanicsburg	40 13	77 01	400	5224	26	628	235	1191
New Castle	41 01	80 22	825	5800	15	419	198	1065
New Cumberland Chem Plant	40 13	76 50	385	5224	26	628	235	1191
Philadelphia IAP	39 53	75 15	5	4865	31	687	417	1424
Philipsburg	40 53	78 05	1923	7469	1	213	54	578
Pittsburgh IAP	40 30	80 13	1137	5930	5	461	105	886
Reading IAP	40 20	75 58	266	4931	28	629	227	1091
Scranton AAP	41 24	75 40	730	6114	13	431	105	798
State College ANG Station	40 48	77 52	1175	6132	12	390	117	773
Tobyhanna Army Depot	41 11	75 25	1990	6816	3	219	54	578
Valley Forge General Hosp	40 07	75 33	245	5114	74	861	417	1424
Wilkes-Barre-Scranton Aprt	41 20	75 44	930	6277	10	406	105	798
Williamsport	41 15	76 55	524	5981	28	555	180	968
Willow Grove NAS	40 12	75 09	361	5368	30	859	479	1536
Wyoming	41 17	75 51	550	5817	23	583	176	987

TABLE 4A—Winter heating degree day data for heating and summer criteria data for air conditioning for sites in the United States. (*continued*)

	Location			Degree Days, heating, annual	Summer Criteria Data Air Conditioning			
					Dry Bulb		Wet Bulb	
STATE Station	Lat, °/min	Long, °/min	Elev, feet		≧ 93°F, h	≧ 80°F, h	≧ 73°F, h	≧ 67°F, h
RHODE ISLAND	N	W						
Davisville	41 36	71 27	25	5840	5	290	182	909
Newport NB	41 30	71 20	10	5840	5	290	182	909
North Kingston ANG Sta	41 37	71 26	27	5840	5	290	182	909
North Smithfield ANG Sta	41 58	71 35	465	6207	13	330	162	864
Providence/Theo T Green MAP	41 44	71 26	51	5972	6	321	162	864
Quonset Point NAS	41 36	71 25	30	5840	5	290	182	909
SOUTH CAROLINA	N	W						
Aiken AFS	33 39	81 41	525	2348	89	1203	1186	2766
Beaufort MCAS	32 29	80 43	38	2126	53	1378	1934	3326
Charleston AFB/MAP	32 54	80 02	45	2146	49	1252	1716	3161
Charleston Army Depot	32 54	79 58	3	2146	49	1252	1716	3161
Columbia	33 57	81 07	213	2598	165	1416	1186	2766
Donaldson AFB/Greenville	34 46	82 23	978	3089	78	1094	618	2259
Florence MAP	34 11	79 43	147	2566	70	1210	1272	2738
Fort Jackson	34 01	80 56	250	2598	165	1416	1186	2766
Georgetown	33 23	79 17	14	2228	33	1206	1649	3075
Greenville-Spartanburg Aprt	34 54	82 13	957	3163	37	1035	661	2301
McEntire ANGB/Columbia	33 55	80 48	237	2828	72	1086	806	2381
Myrtle Beach AFB	33 41	78 56	25	2696	18	1160	1582	2989
North Charleston AFS	32 53	80 01	41	2146	49	1252	1716	3161
North Field	33 37	81 05	290	2598	165	1416	1186	2766
Parris Island MARCORPCRUITDEP	32 21	80 41	33	2126	53	1378	1934	3326
Pointsett	33 49	80 28	200	2453	75	1262	1131	2727
Shaw AFB/Sumter	33 58	80 28	252	2453	75	1262	1131	2727
Sumter	33 54	80 22	169	2482	75	1262	1131	2727
SOUTH DAKOTA	N	W						
Aberdeen MAP	45 27	98 26	1296	8617	47	562	202	837
Ellsworth AFB/Rapid City	44 08	103 06	3276	7049	60	571	10	218
Huron	44 23	98 13	1281	8055	82	656	202	837
Pierre MAP	44 23	100 17	1742	7677	124	757	115	665
Rapid City	44 03	103 04	3162	7324	89	630	11	233
Sioux Falls/Foss Fld	43 34	96 44	1418	7838	48	599	170	796
TENNESSEE	N	W						
Alcoa ANG Sta use Knoxville								
Arnold Eng Dev Cen	35 23	86 05	1067	3883	7	750	420	1721
Bristol/Tri City Aprt	36 29	82 24	1507	4306	16	851	253	1606
Chattanooga/Lovell Field	35 02	85 12	665	3505	99	1158	790	2401
Holston Ordnance Works	36 31	82 40	1200	3695	35	908	384	1943
Kingsport	36 31	82 30	1284	3695	35	908	384	1943
Knoxville/Alcoa ANG Sta	35 49	83 59	980	3478	52	1053	520	2150
Memphis Army Depot	35 05	89 59	295	3227	166	1487	1327	2664
Memphis IAP	35 03	90 00	258	3227	166	1487	1327	2664
Memphis NAS/Millington	35 20	89 53	322	3445	73	1355	1222	2599
Milan Ordnance Plant	35 54	88 42	490	3685	170	1370	1220	2513
Nashville	36 07	86 41	590	3696	104	1221	875	2328
Sewart AFB/Smyrna Aprt	36 00	86 32	543	3949	72	1098	711	2103
Tullahoma Aprt	35 22	86 12	1072	3577	94	1056	420	1721
Tullahoma/Arnold AFS	35 23	86 05	1067	3883	7	750	420	1721
Volunteer Ordnance Works	35 05	85 08	750	3505	99	1158	790	2401
TEXAS	N	W						
Abilene MAP	32 25	99 41	1784	2610	433	1922	340	2403
Aero Maintenance Center	27 46	97 26	40	930	134	2507	3238	3989
Amarillo	35 14	101 42	3604	4183	180	1181	9	739
Austin/Robert Mueller MAP	30 18	97 42	597	1737	430	2041	1959	3400
Beaumont/Jefferson Co	29 57	94 01	16	1518	88	1863	2787	3708
Beaumont Army Hospital	31 49	106 28	4185	2678	370	1917	0	376
Beeville/Chase Field NAS	28 22	97 40	190	1189	301	2144	2776	3786
Bergstrom AFB/Austin	30 12	97 40	541	1712	363	1966	1844	3384
Brooke Army Medical Center	29 28	98 27	785	1570	397	2049	1699	3426
Brooks AFB	29 21	98 27	598	1272	460	2189	2185	3551

TABLE 4A—Winter heating degree day data for heating and summer criteria data for air conditioning for sites in the United States. (*continued*)

	Location				Summer Criteria Data Air Conditioning			
					Dry Bulb		Wet Bulb	
STATE Station	Lat, °/min	Long, °/min	Elev, feet	Degree Days, heating, annual	≧ 93°F, h	≧ 80°F, h	≧ 73°F, h	≧ 67°F, h
Brownsville IAP	25 54	97 26	19	650	103	2456	3391	4090
Brownwood	31 48	98 57	1386	2437	297	1922	1045	3043
Camp Bullis	29 41	98 45	1400	1952	220	1626	1481	3348
Carswell AFB/Fort Worth	32 47	97 26	650	2301	415	1969	1182	2928
Corpus Christi IAP	27 46	97 30	41	930	134	2507	3238	3989
Corpus Christi NAS	27 42	97 17	19	899	15	2845	3329	4036
Dallas/Love Field	32 51	96 51	481	2290	474	2208	1675	3103
Dallas NAS/Hensley Field	32 44	96 58	495	2308	497	2229	1764	3092
Del Rio IAP	29 22	100 55	1026	1523	509	2349	1260	3367
Dyess AFB/Abilene	32 25	99 51	1789	2682	342	1700	209	2089
Eagle Pass AFS	28 52	100 32	884	1423	605	2517	1426	3515
Ellington AFB/Houston	29 37	95 10	40	1384	114	1763	2373	3616
El Paso IAP	31 48	106 24	3918	2678	370	1917	0	376
Fort Bliss/Biggs AAF	31 51	106 23	3947	2432	325	1813	5	373
Fort Hood/Hood AAF	31 09	97 43	923	1959	295	1791	1045	3043
Fort Hood/Robert Gray AAF	31 04	97 50	1015	1959	295	1791	1045	3043
Fort Sam Houston	29 27	98 26	760	1570	397	2049	1699	3426
Fort Wolters	32 50	98 04	900	2432	489	1921	1136	2880
Fort Worth IAP	32 50	97 03	537	2382	469	2095	1415	3087
Galveston	29 18	94 48	7	1224	4	2603	2998	3932
Garland ANG Station	32 54	96 39	558	2290	474	2208	1675	3103
Goodfellow AFB/San Angelo	31 26	100 24	1877	2240	465	1978	245	2424
Harlingen	26 14	97 39	35	693	223	2442	3294	4059
Hondo MAP	29 21	99 11	901	1596	480	2159	1703	3374
Houston IAP	29 58	95 21	96	1434	132	1888	2694	3695
Kelly AFB/San Antonio	29 23	98 35	690	1520	352	1920	1774	3444
Kingsville NAS	27 29	97 49	50	970	258	2422	3154	3935
Lackland AFB	29 23	98 37	670	1520	352	1920	1774	3444
La Porte ANG Station	29 40	95 04	24	1284	66	1568	2347	3782
Laredo AFB	27 32	99 27	512	986	756	2653	2347	3782
Laredo IAP	27 37	99 31	539	986	756	2653	2347	3782
Laughlin AFB	29 22	100 47	1081	1542	509	2349	1260	3367
Lone Star Ordnance Plant	33 27	94 14	360	2531	198	1639	1715	3097
Longhorn Ordnance Works	32 40	94 09	295	2370	156	1518	1558	2996
Lubbock	33 39	101 49	3254	3545	225	1371	41	1266
Lufkin AFS	31 25	94 48	277	1940	239	1861	1948	3129
Midland	31 57	102 11	2851	2621	382	1793	54	1591
Nederland ANG Station	29 57	94 02	16	1518	88	1863	2787	3708
Oilton Msl Tracking Site	27 30	98 58	880	986	649	2570	2204	3701
Orange	30 06	93 44	10	1498	92	1766	2475	3589
Paris/Cox Field	33 38	95 27	547	2903	292	1716	1019	2689
Perrin AFB/Sherman	33 43	96 40	763	2837	292	1716	1019	2689
Port Arthur	29 57	94 01	16	1518	88	1863	2787	3708
Randolph AFB/San Antonio	29 32	98 17	761	1713	298	1779	1481	3348
Red River Army Depot	33 27	94 20	385	2531	198	1639	1715	3097
Reese AFB/Lubbock	33 36	102 03	3338	3453	224	1337	37	965
San Angelo/Mathis Field	31 22	100 30	1903	2240	465	1978	245	2424
San Antonio AFS	29 27	98 27	700	1570	397	2049	1699	3426
San Antonio IAP	29 32	98 28	788	1570	397	2049	1699	3426
Sheppard AFB/Wichita Falls	33 59	98 30	1015	2904	517	1999	826	2611
Tyler/Pounds Field	32 21	95 24	544	2553	248	1825	1948	3129
Waco/James Connally Aprt	31 38	97 04	475	2081	480	2089	1636	3180
Waco/Madison Cooper	31 37	97 13	501	2058	458	2134	1849	3245
Webb AFB/Big Spring	32 13	101 31	2561	2678	331	1662	101	1485
Wichita Falls MAP	33 58	98 29	994	2904	517	1999	826	2611
UTAH	N	W						
Bryce Canyon	37 42	112 09	7585	9133	0	149	0	4
Cedar City	37 42	113 06	5617	6137	42	766	0	9
Deseret Test Center	40 19	112 17	5200	6277	79	717	0	2
Dugway PG/Michales AAF	40 12	112 56	4340	5877	224	1131	0	28
Hill AFB/Ogden	41 07	111 58	4785	6081	51	746	0	8

TABLE 4A—Winter heating degree day data for heating and summer criteria data for air conditioning for sites in the United States. (*continued*)

	Location				Summer Criteria Data Air Conditioning			
					Dry Bulb		Wet Bulb	
STATE Station	Lat, °/min	Long, °/min	Elev, feet	Degree Days, heating, annual	≧ 93°F, h	≧ 80°F, h	≧ 73°F, h	≧ 67°F, h
Hill AF Range	41 03	112 55	4422	5840	174	1069	0	19
Ogden MAP	41 12	112 01	4455	6012	37	727	0	19
Provo	40 13	111 43	4448	5720	185	989	0	26
Salt Lake City IAP	40 46	111 58	4220	5983	139	932	0	26
Tooele Army Depot	40 31	112 25	4700	5941	41	704	0	5
Utah Army Depot	41 15	112 00	4270	6012	59	849	0	19
Wendover AF Range	40 44	114 02	4237	5673	158	1144	0	4
VERMONT	N	W						
Burlington IAP	44 28	73 09	332	7876	4	263	67	546
St Albans AFS	44 46	73 03	1310	8790	1	119	21	307
VIRGINIA	N	W						
Arlington Hall	38 52	77 06	200	4211	55	815	580	1744
Bedford AFS	37 31	79 30	4220	7382	0	87	0	216
Cameron Station	38 48	77 07	60	4211	55	815	580	1744
Camp A P Hill	38 08	77 21	230	4398	90	897	710	1884
Camp Pickett/Blackstone AAF	37 05	77 57	390	3841	66	905	804	2086
Cape Charles AFS	37 08	75 57	13	3474	0	596	856	2184
Charlottesville	38 02	78 31	870	4162	54	964	376	1544
Dahlgren NAVSURFWPNCEN	38 20	77 02	21	4498	39	892	710	1884
Dam Neck	36 47	75 57	10	3639	12	708	856	2184
Dulles IAP	38 57	77 27	313	5010	28	749	386	1417
Fort Belvoir/Davison AAF	38 43	77 11	69	4891	23	781	551	1668
Fort Eustis/Felker AAF	37 08	76 37	12	3752	26	875	807	2065
Fort Lee	37 14	77 21	145	3939	70	932	765	1973
Fort Lee AFS	37 14	77 20	75	3939	70	932	765	1973
Fort Monroe	37 00	76 19	15	3623	21	809	1010	2290
Fort Myer	38 53	77 05	220	4211	41	910	580	1744
Fort Story	36 56	76 00	13	3639	12	708	856	2184
Langley AFB/Hampton	37 05	76 21	10	3623	21	809	1010	2290
Little Creek NAVPHIBASE	36 54	76 09	15	3488	41	874	961	2238
Lynchburg MAP	37 20	79 12	916	4233	31	696	376	1544
Manassas/Davis Field	38 43	77 31	186	4398	90	897	548	1650
Newport News/Patrick Henry	37 08	76 30	41	3549	21	809	1010	2290
Norfolk	36 54	76 12	22	3488	41	874	961	2238
Norfolk NAS/Chambers Field	36 56	76 18	13	3451	39	930	932	2212
Oceana NAS	36 49	76 02	22	3639	12	708	856	2184
Portsmouth	36 51	76 18	10	3488	41	874	961	2238
Quantico MCAS	38 30	77 18	12	4349	37	892	710	1884
Radford Ordnance Works	37 11	80 33	1750	4680	14	609	124	1213
Richmond/Byrd IAP	37 30	77 20	164	3939	70	932	765	1973
Richmond Quartermaster Depot	37 26	77 27	122	3939	70	932	765	1973
Roanoke/Woodrum Aprt	37 19	79 58	1193	4307	38	810	223	1468
Staunton/Shenandoah Valley	38 16	78 54	1201	4307	38	810	223	1468
Vint Hill Farms Station	38 45	77 41	425	5010	28	749	386	1417
Williamsburg	37 16	76 42	70	3671	42	905	807	2065
Yorktown	37 14	76 31	25	3623	21	809	1010	2290
WASHINGTON	N	W						
Aberdeen	46 59	123 49	12	5316	1	38	0	14
Bangor	47 43	122 43	15	5432	2	64	0	26
Bellingham IAP	48 48	122 32	158	5738	0	45	1	46
Blaine AFS	48 55	122 44	65	5738	0	45	1	46
Bremerton NAVSHIPYD	47 34	122 39	7	5432	2	64	0	26
Ephrata MAP	47 18	119 31	1272	5603	81	655	1	52
Everett use Paine AFB								
Fairchild AFB/Spokane	47 37	117 38	2462	6790	32	415	0	5
Fort Lawton	47 39	122 25	225	5678	2	47	1	30
Fort Lewis/Gray AAF	47 05	122 35	301	5339	2	130	2	29

TABLE 4A—Winter heating degree day data for heating and summer criteria data for air conditioning for sites in the United States. (*continued*)

	Location				Summer Criteria Data Air Conditioning			
					Dry Bulb		Wet Bulb	
STATE Station	Lat, °/min	Long, °/min	Elev, feet	Degree Days, heating, annual	≧ 93°F, h	≧ 80°F, h	≧ 73°F, h	≧ 67°F, h
Four Lake Comm Sta ANG	47 33	117 33	2642	6806	32	415	0	5
Keyport	47 42	122 37	17	5432	2	64	0	26
Longview	46 10	122 56	12	5064	9	200	4	101
Madigan Army Hospital	47 06	122 32	275	5328	4	131	0	49
Makah AFS	48 23	124 41	1430	5774	0	0	0	0
Marietta	48 50	122 36	20	5738	0	45	1	46
McChord AFB/Tacoma	47 09	122 29	322	5287	4	131	0	49
Mica Peak AFS	47 34	117 05	5198	8840	0	2	0	0
Moses Lake/Grant Co	47 12	119 19	1185	5809	97	675	1	52
Olympia	46 58	122 54	215	5530	5	139	0	46
Othello AFS	46 50	119 10	1280	5809	97	675	1	52
Paine AFB/Everett	47 55	122 17	596	5678	1	40	1	30
Pasco/Tri-Cities Aprt	46 16	119 07	406	4892	145	844	5	220
Seattle NSA	47 41	122 15	47	4650	3	120	5	93
Seattle-Tacoma IAP	47 27	122 18	400	5185	3	87	0	22
Spokane IAP	47 38	117 31	2366	6835	32	428	0	12
Tacoma	47 15	122 30	100	4835	4	131	0	49
Tatoosh Island	48 23	124 44	115	5774	0	0	0	0
Walla Walla Aprt	46 06	118 17	1206	5187	98	632	3	109
Whidbey Island/Ault Fld	48 21	122 40	47	5520	1	26	1	30
Whidbey Is/Oak Harbor	48 17	122 39	55	5609	1	53	1	30
Yakima Firing Center	46 41	120 28	1262	6109	59	504	1	63
Yakima MAP	46 34	120 32	1052	6009	73	566	1	63
WEST VIRGINIA	N	W						
Beckley/Raleigh Co Aprt	37 47	81 07	2504	5615	0	126	41	515
Charleston/Kanawha Aprt	38 22	81 36	939	4590	25	744	315	1521
Elkins/Randolph Co Aprt	38 53	79 51	1948	5975	1	305	64	715
Fairmont	39 28	80 08	1298	5208	40	662	258	1221
Huntington	38 25	82 30	565	4374	47	797	470	1671
Martinsburg MAP	39 24	77 59	556	5231	35	684	384	1383
Parkersburg	39 16	81 34	615	4817	33	736	401	1528
Wheeling/Ohio Co Aprt	40 11	80 39	1196	5930	5	461	105	886
WISCONSIN	N	W						
Antigo AFS	45 03	89 14	1530	8460	7	234	44	387
Badger Ordnance Works	43 22	89 45	880	7382	16	466	187	868
Camp McCoy	44 01	90 41	870	7558	12	482	128	721
Green Bay/Austin/Straubel	44 29	88 08	682	8098	5	286	128	648
La Crosse MAP	43 52	91 15	651	7417	15	469	206	896
Madison/Truax Field	43 08	89 20	858	7730	16	466	187	868
Milwaukee/Gen Mitchell Fld	42 57	87 54	672	7444	11	346	161	791
Oshkosh/Wittman Field	43 59	88 33	805	7602	9	309	128	648
Volk Field ANG/Camp Douglas	43 56	90 16	915	7773	12	482	128	721
WYOMING	N	W						
Casper IAP	42 55	106 28	5338	7555	20	559	0	1
Cheyenne MAP	41 09	104 49	6126	7255	2	355	0	0
F E Warren AFB/Cheyenne	41 09	104 50	6155	7255	2	355	0	0
Lander/Hunt Field	42 49	108 44	5563	7869	11	428	0	1
Rock Springs	41 36	109 04	6745	8410	1	261	0	0
Sheridan	44 46	106 58	3964	7708	54	561	0	24

TABLE 4B—Winter heating degree day data for heating and summer criteria data for air conditioning for sites outside the United States.

AREA COUNTRY Station	Location			Degree Days, heating, annual	Summer Criteria Data Air Conditioning			
					Dry Bulb		Wet Bulb	
	Lat, °/min	Long, °/min	Elev, feet		≧ 93°F, h	≧ 80°F, h	≧ 73°F, h	≧ 67°F, h
AFRICA								
ALGERIA	N	E						
Alger	36 43	3 15	75	1803	50	774	265	1497
CAMEROON	N	E						
Yaounde	3 50	11 31	2464	0	1	1104	828	4011
ETHIOPIA	N	E						
Addis Ababa	8 59	38 48	7684	2148	3	264	0	13
Asmara	15 17	38 55	7628	1732	0	169	0	22
Massawa	15 37	39 27	33	0	1760	4235	4290	4416
GHANA	N	W						
Accra	5 36	0 10	230	0	2	2973	4180	4377
IVORY COAST	N	W						
Abidjan	5 15	3 56	20	0	2	2973	4180	4377
KENYA	N	E						
Mandera	3 56	41 51	801	0	394	3184	2380	4065
LIBERIA	N	W						
Monrovia	6 15	10 21	26	0	22	1900	3812	4383
LIBYA	N	E						
Benghazi	32 05	20 16	427	1135	210	1535	648	2471
Tripoli IAP	32 41	13 10	262	1360	491	1724	424	2102
Wheelus AB	32 54	13 17	13	1118	114	1396	805	2492
MOROCCO	N	W						
Kenitra/Port Lyautey	34 18	6 36	20	1230	32	338	106	1720
Rabat-Sale	34 03	6 46	276	1646	24	208	147	1504
Tangier/Boukhalf	35 43	5 54	46	1541	9	412	123	1370
NIGERIA	N	E						
Lagos	6 35	3 20	131	0	2	2973	4180	4377
SOMALIA	N	E						
Mogadiscio	2 02	45 21	39	0	5	2118	3837	4344
SOUTH AFRICA	S	E						
Pretoria	25 39	28 13	4094	1632	22	844	1	366
SUDAN	N	E						
Khartoum	15 36	32 33	1257	0	1678	3823	1465	2989
TUNISIA	N	W						
Tunis	36 50	10 14	16	1687	87	1008	540	2078
UNITED ARAB REPUBLIC/EGYPT	N	E						
Alexandria/Nouzha	31 10	29 57	−10	841	23	1217	872	2963
Cairo IAP	30 08	31 24	367	689	295	1892	308	2497
ZAIRE	S	E						
Kinshasa	4 19	15 19	925	0	7	1454	2138	4358
ANTARCTIC CIRCLE								
ANTARCTICA	S	E						
Hallett Station	72 19	170 19	16	22245	0	0	0	0
McMurdo Sound	77 51	166 40	80	23363	0	0	0	0
ASIA								
ADEN	N	E						
Aden IAP	12 50	45 02	10	0	698	4261	4155	4413
AFGHANISTAN	N	E						
Kabul IAP	34 33	69 13	5876	5273	155	1515	18	190
BAHRAIN	N	E						
Bahrain IAP/Muharraq	26 16	50 37	6	172	1298	4174	3984	4388
BANGLADESH	N	E						
Dacca	23 46	90 23	23	79	85	3590	4214	4367
BURMA	N	E						
Rangoon	16 54	96 08	108	0	51	1979	4395	4416

TABLE 4B—Winter heating degree day data for heating and summer criteria data for air conditioning for sites outside the United States. (*continued*)

AREA COUNTRY Station	Location			Degree Days, heating, annual	Summer Criteria Data Air Conditioning			
					Dry Bulb		Wet Bulb	
	Lat, °/min	Long, °/min	Elev, feet		≧ 93°F, h	≧ 80°F, h	≧ 73°F, h	≧ 67°F, h
CAMBODIA	N	E						
Phnom Penh	11 33	104 51	33	0	182	2845	4342	4392
CEYLON	N	E						
Colombo	6 49	79 53	16	11	1	3274	4201	4411
CHINA	N	E						
Peking	39 48	116 28	105	5580	56	922	374	1374
Shanghai	31 10	121 26	16	3435	74	1255	1805	2750
HONG KONG	N	E						
Hong Kong IAP	22 19	114 12	16	543	11	2973	3647	4183
INDIA	N	E						
Bombay	19 05	72 51	36	0	95	2346	4345	4392
Calcutta	22 39	88 27	13	108	365	3412	4248	4398
Hyderabad	17 27	78 28	1742	80	305	1956	1574	4345
Madras	13 00	80 11	49	0	590	3644	4376	4392
New Delhi	28 35	77 12	705	456	1078	3414	2565	3429
INDONESIA	S	E						
Djakarta	6 09	106 51	16	0	0	2006	4114	4344
IRAN	N	E						
Abadan IAP	30 22	48 15	10	784	1745	3510	529	2314
Esfahan	32 37	51 40	5243	3545	250	1407	9	36
Kerman	30 16	56 57	5735	2819	378	2091	16	66
Mashhad	36 16	59 38	3245	4279	188	1270	6	60
Shiraz IAP	29 32	52 35	4911	2778	654	1911	5	73
Tabriz	38 08	46 15	4482	5194	70	866	0	23
Tehran/Mehrabad IAP	35 41	51 19	3949	3428	496	2007	0	19
IRAQ	N	E						
Baghdad IAP	33 14	44 14	112	1389	1554	3043	174	1485
ISRAEL	N	E						
Jerusalem	31 47	35 13	2654	2313	24	748	0	383
Tel Aviv	32 00	34 54	131	1251	130	1390	651	2277
JAPAN	N	E						
Akizuki	34 11	132 33	262	3025	11	995	1471	2368
Ashiya	33 52	130 38	105	3176	12	844	1380	2336
Atsugi NAS	35 27	139 28	200	3225	6	655	1067	2175
Bolo Range/Okinawa	26 25	127 44	131	452	1	2193	3023	3914
Camp Asaka	35 48	139 36	115	3588	35	786	965	2035
Camp Chinen/Okinawa	26 09	127 47	476	372	0	1700	2560	3222
Camp Hardy/Okinawa	26 28	128 00	49	352	0	1860	2815	3895
Camp Kubasaki/Okinawa	26 17	127 49	16	507	2	2164	3181	3992
Camp Kue/Okinawa	26 18	127 46	16	452	1	2193	3023	3914
Camp Sansone/Okinawa	26 21	127 45	33	452	1	2193	3023	3914
Camp Sukiran/Okinawa	26 17	127 46	164	507	2	2164	3181	3992
Camp Zama/Rankin Fld	35 30	139 24	359	3225	6	655	1067	2175
Chitose AS	42 50	141 43	73	7542	0	93	158	677
Fuchu AS	35 40	139 30	173	3826	23	671	965	2035
Futema MCAS/Okinawa	26 16	127 45	245	507	2	2164	3181	3992
Hakata AS	33 40	130 22	20	3176	12	844	1380	2336
Hakodate	41 49	140 45	116	7008	0	84	159	760
Iruma AB	35 51	139 25	295	3791	30	614	1029	2084
Itazuke Aux Airfield	33 35	130 27	22	3253	22	1055	1454	2362
Iwakuni MCAS	34 09	132 14	8	3025	11	995	1471	2368
Kadena AB/Okinawa	26 21	127 46	140	452	1	2193	3023	3914
Kami Seya	35 29	139 29	229	3225	6	655	1067	2175
Kisarazu	35 24	139 55	12	2895	2	594	1220	2229
Misawa AB	40 42	141 22	118	5942	3	190	190	872
Morioka	39 42	141 10	512	6311	1	290	355	1121
Nagasaki	32 44	129 51	87	2734	9	1103	1579	2499
Nagoya/Komaki AB	35 15	136 56	52	3501	47	878	1227	2251

TABLE 4B—Winter heating degree day data for heating and summer criteria data for air conditioning for sites outside the United States. (*continued*)

AREA COUNTRY Station	Location			Degree Days, heating, annual	Summer Criteria Data Air Conditioning			
					Dry Bulb		Wet Bulb	
	Lat, °/min	Long, °/min	Elev, feet		≧ 93°F, h	≧ 80°F, h	≧ 73°F, h	≧ 67°F, h
Naha AB/Okinawa	26 12	127 39	13	372	0	2456	3222	4037
Osaka IAP	34 47	135 27	49	3449	33	906	1176	2204
Sagami	35 35	139 25	328	3826	23	671	965	2035
Sapporo	43 03	141 20	50	7360	0	143	145	650
Sasebo NB	33 09	129 43	50	2909	9	1103	1579	2499
Seburiyama	33 26	130 22	3460	5814	0	21	7	586
Tachikawa AB	35 42	139 24	305	3826	23	671	965	2035
Tokyo IAP	35 33	139 46	9	3281	1	723	1099	2048
Yokohama	35 26	139 38	33	3281	1	723	1099	2048
Yokosuka FWC	35 17	139 40	174	2782	1	574	1278	2315
Yokota AB	35 44	139 20	456	3818	12	582	912	1961
JORDAN	N	E						
Amman	31 58	35 59	2543	2273	206	1363	53	525
KOREA	N	E						
Anyang	37 23	126 55	131	5555	11	650	894	1800
Ascom City	37 30	126 42	59	5276	5	797	1019	1913
Chinhae	35 08	128 40	16	4007	13	788	1207	2138
Inchon	37 28	126 38	33	5276	5	797	1019	1913
Kangnung	37 45	128 57	20	4862	19	491	600	1543
Kimpo	37 37	126 44	33	5681	7	567	925	1875
Noon-Ni Air Range	37 02	126 45	40	5068	4	834	1183	2062
Kumchon	36 07	128 07	328	4750	70	973	1120	1994
Kunsan AB	35 54	126 37	36	4802	4	755	1212	2090
Kwangju AB	35 07	126 49	52	4445	44	1052	1340	2277
Mangil-San	36 56	126 27	991	5510	0	168	555	1557
Mosulpo	33 12	126 16	43	3230	1	787	1481	2375
Munsan	37 51	126 49	167	5640	19	699	867	1773
Osan AB	37 05	127 02	35	5555	11	650	894	1800
Pusan	35 09	129 03	112	3841	1	608	1029	2023
Pusan IAP	35 10	129 08	7	3841	1	608	1029	2023
Pyongtaek	36 57	127 02	62	5264	23	874	1099	2024
Seoul	37 26	127 06	75	5555	11	650	894	1800
Seoul/Kimpo IAP	37 33	126 48	59	5681	7	567	925	1875
Taegu	35 53	128 40	98	4622	95	1018	1120	1994
Taejon	36 20	127 23	226	5363	23	814	1109	2066
Tongduchon	37 54	127 04	263	5334	67	1105	1013	1968
Uijongbu	37 44	127 03	184	5640	19	699	867	1773
Waegwan	35 59	128 24	33	4622	95	1018	1120	1994
Yonchon	35 59	128 59	295	4750	70	973	1120	1994
KUWAIT	N	E						
Kuwait IAP	29 13	47 58	184	768	2235	3820	517	2173
LAOS	N	E						
Saravane	15 43	106 25	574	6	172	2679	4168	4388
Vientiane	17 59	102 34	561	17	171	2121	4090	4388
LEBANON	N	E						
Beirut IAP	33 49	35 29	85	944	2	1058	1132	2927
MALAYSIA	N	E						
Butterworth	5 28	100 24	10	0	9	2830	4306	4398
Kuala Lumpur	3 07	101 33	89	0	45	2009	4004	4406
NEPAL	N	E						
Katmandu IAP	27 42	85 22	4422	1663	22	843	995	3020
PAKISTAN	N	E						
Karachi Aprt	24 54	67 09	102	222	416	3951	3870	4240
Lahore	31 33	74 20	702	939	1106	3485	2742	3678
Peshawar	34 00	71 31	1181	1284	913	3272	1895	2920
SAUDI ARABIA	N	E						
Dhahran AB	26 16	50 10	75	282	1800	3904	2055	3674
Riyadh IAP	24 42	46 44	2047	506	1813	3392	82	710

TABLE 4B—Winter heating degree day data for heating and summer criteria data for air conditioning for sites outside the United States. (*continued*)

AREA COUNTRY Station	Location			Degree Days, heating, annual	Summer Criteria Data Air Conditioning			
					Dry Bulb		Wet Bulb	
	Lat, °/min	Long, °/min	Elev, feet		≧ 93°F, h	≧ 80°F, h	≧ 73°F, h	≧ 67°F, h
SINGAPORE	N	E						
Singapore Aprt	1 21	103 55	59	0	4	2075	4349	4404
TAIWAN	N	E						
Chiai	23 28	120 27	98	337	27	2207	3654	4218
Chiai AB	23 28	120 23	82	337	27	2207	3654	4218
Ching Chuan Kang AB	24 16	120 37	666	607	8	1675	3183	4067
Gold Mountain	25 08	121 33	1378	1020	2	1138	2684	3887
Grass Mountain	25 08	121 33	1302	1020	2	1138	2684	3887
San Yi	24 08	120 39	164	394	88	2164	3306	4076
Shu Lin Kou AS	25 05	121 23	820	869	6	1400	2976	3981
Taichung	24 11	120 39	364	475	40	1954	3306	4076
Tainan AB	22 57	120 12	56	214	10	2478	3825	4285
Taipei IAP	25 04	121 33	20	556	74	1932	3266	4094
THAILAND	N	E						
Bangkok/Don Muang IAP	13 55	100 37	12	0	353	3144	4368	4391
Camp Friendship	15 04	102 08	591	0	373	2723	3791	4402
Camp Nam Pung	16 38	102 58	686	12	151	2730	3875	4375
Camp Samae San	12 34	100 57	200	0	4	2951	4355	4392
Camp Vayama	13 42	100 52	6	0	353	3144	4368	4391
Chiangmai	18 46	98 58	1063	18	141	2123	3898	4392
Korat	14 56	102 04	797	4	250	2685	3791	4402
Nakhon Phanom	17 23	104 39	577	27	188	2489	3939	4360
Ubon	15 14	104 52	443	1	170	2598	4070	4388
Udorn	17 23	102 47	574	12	151	2730	3875	4375
U-Tapao	12 40	101 00	33	0	12	3868	4355	4392
TURKEY	N	E						
Ankara AS	39 57	32 53	2960	5148	80	747	0	50
Ankara/Esenboga	40 07	32 59	3127	5513	60	663	0	50
Ankara/Murted	40 05	32 34	2750	4833	101	833	0	50
Balikesir	39 37	27 56	348	3411	92	829	37	767
Cigli AB/Izmir	38 31	27 01	17	2463	145	1237	45	648
Diogenes Sta	42 02	35 11	164	3522	1	166	117	1044
Diyarbakir AB	37 54	40 12	2251	3754	647	2124	29	472
Eskisehir	39 47	30 34	2575	5487	65	634	4	149
Incirlik AB/Adana	37 00	35 26	239	1728	263	1772	960	2278
Istanbul/Yesilkoy	40 58	28 49	92	3604	4	348	48	856
Izmir AS	38 27	27 15	92	2463	145	1237	45	648
Izmit	40 46	29 54	249	3401	35	536	88	844
Karamursel AS	40 43	29 31	18	3433	20	422	88	844
Malatya	38 21	38 18	3274	4798	147	1187	0	47
Nicosia/Cyprus	35 09	33 17	735	1880	278	1496	235	1568
Samsun	41 17	36 20	144	3648	3	182	117	1044
Yamanlar	38 32	27 07	3202	5041	70	514	1	173
VIETNAM	N	E						
Cam Ranh Bay	12 00	109 13	47	13	183	3324	4063	4416
Danang	16 03	108 12	30	5	359	3039	4188	4373
Nha Trang	12 14	109 12	16	0	162	3284	4213	4415
Pleiku	14 00	108 01	2435	29	4	797	1024	4095
Saigon/Tan Son Nhut	10 49	106 39	33	0	146	2704	4351	4391
ATLANTIC OCEAN								
ASCENSION ISLAND	S	W						
Ascension AAFB	7 58	14 24	282	0	0	1541	1689	4371
AZORES	N	W						
Lajes Field	38 46	27 06	180	1332	0	24	17	889
BERMUDA	N	W						
Bermuda NAS/Kindley AFB	32 22	64 41	10	325	0	1272	2014	3626
ICELAND	N	W						
Havalfjordur	64 24	21 28	20	9016	0	0	0	0
Keflavik NAS	63 59	22 36	169	8838	0	0	0	0
Reykjavik	64 08	21 56	59	9016	0	0	0	0

TABLE 4B—Winter heating degree day data for heating and summer criteria data for air conditioning for sites outside the United States. (*continued*)

AREA COUNTRY Station	Location			Degree Days, heating, annual	Summer Criteria Data Air Conditioning			
					Dry Bulb		Wet Bulb	
	Lat, °/min	Long, °/min	Elev, feet		≧ 93°F, h	≧ 80°F, h	≧ 73°F, h	≧ 67°F, h
OCEAN STATION VESSELS	N	W						
B	56 30	51 00	0	9473	0	0	0	0
C	52 45	35 30	0	6509	0	0	0	0
D	44 00	41 00	0	2612	0	0	49	958
E	35 00	48 00	0	322	0	391	1377	3406
AUSTRALIA								
AUSTRALIAN CAPITAL TERRITORY	S	E						
Canberra	35 19	149 11	1873	4027	15	315	1	113
NEW SOUTH WALES	S	E						
Sydney IAP	33 57	151 11	10	1586	16	201	73	1207
NORTHERN TERRITORY	S	E						
Alice Springs	23 48	133 54	1781	1186	705	2332	122	894
Darwin	12 26	130 52	95	0	23	3186	4115	4322
QUEENSLAND	S	E						
Brisbane	27 26	153 05	7	529	5	841	554	2760
Townsville	19 15	146 46	10	46	10	2120	2820	4187
SOUTH AUSTRALIA	S	E						
Adelaide	34 56	138 35	141	2001	94	664	24	210
Woomera	31 09	136 48	538	1590	427	1531	49	475
VICTORIA	S	E						
Melbourne IAP	37 40	144 50	423	3187	39	299	4	212
WESTERN AUSTRALIA	S	E						
Northwest Cape	22 20	114 03	126	132	753	2483	1462	3145
Perth IAP	31 56	115 38	56	1415	151	822	146	908
CARIBBEAN SEA								
ANTIGUA	N	W						
Parham	17 06	61 46	75	3	0	3579	4292	4416
St Johns/Coolidge Field	17 08	61 47	62	3	0	3579	4292	4416
BAHAMA ISLANDS	N	W						
Allans Cay	26 59	77 40	12	150	0	2356	3364	4215
Eleuthera AAFB	25 16	76 19	45	9	0	2939	3807	4349
Grand Bahama AAFB	26 37	78 22	7	150	0	2356	3364	4215
Grand Turk AAFB	21 27	71 09	26	0	0	3850	4208	4404
Little Carter Cay	27 05	78 00	21	150	0	2356	3364	4215
Mayaguana AAFB	22 22	73 01	80	0	0	3350	4017	4383
North Creek	21 30	71 10	80	0	0	3850	4208	4404
San Salvador Island	24 04	74 32	10	0	0	2843	3827	4361
CUBA	N	W						
Guantanamo Bay NAS	19 54	75 09	51	0	131	2790	3935	4411
Havana/Jose Marti	22 59	82 24	246	46	3	1653	2966	4272
DOMINICAN REPUBLIC	N	W						
Santo Domingo/Cauce	18 26	69 40	46	0	3	1972	3689	4404
HAITI	N	W						
Port Au Prince	18 35	72 18	108	0	187	2455	2575	4406
JAMAICA	N	W						
Kingston	17 56	76 47	10	0	75	2144	3233	4406
PUERTO RICO	N	W						
Fort Buchanan	18 25	66 08	16	0	1	2227	3655	4413
Ramey AFB/Aguadilla	18 30	67 08	236	13	0	2087	3230	4392
Roosevelt Roads NAS	18 15	65 38	39	0	1	3154	4103	4415
Sabana Seca	18 26	66 11	200	0	1	2227	3655	4413
San Juan/Isle Verde	18 26	66 00	10	0	1	2227	3655	4413
VIRGIN ISLANDS	N	W						
St Thomas/Truman Field	18 20	64 58	7	2	0	3126	4153	4416

TABLE 4B—Winter heating degree day data for heating and summer criteria data for air conditioning for sites outside the United States. (*continued*)

AREA COUNTRY Station	Location			Degree Days, heating, annual	Summer Criteria Data Air Conditioning			
	Lat, °/min	Long, °/min	Elev, feet		Dry Bulb		Wet Bulb	
					≧ 93°F, h	≧ 80°F, h	≧ 73°F, h	≧ 67°F, h
CENTRAL AMERICA								
CANAL ZONE	N	W						
Albrook AFB	8 58	79 33	30	0	9	1871	4260	4416
Fort Amador	8 57	79 33	16	0	9	1871	4260	4416
Fort Clayton	8 59	79 35	33	0	9	1871	4260	4416
Fort Gulick	9 19	79 53	16	0	0	2331	4293	4392
Fort Kobbe	8 55	79 36	98	16	4	1963	3832	4390
Howard AFB/Balboa	8 55	79 36	51	16	4	1963	3832	4390
Quarry Heights	8 57	79 33	175	0	9	1871	4260	4416
Rodman Naval Station	8 57	79 34	15	0	9	1871	4260	4416
COSTA RICA	N	W						
San Jose	9 56	84 05	3845	49	0	434	38	2197
EL SALVADOR	N	W						
San Salvador	13 42	89 07	2021	0	56	1337	2060	4315
GUATEMALA	N	W						
Guatemala City	14 35	90 31	4885	185	0	48	1	206
HONDURAS	N	W						
Tegucigalpa	14 03	87 13	3305	76	5	892	96	2556
NICARAGUA	N	W						
Managua	12 07	86 11	174	0	45	2085	3508	4410
EUROPE								
AUSTRIA	N	E						
Innsbruck	47 16	11 24	1909	6408	1	164	1	117
Vienna/Schwechat	48 07	16 34	600	5845	2	180	4	194
BELGIUM	N	E						
Brussels IAP	50 54	4 28	178	5721	0	53	8	113
Chievres AB	50 34	3 49	223	6147	0	48	14	148
Ostend	51 12	2 52	13	5912	0	14	3	51
Uccle	50 48	4 21	328	5871	0	52	10	143
DENMARK	N	E						
Copenhagen/Kastrup	55 38	12 40	16	6630	0	2	0	28
FINLAND	N	E						
Helsinki/Seutula	60 19	24 58	167	9100	0	37	0	38
FRANCE	N	E						
Bordeaux/Merignac	44 50	OW42	161	4033	4	199	67	510
Chalons	48 57	4 21	262	5588	4	135	20	213
Lyon/Bron	45 44	4 57	656	4900	2	218	23	322
Marseille/Marignane	43 27	5 13	66	3121	5	445	108	875
Nantes	47 10	1W36	89	4578	2	107	23	271
Paris/Orly	48 44	2 24	292	4986	0	98	6	180
GERMANY	N	E						
Amberg AAF	49 25	11 50	1312	7313	1	107	2	57
Ansbach AAF	49 18	10 35	1676	6655	0	87	6	85
Aschaffenburg AAF	49 58	9 08	380	5730	4	171	14	193
Augsburg	48 22	10 52	1588	6569	1	158	1	139
Babenhausen	49 57	8 58	430	5730	4	171	14	193
Bad Aibling	47 52	11 59	1591	6500	3	146	0	77
Bad Hersfeld/Johannesberg	50 51	9 43	787	6404	1	99	1	105
Bad Kissingen	50 11	10 07	984	6702	0	81	1	72
Bad Kreuznach	49 50	7 52	377	5508	3	218	11	212
Bad Tolz/Greiling AAF	47 45	11 35	2572	6999	0	55	0	53
Bamberg AAF	49 55	10 54	797	5995	1	152	4	118
Baumholder AAF	49 39	7 18	1444	6513	0	83	1	91
Bayreuth	49 56	11 34	1148	6950	1	107	2	57
Berchtesgaden	47 38	13 01	1778	6813	1	103	0	77
Berlin/Tempelhof AB	52 29	13 24	164	6154	3	101	1	81

TABLE 4B—Winter heating degree day data for heating and summer criteria data for air conditioning for sites outside the United States. (*continued*)

AREA COUNTRY Station	Location			Degree Days, heating, annual	Summer Criteria Data Air Conditioning			
					Dry Bulb		Wet Bulb	
	Lat, °/min	Long, °/min	Elev, feet		≧ 93°F, h	≧ 80°F, h	≧ 73°F, h	≧ 67°F, h
Bitburg AB	49 57	6 34	1228	6541	0	47	0	46
Bremen	53 02	8 47	16	6301	0	94	12	166
Bremerhaven	53 33	8 33	7	6278	0	35	5	107
Buedingen	50 18	9 07	951	6702	0	81	1	72
Butzbach	50 26	8 41	591	6300	0	109	4	91
Coburg	50 17	10 59	1024	6734	1	144	3	104
Crailsheim	49 08	10 02	1404	6655	0	87	6	85
Darmstadt	49 52	8 32	384	5971	5	134	5	156
Erding AB	48 19	11 57	1514	6749	4	160	11	155
Erlangen	49 34	11 07	919	6723	3	134	1	109
Eschwege	51 12	9 50	525	6474	1	87	11	158
Feucht AAF	49 23	11 11	1265	6675	0	157	4	119
Finthen AAF	49 58	8 08	922	6038	2	137	11	178
Frankfurt/Rhein Main AB	50 02	8 34	368	5971	5	134	5	156
Friedberg/Ockstadt AAF	50 20	8 44	525	6300	0	109	4	91
Fulda/Sickels AAF	50 32	9 38	1093	6702	0	81	1	72
Gablingen	48 27	10 52	1542	6569	1	158	1	139
Garmisch	47 29	11 03	2470	7405	0	71	0	58
Gelnhausen	50 12	9 11	518	5730	4	171	14	193
Germersheim	49 13	8 22	328	5375	6	229	19	262
Giebelstadt AAF	49 40	9 56	984	6723	3	134	1	109
Giessen	50 35	8 42	591	6300	0	109	4	91
Goppingen	48 42	9 42	1083	6133	2	121	2	85
Grafenwohr AAF	49 41	11 56	1362	7313	1	107	2	57
Griesheim	50 04	8 35	368	5971	5	134	5	156
Hahn AB/Hunsruck	49 57	7 16	1650	7069	0	28	0	31
Hanau AAF	50 10	8 57	390	5730	4	171	14	193
Hannover	52 28	9 41	183	6398	0	91	11	158
Heidelberg AAF	49 23	8 39	359	5459	5	219	20	260
Heilbronn	49 08	9 13	558	5750	3	200	13	180
Herzogenaurach	49 34	10 54	968	6723	3	134	1	109
Hoppstadten AAF	49 36	7 11	1188	6423	2	111	4	97
Illesheim AAF	49 28	10 23	1168	6520	1	180	3	153
Kaiserslautern	49 26	7 50	853	6423	2	111	4	97
Karlsruhe AAF	49 01	8 22	410	5295	6	239	18	265
Kinsbach	49 26	7 36	781	6423	2	111	4	97
Kirch Goens	50 28	8 39	771	6300	0	109	4	91
Kitzingen AAF	49 45	10 12	689	6035	6	189	5	158
Landshut	48 32	12 11	1509	6749	4	160	11	155
Landstuhl	49 24	7 32	787	6423	2	111	4	97
Lenggries	47 41	11 34	2264	6800	0	99	0	53
Lindsey AS	50 02	8 15	450	5759	3	116	2	114
Mainz	49 59	8 16	397	5759	3	116	2	114
Mannheim/Colman Barracks	49 30	8 29	295	5133	8	326	21	310
Muenster	51 59	7 44	164	6048	3	107	9	118
Munich	48 05	11 36	1860	6813	1	103	0	77
Nellingen	48 33	9 47	2264	7313	0	44	0	32
New Ulm	48 23	10 02	1509	6813	1	82	2	85
Nurnberg/Furth AAF	49 30	11 04	1030	6723	3	134	1	109
Oberammergau	47 35	11 05	3937	7400	0	10	0	1
Oldenburg	59 09	8 14	33	6301	0	94	12	166
Pirmasens	49 13	7 36	1411	6415	0	60	1	79
Ramstein AB/Landstuhl	49 26	7 36	780	6423	2	111	4	97
Rhein Main AB	50 02	8 34	368	5971	5	134	5	156
Schleissheim	48 15	11 33	1575	6749	4	160	11	155
Sembach AB	49 30	7 52	1052	6453	0	84	1	72
Siegenburg Range	48 45	11 48	1325	6749	4	160	11	155
Spangdahlem AB	49 59	6 42	1197	6587	0	49	1	60
Stuttgart/Echterdingen AB	48 41	9 13	1300	6283	1	92	2	85
Tempelhof AB/Berlin	52 29	13 24	164	6154	3	101	1	81

TABLE 4B—Winter heating degree day data for heating and summer criteria data for air conditioning for sites outside the United States. (*continued*)

AREA COUNTRY Station	Location			Degree Days, heating, annual	Summer Criteria Data Air Conditioning			
					Dry Bulb		Wet Bulb	
	Lat, °/min	Long, °/min	Elev, feet		≧ 93°F, h	≧ 80°F, h	≧ 73°F, h	≧ 67°F, h
Todendorf	54 22	10 33	10	6468	0	30	5	107
Wiesbaden AB	50 03	8 20	460	5759	3	116	2	114
Wurzburg	49 49	9 53	577	5952	4	179	3	116
Zweibrucken AB	49 13	7 24	1133	6215	0	78	1	79
GREECE	N	E						
Araxos/Patrai	38 10	21 25	50	2033	38	869	198	1694
Athens/Hellinikon Aprt	37 54	23 44	33	1779	60	1343	412	1768
Elefsis	38 04	23 33	144	2126	106	1347	105	1142
Iraklion AS/Crete	35 20	25 11	125	1441	20	737	138	1528
Larisa	39 39	22 27	240	3537	104	977	101	975
Lefkas	38 50	20 43	7	2004	15	663	229	1503
Nea Makri	38 06	23 59	10	1779	60	1343	412	1768
Parnis	38 10	23 45	4544	5869	0	38	2	94
Piraeus	37 59	23 34	7	1779	60	1343	412	1768
Souda Bay/Crete	35 32	24 09	479	1907	53	836	36	1008
Tanagra	38 19	23 32	456	2671	71	961	108	963
HUNGARY	N	E						
Budapest/Ferihegy	47 26	19 14	443	5802	2	241	62	438
IRELAND	N	W						
Dublin IAP	53 26	6 15	223	5683	0	1	0	1
Shannon IAP	52 41	8 55	46	5455	0	2	0	10
ITALY	N	E						
Aviano AB	46 02	12 36	413	4386	4	340	69	670
Brindisi	40 39	17 57	49	2410	12	486	313	1608
Cagliari/Elmas/Sardinia	39 15	9 03	13	2334	5	418	261	1411
Camp Darby/Leghorn	43 39	10 19	16	3286	11	417	175	1082
Camp Ederle/Vicenza	45 33	11 33	115	4585	9	500	191	1103
Ceggia	45 41	12 38	7	4286	15	469	59	644
Cima Gallina	46 56	11 30	8790	12500	0	0	0	0
Finale Legure	44 14	8 11	1640	5937	0	79	13	103
Firenze	43 48	11 12	131	3308	63	658	95	935
Ghedi/Brescia	45 25	10 17	335	4951	0	433	201	1005
La Maddalena/Sardinia	41 13	9 25	30	2472	1	312	192	1114
Livorno/Leghorn	43 33	10 19	49	2538	1	178	88	1333
Martina Franca	40 40	17 16	1190	4004	32	463	29	413
Milano/Linate	45 26	9 17	351	4802	1	429	173	987
Monte Calvarina	45 31	11 16	2221	5200	0	44	0	59
Monte Cimone	44 12	10 42	7103	10664	0	0	0	0
Monte Corna	45 22	10 31	645	4723	3	450	190	980
Monte Paganella	46 09	11 02	6972	10577	0	0	0	0
Monte Venda	45 19	11 41	1886	5116	0	59	13	103
Monte Vergine	40 56	14 43	4880	6781	0	15	0	1
Naples NAF	40 53	14 18	289	2671	4	472	132	1061
Pisa/San Guisto	43 40	10 23	7	3286	11	417	175	1082
Rimini	44 01	12 38	39	4033	1	342	223	1042
Rome/Ciampino	41 48	12 35	423	2882	35	729	255	1286
San Vito Dei Normanni AS	40 39	17 42	361	2674	12	486	313	1608
Sigonella NAF/Sicily	37 24	14 55	72	2240	103	1124	243	1532
Venezia/Tessera	45 30	12 20	7	4357	0	374	269	1176
Verona/Villafranca	45 23	10 52	220	4723	3	468	120	1026
Vicenza	45 34	11 31	128	4585	9	500	191	1103
NETHERLANDS	N	E						
Amsterdam/Schiphol	52 18	4 46	−13	5880	0	31	10	126
Emma Mine Schinnen	50 55	5 57	230	5734	1	60	3	126
Hoek Van Holland	51 59	4 09	26	5667	0	27	3	100
Soesterberg AB	52 08	5 16	66	6126	0	56	6	106
Steenwijkerwold	52 46	6 11	33	6335	0	37	10	126
Thardo	52 24	5 53	49	5880	1	26	10	126
The Hague	52 02	4 21	−7	5880	0	31	10	126
Volkel	51 39	5 42	72	6207	0	65	3	126

TABLE 4B—Winter heating degree day data for heating and summer criteria data for air conditioning for sites outside the United States. (*continued*)

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					Dry Bulb		Wet Bulb	
	Lat, °/min	Long, °/min	Elev, feet		≧ 93°F, h	≧ 80°F, h	≧ 73°F, h	≧ 67°F, h
NORWAY	N	E						
Oslo/Fornebu	59 54	10 37	56	8292	0	72	0	24
POLAND	N	E						
Warsaw/Okecie	52 11	20 59	361	7166	0	105	3	153
PORTUGAL	N	W						
Lisbon/Portela	38 46	9 08	374	1972	19	332	27	493
SPAIN	N	W						
Alicante/Santa Pola	38 17	0 33	141	1825	11	679	361	1809
Barcelona/Montadas	41 17	2E04	13	2898	0	236	141	1204
Cordoba	37 51	4 50	295	2285	415	1522	190	1297
Humosa	40 30	3 15	2900	4603	21	528	1	40
Madrid	40 25	3 41	2149	3895	106	804	8	317
Malaga	36 40	4 29	36	1896	38	647	155	1351
Menorca/Mahon	39 52	4E14	289	2216	3	454	258	1621
Moron AB	37 10	5 37	287	2069	281	1236	43	781
Rota Naval Station	36 39	6 21	86	1715	35	674	113	1269
Sevilla/San Pablo	37 25	5 54	112	2240	265	1207	236	1411
Torrejon AB/Madrid	40 29	3 27	1991	3905	94	833	5	101
Valencia	39 30	0 28	213	2469	13	637	250	1554
Zaragoza AB	41 40	1 02	863	3339	78	705	10	389
SWEDEN	N	E						
Goteborg/Torslanda	57 43	11 47	26	7145	0	22	0	14
Stockholm/Bromma	59 21	17 57	49	7832	0	48	0	28
SWITZERLAND	N	E						
Bern	46 55	7 30	1673	6450	1	84	0	41
Geneva/Cointrin	46 15	6 08	1411	5663	0	149	0	135
UNITED KINGDOM	N	W						
Aberdeen/Dyce/Scotland	57 12	2 12	236	6901	0	0	0	1
Alconbury RAF Sta	52 22	0 13	161	5732	0	17	1	23
Bentwaters RAF Sta	52 08	1E26	85	5685	0	5	0	20
Botley Hill	51 17	0E00	870	6395	0	1	1	30
Bovington	51 43	0 32	515	5852	0	15	1	30
Burtonwood Army Depot	53 24	2 39	75	5915	0	12	0	30
Chicksands RAF Sta	52 18	0 32	299	5732	0	17	1	23
Christmas Commons	51 38	0 58	794	6050	0	8	0	23
Cold Blow	51 18	0E37	630	6345	0	1	1	30
Croughton RAF Sta	51 59	1 12	400	5852	0	15	1	30
Daventry	51 12	1 05	500	5852	0	15	1	30
Dunkirk	51 18	0E59	250	5582	0	9	1	50
Edinburgh/Scotland	55 57	3 21	135	6518	0	1	0	3
Edzell/Scotland	56 49	2 36	155	6222	0	9	0	3
Felixstowe	51 58	1E28	101	5672	0	8	0	22
Flyingdales	54 22	0 40	761	6800	0	0	0	38
Garrowby Hill	54 00	0 46	777	6800	0	0	0	38
Greenham Common	51 23	1 17	397	5707	0	17	1	23
High Wycombe	51 38	0 46	500	5852	0	15	1	30
Lakenheath RAF Sta	52 24	0E34	33	5798	0	24	0	36
Leuchars/Scotland	56 23	2 52	39	6651	0	0	0	3
Liverpool Aprt	53 20	2 51	85	5646	0	9	0	31
London/Gatwick Aprt	51 09	0 11	204	5945	0	16	1	50
London/Heathrow Aprt	51 29	0 27	79	5188	0	26	0	43
Londonderry/N Ireland	55 00	7 17	50	5825	0	0	0	1
Martlesham Heath	52 03	1E14	22	5790	0	12	0	24
Menwith Hill Sta	53 59	1 42	492	6251	0	12	0	30
Mildenhall RAF Sta	52 22	0E29	33	5602	0	26	1	37
Molesworth	52 23	0 25	244	5732	0	17	1	23
Mormond Hill	57 36	2 02	745	7300	0	0	0	0
Oxford/Brize Norton	51 45	1 35	285	5938	0	18	1	28
Prestwick Aprt/Scotland	55 30	4 35	66	6404	0	1	0	5
Sculthorpe RAF Sta	52 50	0E45	217	5898	0	15	1	32

TABLE 4B—Winter heating degree day data for heating and summer criteria data for air conditioning for sites outside the United States. (*continued*)

AREA COUNTRY Station	Location			Degree Days, heating, annual	Summer Criteria Data Air Conditioning			
					Dry Bulb		Wet Bulb	
	Lat, °/min	Long, °/min	Elev, feet		≧ 93°F, h	≧ 80°F, h	≧ 73°F, h	≧ 67°F, h
South Ruislip	51 34	0 25	211	5188	0	26	0	43
Swingate	51 08	1E20	250	5304	0	2	3	59
Upper Heyford RAF Sta	51 56	1 15	436	5852	0	15	1	30
Wethersfield RAF Sta	51 58	0E30	331	5894	0	15	1	26
Woodbridge RAF Sta	52 05	1E24	95	5672	0	8	0	22
USSR	N	E						
Moscow/Sheremetievo	55 58	37 25	623	9583	4	98	3	110
YUGOSLAVIA	N	E						
Belgrade IAP	44 49	20 17	325	6067	9	368	31	510
INDIAN OCEAN								
CHAGOS ARCHIPELAGO	S	E						
Diego Garcia NB	7 20	72 25	8	0	0	3532	4335	4416
SEYCHELLES	S	E						
Mahe/Anse La Rue	4 40	55 31	10	0	0	1361	4017	4392
NORTH AMERICA								
CANADA	N	W						
Argentia NAS/Placentia	47 19	53 59	51	7754	0	0	0	17
Armstrong Ont	50 17	88 54	1056	12719	1	72	8	107
Brevoort Island NWT	63 21	64 10	1207	17780	0	0	0	0
Broughton Island NWT	67 33	63 47	1900	19351	0	0	0	0
Bryon Bay NWT	68 45	109 04	358	21004	0	0	0	0
Calgary Aprt Alta	51 06	114 01	3540	9703	0	93	0	2
Cambridge Bay Aprt NWT	69 06	105 07	82	22022	0	0	0	0
Cape Dyer NWT	66 35	61 37	1289	18354	0	0	0	0
Cape Harrison Nfld	54 46	58 27	33	10807	0	19	0	10
Cape Hooper NWT	68 26	66 47	1299	19417	0	0	0	0
Cape Parry NWT	70 10	124 41	56	19854	0	0	0	0
Cape Young NWT	68 56	116 55	59	19854	0	0	0	0
Churchill Man	58 54	94 04	98	16728	0	18	1	18
Clinton Point NWT	69 35	120 45	321	19854	0	0	0	0
Dewar Lakes NWT	68 39	71 14	1690	20524	0	0	0	0
Edmonton/Namao Aprt Alta	53 40	113 28	2256	10363	0	79	0	23
Fort Nelson BC	58 50	122 35	1230	13164	0	57	0	7
Fort Smith Aprt NWT	60 01	111 58	665	14176	0	52	0	22
Frobisher Bay NWT	63 45	68 33	68	17876	0	0	0	0
Gander IAP Nfld	48 57	54 34	482	9254	0	30	2	101
Gladman Point NWT	68 40	97 48	75	21873	0	0	0	0
Goose Bay AB Nfld	53 19	60 25	144	11887	2	49	1	23
Grande Prairie Alta	55 11	118 53	2190	11129	0	50	1	12
Halifax IAP NS	44 53	63 31	477	8327	0	36	5	166
Hall Beach NWT	68 47	81 15	26	21083	0	0	0	0
Hopedale AS Nfld	55 27	60 14	33	11680	0	2	0	2
Inuvik NWT	68 18	133 29	200	18200	0	9	0	1
Jenny Lind NWT	68 39	101 44	59	22022	0	0	0	0
Kamloops BC	50 43	120 25	1133	6799	40	390	1	56
Kapuskasing Aprt Ont	49 25	82 28	752	11560	1	100	14	153
Komakuk Beach YT	69 35	140 11	3	19994	0	0	0	0
Lady Franklin Point NWT	68 30	113 13	69	20938	0	0	0	0
Longstaff Bluff NWT	68 57	75 18	522	19444	0	0	0	0
Mackar Inlet NWT	68 18	85 41	1309	21466	0	0	0	0
Melville AS Nfld	53 18	60 32	934	12091	0	26	0	9
Montreal IAP Que	45 28	73 45	98	8157	2	205	79	545
Nicholson Peninsula NWT	69 54	128 58	321	19854	0	0	0	0
North Bay Ont	46 22	79 25	1210	9654	0	72	8	206
Ottawa IAP Ont	45 19	75 40	413	8693	3	210	56	448
Padloping Island NWT	67 06	62 21	130	16648	0	0	0	0
Pelly Bay NWT	68 26	89 43	1060	21426	0	0	0	1
Porquis Junction Ont	48 44	80 48	100	11400	2	115	9	133

TABLE 4B—Winter heating degree day data for heating and summer criteria data for air conditioning for sites outside the United States. (*continued*)

AREA COUNTRY Station	Location			Degree Days, heating, annual	Summer Criteria Data Air Conditioning			
					Dry Bulb		Wet Bulb	
	Lat, °/min	Long, °/min	Elev, feet		≧ 93°F, h	≧ 80°F, h	≧ 73°F, h	≧ 67°F, h
Port Hardy BC	50 41	127 22	75	6677	0	1	0	1
Prince George BC	53 53	122 41	2218	9755	0	60	0	1
Resolute Aprt NWT	74 43	94 59	209	22673	0	0	0	0
Resolution Island NWT	61 35	64 39	1201	17111	0	0	0	0
Saglek AS Nfld	58 28	62 39	269	11822	0	0	0	2
St Anthony Nfld	51 22	55 38	344	10639	0	0	0	18
St Johns/Torbay Aprt Nfld	47 37	52 45	463	8991	0	6	3	95
Sandspit BC	53 15	131 49	20	7182	0	0	0	1
Saskatoon Sask	52 10	106 41	1645	10856	6	213	1	52
Shepherd Bay NWT	68 49	93 26	167	21873	0	0	0	0
Shingle Point YT	68 57	137 13	174	19994	0	0	0	0
Sioux Lookout Ont	50 07	91 54	1280	11156	0	77	4	114
Stephenville Aprt Nfld	48 32	58 33	44	8717	0	5	1	35
The Pas Man	53 58	101 06	894	12476	1	75	8	95
Thunder Bay/Lakehead Ont	48 22	89 19	644	10568	0	87	10	127
Toronto IAP Ont	43 41	79 38	578	7468	7	306	95	571
Tuktoyaktuk NWT	69 27	133 00	59	19854	0	0	0	0
Vancouver IAP BC	49 11	123 10	16	5606	0	9	1	29
Whitehorse YT	60 43	135 04	2289	12475	0	18	0	0
Winnipeg IAP Man	49 54	97 14	786	10679	4	230	36	257
Yarmouth NS	43 50	66 05	136	7340	0	1	1	35
Yellowknife NWT	62 28	114 27	682	15634	0	6	0	1
GREENLAND	N	W						
Easterly Ice Cap	65 11	43 50	7998	23226	0	0	0	0
Kulusak	65 32	37 11	118	13140	0	0	0	0
Qaqatoqaqa	66 38	52 52	4721	17547	0	0	0	0
Sondrestrom AB	67 01	50 48	165	15278	0	0	0	0
Thule AB	76 32	68 42	253	19613	0	0	0	0
Westerly Ice Cap	66 29	46 17	7000	22104	0	0	0	0
MEXICO	N	W						
Mexico City/Tacubaya	19 24	99 11	7575	2572	2	245	0	1
PACIFIC OCEAN								
CAROLINE ISLANDS	N	E						
Koror/Central Babelthuap	7 22	134 33	186	0	0	2588	4384	4392
Koror Is Aprt	7 20	134 29	95	0	0	2588	4384	4392
Ponape	6 58	153 13	123	0	0	2388	4313	4416
Truk	7 28	151 51	6	0	2	3058	4404	4416
Yap	9 29	138 05	51	0	0	2667	4376	4392
FIJI ISLANDS	S	E						
Nandi	17 45	177 27	62	0	2	1896	3253	4331
JOHNSTON ISLAND	N	W						
Johnston AFB	16 44	169 32	7	0	0	2766	3926	4388
LINE ISLANDS	N	W						
Christmas Is Aprt	1 59	157 22	5	0	0	2425	4188	4344
MARIANA ISLANDS	N	E						
Guam/Agana NAS	13 29	144 48	298	0	1	2487	4305	4416
Guam/Andersen AFB	13 35	144 55	624	5	0	2301	4223	4416
Saipan/Kobler Fld	15 07	145 53	108	0	0	3533	4383	4392
Tinian/North Aux Afld	15 04	145 38	85	0	0	3533	4383	4392
Tinian/West Aux Afld	15 00	145 38	252	0	0	3538	4383	4392
MARSHALL ISLANDS	N	E						
Eniwetok	11 21	162 20	13	0	0	4098	4389	4392
Kwajalein/Bucholz AAF	8 43	167 44	9	0	2	3727	4410	4416
Majuro	7 06	171 24	10	0	0	3634	4385	4392
MIDWAY ISLAND	N	W						
Midway Island NAVSTA	28 12	177 23	12	119	0	901	1823	3729

TABLE 4B—Winter heating degree day data for heating and summer criteria data for air conditioning for sites outside the United States. *(continued)*

AREA COUNTRY Station	Location			Degree Days, heating, annual	Summer Criteria Data Air Conditioning			
					Dry Bulb		Wet Bulb	
	Lat, °/min	Long, °/min	Elev, feet		≧ 93°F, h	≧ 80°F, h	≧ 73°F, h	≧ 67°F, h
NEW ZEALAND	S	E						
Christchurch	43 29	172 32	123	4623	0	63	1	24
Mount John	43 59	170 28	3300	8828	0	2	0	0
Timaru	44 18	171 14	89	4623	0	63	1	24
Wellington Aprt	41 20	174 48	40	3298	0	1	0	17
OCEAN STATION VESSELS	N	W						
N	30 00	140 00	0	410	0	0	0	619
V	34 00	164 00	0	788	0	413	1724	3189
PHILIPPINE ISLANDS	N	E						
Baguio	16 25	120 36	4921	157	0	64	1	1077
Clark AB	15 11	120 33	478	0	69	1955	3671	4411
Cubi Point NAS	14 47	120 17	55	0	85	2590	4189	4416
John Hay AB	16 24	120 37	4951	157	0	64	1	1077
Manila	14 31	121 01	74	0	122	2148	4258	4413
Sangley Pt FWC	14 30	120 54	8	0	42	3329	4343	4416
San Miguel	14 58	120 04	13	0	85	2590	4189	4416
Subic Bay NB	14 49	120 17	12	0	85	2590	4189	4416
Wallace AS	16 35	120 19	10	0	85	2590	4189	4416
PHOENIX ISLANDS	S	W						
Birnie Is	3 35	171 31	8	0	3	3843	4346	4416
Canton Aux Afld	2 46	171 43	10	0	3	3843	4346	4416
Enderbury Is	3 09	171 05	8	0	3	3843	4346	4416
Hull Is	4 30	172 14	5	0	3	3843	4346	4416
SOCIETY ISLANDS	S	W						
Tahiti Is/FAAA Aprt	17 33	149 37	7	0	0	1574	2843	4329
WAKE ISLAND	N	E						
Wake Island AFB	19 17	166 38	14	0	0	3558	4325	4389
SOUTH AMERICA								
ARGENTINA	S	W						
Buenos Aires/Ezeiza	34 50	58 32	65	2196	38	519	162	1127
La Quiaca	22 06	65 36	11348	5916	0	1	0	0
BRAZIL	S	W						
Belem/Valdecas	1 23	48 29	52	0	2	1526	4049	4391
Rio de Janeiro Aprt	22 54	43 10	10	4	51	1792	2852	4144
CHILE	S	W						
Santiago/Pupahuel	33 23	70 47	1575	2627	7	720	5	206
COLUMBIA	N	W						
Bogota/Eldorado	4 42	74 08	8356	3706	0	0	0	1
EQUADOR	S	W						
Quito/Mariscal Sucre	0 08	78 29	9222	3465	0	0	0	0
FRENCH GUIANA	N	W						
Cayenne	4 49	52 22	30	0	2	1780	4122	4416
PARAGUAY	S	W						
Asuncion/Stroessner	25 14	57 31	292	276	352	1679	1521	3758
PERU	S	W						
Lima/Callao	12 01	77 07	112	262	0	113	104	2546
SURINAM	N	W						
Zanderij/Paramaribo	5 27	55 12	54	0	154	1918	4085	4392
URUGUAY	S	W						
Montevideo/Carrasco	34 50	56 02	75	1942	16	359	88	885
VENEZUELA	N	W						
Caracas/La Carlota	10 30	66 53	2740	36	0	684	177	3444

TABLE 4C—Cooling degree day data for sites in the United States.

STATE Station	Annual Cooling, Degree Days
ALABAMA	
Alabama Ordnance Works	1886
Anniston Army Depot	1886
Birmingham MAP	1928
Brookley AFB/Mobile	2549
Craig AFB/Selma	2550
Florence	1834
Fort McClellan/Reilly AAF	1886
Fort Rucker/Cairns AAF	2386
Gadsden	1751
Gunter AFS	2489
Hall ANG Station	2386
Hunter Loop Comm Facility	2489
Huntsville	1808
Maxwell AFB/Montgomery	2489
Mobile/Bates Field	2577
Montgomery/Dannelly Field	2238
Muscle Shoals	1834
Redstone Arsenal	1808
Sheffield	1834
Tuscaloosa MAP	2138
ALASKA	
Anchorage IAP	0
Annette	14
Barrow	0
Bethel	0
Bettles	0
Big Delta/Allen AAF	34
Cold Bay AFS	0
Cordova	0
Eielson AFB/Fairbanks	30
Elmendorf AFB/Anchorage	8
Fairbanks IAP	52
Gulkana	9
Homer	0
Juneau MAP	0
King Salmon	0
Kodiak	0
Kotzebue	0
McGrath MAP	14
Nenana	19
Nome MAP	0
Northway Aprt	19
St. Paul Island	0
Shemya AFB	0
Sitka	0
Tanana	20
Unalakleet	0
Yakutat	0
ARIZONA	
Davis-Monthan AFB/Tucson	2985
Flagstaff	140
Fort Huachuca/Libby AAF	1573
Gila Bend	3943
Holbrook	1091
Luke AFB/Glendale	3601
Navajo Army Depot	140
Phoenix/Sky Harbor IAP	3508
Tucson IAP	2896
Williams AFB/Chandler	3503
Winslow MAP	1203
Yuma MCAS/IAP	4195
Yuma Test Station	4261
ARKANSAS	
Blytheville AFB	1789
El Dorado/Goodwin Field	2204
Fayetteville/Drake Field	1487
Fort Chaffee	2022
Fort Smith MAP	2022
Harrison	1447
Hot Springs	2205
Little Rock/Adams Field	1925
Little Rock AFB	2034
Pine Bluff Arsenal	2314
Texarkana/Webb Field MAP	2245
Walnut Ridge MAP	1938
CALIFORNIA	
Alameda NAS/Nimitz Field	189
Arcata	0
Bakersfield/Meadows Field	2179
Barstow-Daggett Aprt	2729
Beale AFB/Marysville	1525
Berkeley	86
Bishop	1037
Blue Canyon Aprt	302
Burbank	1179
Camp Parks Comm Annex	713
Camp Roberts	699
Castle AFB/Merced	1566
Centerville Beach	0
Chico MAP	1385
China Lake NAF/Armitage Fld	2549
Chula Vista	333
Compton	1085
Concord NAD	713
Corona	1154
Coronado	409
Costa Mesa ANG Station	674
Crows Landing	1171
Cuddeback Dry Lake Range	1829
Daggett	2729
Dixon	995
Edwards AFB	1829
El Centro NAF	4370
El Toro MCAS/Santa Ana	867
Fallbrook Annex	907
Fort Baker	0
Fort Barry	0
Fort Irwin	2272
Fort MacArthur	615
Fort Mason	0
Fort Ord/Fritzsche AAF	37
Fresno/Air Terminal	1671
George AFB/Victorville	1807
Hamilton AFB/San Rafael	244
Imperial Beach NF/Ream Fld	409
Klamath AFS	7
Kramer	1829
Lemoore NAS/Reeves Field	1771
Letterman Army Hospital	0
Livermore	713
Long Beach	615
Long Beach/Daugherty Field	985
Los Alamitos NAS	674
Los Angeles City Office	1185
Los Angeles IAP	615
March AFB/Riverside	1343

TABLE 4C—Cooling degree day data for sites in the United States. (*continued*)

STATE Station	Annual Cooling, Degree Days
Mare Island NAVSHIPYD	244
Mather AFB/Sacramento	1303
McClellan AFB/Sacramento	1406
Miramir NAS/Mitscher Field	717
Moffett Field NAS	239
Mojave	1958
Montague/Siskiyou Co Aprt	562
Monterey FWC	32
Monterey/Presidio	32
Mt Laguna AFS	449
North Highlands ANGB	1406
Norton AFB/San Bernardino	1499
Oakland Army Base	128
Oakland IAP	128
Oakland Navy Hospital	420
Ontario IAP	1499
Palmdale	1724
Pasadena	1187
Pendleton MCB	717
Pendleton MCB Coast	584
Pillar Point AFS	5
Pt Arena AFS	0
Pt Arguello	0
Pt Mugu NAS/Port Hueneme	200
Pt Sur NF	32
Pamona	1109
Port Hueneme	200
Red Bluff MAP	1904
Red Mountain Flight Annex	2113
Riverbank AAP	1566
Sacramento	1159
Sacramento Army Depot	1159
San Bernardino	1557
San Bruno	108
San Clemente Is NALF	201
Sandberg	800
San Diego FWF	584
San Diego IAP	722
San Francisco IAP	108
San Francisco/Presidio	39
San Jose MAP	444
San Luis Obispo	246
San Nicolas Island	204
San Pedro	615
San Rafael	280
Santa Ana MCAS	972
Santa Barbara MAP	218
Santa Catalina	613
Santa Maria	84
Santa Rosa/Sonoma Co Aprt	315
Seal Beach NAD	615
Shafter AFS	2179
Sharpe Army Depot	1259
Skaggs Is NSGA	244
Stockton	1259
Sunnyvale	239
Travis AFB/Fairfield	831
Treasure Is NS	189
Twentynine Palms MCB	2948
Two Rock Ranch Station	293
Vandenberg AFB/Lompoc	66
Van Nuys/Los Angeles	1179
West Coast Radio Station	781

STATE Station	Annual Cooling, Degree Days
COLORADO	
Buckley ANGB/Denver	582
Colorado Springs/Peterson	461
Denver/Stapleton IAP	625
Ent AFB/Colorado Springs	561
Fitzsimons AH/Denver	625
Fort Carson/Butts AAF	692
Grand Junction/Walker Field	1140
La Junta	998
Lamar	1199
Lowry AFB/Denver	625
Pueblo Army Depot	981
Pueblo Memorial Aprt	981
Rocky Mountain Arsenal	625
Trinidad	705
USAF Academy/Colorado Springs	100
CONNECTICUT	
Bradley IAP/Windsor Locks	584
Bridgeport	735
Groton	376
Hartford/Brainard Aprt	605
New Haven	573
Stamford	735
Waterbury	547
DELAWARE	
Dover AFB	1115
Lewes	957
Wilmington	992
Wilmington Airport	992
DISTRICT OF COLUMBIA	
Army Map Service	1291
Bolling-Anacostia Mil Cmplx	1517
Fort McNair	1517
Walter Reed Army Medical Cen	1217
Washington National Aprt	1415
Washington Navy Yard	1517
FLORIDA	
Apalachicola	2663
Avon Park	3656
Big Coppitt Key	4663
Bowman Bayou	2679
Brandon	3298
Cape Canaveral AFS	2813
Clausen	2370
Cocoa Beach	3405
Daytona Beach	2919
Eglin AFB/Valparaiso	2620
Fort Lauderdale	3967
Fort Myers/Page Fld	3711
Gainesville MAP	2906
Homestead AFB	3906
Hurlburt Field/Eglin No 9	2370
Jacksonville AFS	3059
Jacksonville/Cecil Fld NAS	2775
Jacksonville IAP	2596
Jacksonville NAS/Towers Fld	3059
Jupiter	3786
Key West IAP	4888
Key West NAS	4663
Lakeland	3298
Lynn Haven	2778
Macdill AFB/Tampa	3493
Mayport NAVSTA	2683
McCoy AFB/Orlando	3354

TABLE 4C—Cooling degree day data for sites in the United States. (*continued*)

STATE Station	Annual Cooling, Degree Days
Melbourne Beach	3265
Miami IAP	4038
Milton/Whiting Field NAS	2588
Orlando	3447
Panama City/Bay County	2778
Patrick AFB/Cocoa Beach	3405
Pensacola/Ellyson Field NAS	2562
Pensacola NAS/F Sherman Fld	2642
Pensacola/Saufley Field NAS	2562
Ponce de Leon	2919
Richmond AFS	3906
Rivera Beach	3786
St. Augustine	2794
St. Petersburg/Clearwater IAP	3410
Tallahassee MAP	2563
Tampa IAP	3366
Tyndall AFB/Panama City	2737
Valkaria	3352
Vero Beach	3512
West Palm Beach	3786
GEORGIA	
Albany NAS/Turner AFB	2631
Athens MAP	1722
Atlanta Army Depot	1589
Atlanta/Hartsfield IAP	1589
Atlanta NAS/Dobbins AFB	1611
Augusta/Bush Field	1995
Augusta/Daniel Field	1995
Columbus Metro Aprt	2143
Dobbins AFB/Marietta	1611
Fort Benning/Lawson AAF	2203
Fort Gordon	1995
Fort McPherson/Atlanta	1589
Fort Stewart/Wright AAF	2414
Glynco NAS/Brunswick	2423
Hunter AAF/Savannah	2372
Macon/L B Wilson Aprt ANG	2294
McCollum Aprt ANG/Marietta	1611
McKinnon Aprt ANG/Brunswick	2774
Moody AFB/Valdosta	2716
Moultrie/Spence AF Aux Fld	2513
Robins AFB/Macon	2276
Rome/Russell Field	1615
Savannah AFS	2372
Savannah ANG Sta	2372
Savannah MAP ANG	2317
Statesboro Radar Bomb Site	2317
Turner AFB/Albany NAS	2631
HAWAII	
Barbers Point NAS	3929
Barking Sands	3497
Bellows AFB	3719
Ford Island	4221
Ft DeRussy	4221
Ft Ruger	3881
Ft Shafter	4221
Helemano	2807
Hickam AFB/Honolulu IAP	4221
Hilo	3066
Kaala AFS	24
Kaena Point	1850
Kahului	3732
Kaneohe Bay MCAS	4080
Kunia Comm Annex	2821
Lihue	3719
Palehua AF Solar Obsy	1925
Pearl Harbor	4221
Punamano AFS	3623
Schofield Barracks	2821
South Point AFS	2873
Tripler Army Hospital	4221
Wahiawa	2821
Wheeler AFB	2821
IDAHO	
Boise	714
Idaho Falls/Fanning Fld	286
Lewiston	657
Mountain Home AFB	907
Pocatello	437
Saylor Creek	513
Twin Falls	399
Wilder	568
ILLINOIS	
Chanute AFB	1052
Chicago/Midway Aprt	925
Chicago/O'Hare IAP	664
Danville/Vermilion Co	997
Decatur	1197
Forest Park NOP	925
Fort Sheridan/Haley AAF	826
Galesburg MAP	951
Glenview NAS	832
Granite City Army Depot	1640
Great Lakes NTC	826
Joliet MAP	933
Moline/Quad City Arpt	893
Peoria	968
Quincy MAP	1380
Rock Island Arsenal	1007
Savanna Army Depot	741
Scott AFB/Belleville	1421
Springfield/Capital	1116
INDIANA	
Anderson MAP	981
Bakalar AFB/Columbus	1017
Bloomington/Monroe County	1177
Camp Atterbury	1017
Crane	1302
Evansville/Dress Rgnl Aprt	1364
Fort Benjamin Harrison	974
Fort Wayne/Baer Fld	748
Gary MAP	859
Grissom AFB/Bunker Hill	837
Indiana AAP	1268
Indianapolis/Weir Cook MAP	974
Jefferson Proving Ground	1191
Newport AAP	1094
South Bend/St Joseph Aprt	695
Terre Haute/Hulman Fld	1110
IOWA	
Burlington MAP	994
Cedar Rapids MAP	812
Des Moines MAP	928
Dubuque MAP	606
Fort Dodge MAP	779

TABLE 4C—Cooling degree day data for sites in the United States. (*continued*)

STATE Station	Annual Cooling, Degree Days
Iowa Army Ammunition Plant	994
Iowa City MAP	886
Mason City MAP	580
Sioux City MAP	932
Waterloo MAP	675
KANSAS	
Chanute	1595
Dodge City	1411
Forbes ANGB/Topeka	1430
Fort Leavenworth/Sherman AAF	1292
Fort Riley/Marshall AAF	1503
Goodland/Renner Fld	925
Hutchinson MAP	1626
Kansas City/Fairfax MAP	1420
Kansas Ordnance Plant	1808
McConnell AFB/Wichita	1687
Olathe NAS	1370
Parsons/Tri City	1677
Salina MAP	1627
Schilling Manor	1627
Smoky Hill AF Range	1626
Sunflower Ordnance Works	1370
Topeka/Philip Billard	1361
Wichita	1673
KENTUCKY	
Ashland	1173
Blue Grass Army Depot	1197
Covington	1080
Fort Campbell/Campbell AAF	1472
Fort Knox/Godman AAF	1360
Lexington/Blue Grass Field	1197
Louisville/Standiford Field	1268
Owensboro	1444
Richmond	1197
LOUISIANA	
Alexandria/Esler Field	2193
Barksdale AFB/Shreveport	2451
Baton Rouge/Ryan Aprt	2585
Claibourne	2606
England AFB/Alexandria	2606
Fort Polk/Polk AAF	2666
Hammond ANG Comm Sta	2575
Lafayette	2632
Lake Charles AFS	2739
Lake Charles MAP	2739
Louisiana Ordnance Plant	2451
Monroe MAP	2367
New Orleans Army Terminal	2706
New Orleans/Moisant IAP	2706
New Orleans NAS	2703
Shreveport	2538
MAINE	
Augusta	271
Bangor IAP/Dow AFB	304
Bar Harbor	167
Brunswick NAS	308
Bucks Harbor AFS	121
Caribou MAP	128
Caswell AFS	152
Charleston AFS	93
Loring AFB	152
Millinocket	231
Portland	252
Searsport	200
Winter Harbor	167
MARYLAND	
Aberdeen PG/Phillips AAF	1076
Andrews AFB	1237
Annapolis USNA	1155
Bainbridge NTC	1076
Baltimore/Martin Aprt	1115
Baltimore/Washington IAP	1108
Bethesda NAVNATMEDCEN	1147
Cumberland MAP	828
Edgewood Arsenal	1115
Fort Detrick	948
Fort Holabird	1491
Fort Meade/Tipton AAF	1039
Fort Richie	688
Frederick	948
Hagerstown	891
Indian Head NOS	1348
Patuxent River NAS	1377
White Oak NAVSURFWPNCEN	1161
MASSACHUSETTS	
Army Mat/Mech Res Cen	661
Boston/Logan IAP	661
Boston Navy Base	661
Fall River	599
Fort Devens/Devens AAF	560
Hanscom AFB/Bedford	591
Lawrence MAP	566
Lynn	661
Maynard	591
Nantucket	284
Natick Laboratories	636
New Bedford MAP	635
North Truro AFS	502
Otis AFB/Falmouth	490
Pittsfield MAP	317
Quincy	661
Salem	450
South Weymouth NAS	666
Springfield	740
Wellesly ANG Station	636
Westfield/Barnes MAP	584
Westover AFB	584
Worcester	387
MICHIGAN	
Alpena/Phelps Collins Field	208
Ann Arbor	706
Battle Creek Aprt	628
Bayshore	349
Benton Harbor/Ross Field	638
Calumet AFS	105
Detroit Arsenal	743
Detroit/City Aprt	743
Empire AFS	302
Flint/Bishop Aprt	438
Grand Rapids/Kent County	575
Hancock/Houghton Co Mem	167
Houghton	167
Kincheloe AFB	173
K I Sawyer AFB	198

TABLE 4C—Cooling degree day data for sites in the United States. (*continued*)

STATE Station	Annual Cooling, Degree Days
Lansing/Capital City Aprt	535
Michigan Army Missile Plant	743
Mount Clemens NAF	661
Muskegon/Muskegon Co Aprt	469
Port Austin AFS	366
Port Huron	605
Saginaw/Tri City Aprt	487
Sault Sainte Marie AFS	139
Selfridge ANGB/Mt Clemens	661
Traverse City Aprt	376
Wurtsmith AFB/Oscada	363
Ypsilanti	726
MINNESOTA	
Baudette AFS	254
Bemidji MAP	241
Duluth IAP	176
Finland AFS	148
International Falls IAP	176
Minneapolis-St. Paul IAP	527
Rochester MAP	474
Twin Cities Ordnance Plant	527
MISSISSIPPI	
Columbus AFB	2039
Gulfport	2682
Jackson/Allen Thompson Fld	2321
Keesler AFB/Biloxi	2793
Meridian/Key Field ANG	2231
Meridian NAS/McCain Fld	1935
MISSOURI	
Columbia Regional Aprt	1269
Fort Leonard Wood/Forney AAF	1314
Gateway AAP	1605
Hannibal	1138
Jefferson Barracks ANG	1640
Joplin MAP	1670
Kansas City MAP	1420
Lake City Arsenal	1261
Malden MAP	1780
Richards-Gebaur AFB/Grandview	1261
St. Joseph/Rosecrans Aprt	1334
St. Louis AFS	1475
St. Louis/Lambert IAP	1475
St. Louis Ordnance Depot	1640
Springfield MAP	1382
Whiteman AFB/Knob Noster	1410
MONTANA	
Billings/Logan IAP	498
Butte	58
Cut Bank	140
Dillon	199
Glasgow AFB	404
Great Falls IAP	339
Havre AFS	304
Helena	256
Kalispell AFS	9
Lewistown	192
Malmstrom AFB	370
Miles City	752
Missoula	188
Opheim AFS	350
NEBRASKA	
Cornhusker AAP	1036
Grand Island	1036
Hastings MAP	1107
Lincoln MAP	1148
North Platte/Lee Bird Fld	802
Offutt AFB	1157
Omaha/Eppley Airfield	1173
Scottsbluff	666
NEVADA	
Bald Mountain	102
Beatty	826
Carson City	354
Cherry Creek	16
Desert Rock Camp	1898
Egan Range	300
Elko MAP	342
Ely	207
Fallon AFS	892
Fallon NAS/Van Voorhis Fld	892
Goshute	124
Hawthorne NAD	487
Indian Springs AF Aux Fld	1998
Las Vegas/McCarran IAP	2946
Nellis AFB/Las Vegas	3089
Reno IAP	329
Stead AFB/Reno	385
Tonopah AFS	262
Tonopah MAP	631
Winnemucca AFS	102
Winnemucca MAP	407
Worthington Mountain	308
NEW HAMPSHIRE	
Concord MAP	349
Grenier Fld/Manchester	378
Hanover	327
Manchester	378
NH Satellite Tracking	320
Pease AFB/Portsmouth	481
Portsmouth	252
NEW JERSEY	
Atlantic City	864
Bayonne NSC	1024
Burlington Ordnance Plant	1181
Camden	1104
Clifton	958
Coyle ANG	983
Dover	504
Earle NAD	770
Elizabeth	953
Fort Dix	983
Fort Hancock	951
Fort Monmouth	770
Gibbsboro AFS	872
Jersey City	871
Lakehurst NAS	947
McGuire AFB	983
Newark IAP	1024
Perth Amboy	1024
Picatinny Arsenal	430
Trenton	968
NEW MEXICO	
Albuquerque IAP/Kirtland AFB	1394
Cannon AFB/Clovis	1297
Carlsbad	1993
Cloudcroft	36
Farmington MAP	749

TABLE 4C—Cooling degree day data for sites in the United States. (*continued*)

STATE Station	Annual Cooling, Degree Days
Holloman AFB/Alamogordo	1870
Kirtland AFB/Albuquerque IAP	1394
Las Cruces	1585
Melrose Range	1230
Roswell	1560
Sacramento Peak	122
Truth Or Consequences	1558
Tucumcari	1357
Walker AFB/Roswell	1560
White Sands Missile Range	2243
Wingate Army Depot	593
Zuni	473
NEW YORK	
Albany	574
Army Procurement Center	1048
Binghampton/Broome Co Aprt	369
Brooklyn Navy Shipyard	1048
Buffalo IAP	437
Camp Drum	452
Dunkirk MAP	373
Fort Hamilton	861
Fort Tilden	861
Fort Totten	1048
Fort Wadsworth	861
Freeport	861
Glen Falls/Warren Co Aprt	495
Griffiss AFB/Rome	472
Huntington	881
Ithaca/Tompkins Co Aprt	384
Jamestown/Chautauqua Co	470
Liverpool	551
Lockport AFS	493
Montauk AFS	359
New Rochelle	913
New York/JFK IAP	861
New York/La Guardia Aprt	1048
New York NB	1048
Newburgh/Stewart Aprt	731
Niagara Falls IAP	549
Ogdensburg	417
Oswego	435
Plattsburg AFB	341
Poughkeepsie/Dutchess Co	809
Rochester/Monroe Co Aprt	531
Roslyn	881
Saint Albans NAVHOSP	861
Saratoga AFS	540
Schenectady	642
Seneca Army Depot	655
Suffolk Co/Westhampton Bch	547
Syracuse/Hancock IAP	591
Troy	574
Utica/Oneida Co Aprt	467
Watertown IAP	461
Watervliet Arsenal	654
Westchester Co/White Plains	810
West Point USMA	830
Whitestone	1048
Yonkers	913
Youngstown	549
NORTH CAROLINA	
Asheville MAP	872
Badin ANG	1596
Camp Lejeune MCS	1810
Cape Hatteras	1550
Charlotte/Douglas MAP	1596
Cherry Point MCAS	1922
Dare County	1617
Edenton Recovery Site	1622
Elizabeth City CGAS/MAP	1593
Fort Bragg/Simmons AAF	1760
Fort Fisher AFS	1901
Greensboro	1341
New River MCAS	1810
Pope AFB/Fayetteville	1828
Raleigh/Raleigh-Durham Aprt	1394
Roanoke Rapids AFS	1492
Seymour Johnson AFB	1769
Sunnypoint Mil Ocean Trml	1901
Wadesboro ANG	1679
Wilmington/New Hanover Co	1964
Winston-Salem	1546
NORTH DAKOTA	
Bismarck MAP	487
Dickinson MAP	399
Fargo/Hector Field	473
Finley AFS	337
Fortuna AFS	376
Grand Forks AFB	400
Minot AFB	398
OHIO	
Akron/Akron-Canton Aprt	634
Blue Ash ANGB/Cincinnati	1080
Camp Perry ANG	857
Chillicothe	1017
Cincinnati Aprt/Covington	1080
Cleveland/Hopkins IAP	613
Clinton County AFB/Wilmington	908
Columbis IAP	809
Dayton MAP	936
Fort Hayes	809
Gentile AFS	1036
Lima/Allen Co Aprt	828
Lima Ordnance Mod Center	828
Lorain Co Reg Aprt	676
Mansfield/Lahm MAP	818
Newark	761
Portsmouth	1217
Ravenna AAP	577
Rickenbacker AFB/Columbus	933
Ridgewood AAP	1080
Springfield MAP	1009
Toledo/Toledo Express Aprt	685
Wright-Patterson AFB/Dayton	1036
Youngstown MAP	518
Zanesville MAP	754
OKLAHOMA	
Altus AFB	2347
Clinton-Sherman AFB	1904
Fort Sill/Post AAF	2217
McAlster NAD	2106
Norman	2067
Oklahoma City AFS	2068
Oklahoma City Aprt	1876
Stillwater/Searcy Field	1947
Tinker AFB/Oklahoma City	2068
Tulsa IAP	1949
Vance AFB/Enid	2088

TABLE 4C—Cooling degree day data for sites in the United States. (*continued*)

STATE Station	Annual Cooling, Degree Days
OREGON	
Astoria	13
Burns	289
Corvallis MAP	231
Eugene	239
Grants Pass	553
Keno AFS	50
Kingsley Field	228
Klamath Falls	228
Medford	562
Mt Hebo AFS	27
North Bend AFS	0
Pendleton	656
Portland IAP	300
Redmond	170
Salem/McNary Field	232
Umatilla Army Depot	738
PENNSYLVANIA	
Allentown	772
Altoona/Blair Co Aprt	617
Brookville	417
Carlisle Barracks	995
Columbia	1025
Erie IAP	373
Folsom	1104
Fort Indiantown Gap	945
Frankford Arsenal	1104
Harrisburg IAP/Olmsted	1025
Johnstown/Cambria Co Aprt	170
Lancaster	826
Letterkenny Army Depot	793
Mechanicsburg	1025
New Castle	665
New Cumberland Chem Plant	1025
Philadelphia IAP	1104
Philipsburg	277
Pittsburgh/Gtr Pittsburg IAP	647
Reading MAP	1066
Scranton AAP	630
State College ANG Station	583
Tobyhanna Army Depot	434
Valley Forge General Hosp	950
Wilkes-Barre-Scranton Aprt	608
Williamsport	698
Willow Grove NAS	946
RHODE ISLAND	
Davisville	690
Newport NB	690
North Kingston ANG Sta	690
North Smithfield ANG Sta	502
Providence/Theo T Green MAP	532
Quonset Point NAS	690
SOUTH CAROLINA	
Aiken AFS	2012
Beaufort MCAS	2294
Charleston AFB/MAP	2078
Charleston Army Depot	2078
Columbia	2087
Donaldson AFB/Greenville	1650
Florence MAP	1952
Fort Jackson	2087
Georgetown	2170
Greenville-Spartanburg Aprt	1573
McEntire ANGB/Columbia	1781
Myrtle Beach AFB	1823
North Charleston AFS	2078
North Field	2087
Parris Island MARCORPCRUITDEP	2294
Pointsett	2160
Shaw AFB/Sumter	2160
Sumter	2078
SOUTH DAKOTA	
Aberdeen MAP	566
Ellsworth AFB/Rapid City	738
Huron	716
Pierre MAP	858
Rapid City	661
Sioux Falls/Foss Fld	719
TENNESSEE	
Alcoa ANG Sta	1569
Arnold Eng Dev Cen	1212
Bristol/Tri City Aprt	1107
Chattanooga/Lovell Field	1636
Holston Ordnance Works	1235
Kingsport	1235
Knoxville/Alcoa ANG Sta	1569
Memphis Army Depot	2029
Memphis IAP	2029
Memphis NAS/Millington	1996
Milan Ordnance Plant	1637
Nashville	1694
Stewart AFB/Smyrna	1694
Tullahoma Aprt	1423
Tullahoma/Arnold AFS	1212
Volunteer Ordnance Works	1636
TEXAS	
Abilene MAP	2466
Aero Maintenance Center	3474
Amarillo	1433
Austin/Robert Mueller MAP	2908
Beaumont/Jefferson Co	2798
Beaumont Army Hospital	2098
Beeville/Chase Field NAS	3389
Bergstrom AFB/Austin	3078
Brooke Army Medical Center	2994
Brooks AFB	3339
Brownsville IAP	3874
Brownwood	2588
Camp Bullis	2270
Carswell AFB/Fort Worth	2858
Corpus Christi IAP	3474
Corpus Christi NAS	3687
Dallas/Love Field	2755
Dallas NAS/Hensley Field	2751
Del Rio IAP	3363
Dyess AFB/Abilene	2500
Eagle Pass AFS	3621
Ellington AFB/Houston	2937
El Paso IAP	2098
Fort Bliss/Biggs AAF	2253
Fort Hood/Hood AAF	2792
Ford Hood/Robert Gray AAF	2792
Fort Sam Houston	2994
Fort Wolters	2440
Fort Worth IAP	2587
Galveston	3004

TABLE 4C—Cooling degree day data for sites in the United States. (*continued*)

STATE Station	Annual Cooling, Degree Days
Garland ANG Station	2755
Goodfellow AFB/San Angelo	2702
Harlingen	3939
Hondo MAP	3009
Houston IAP	2889
Kelly AFB/San Antonio	3190
Kingsville NAS	3669
Lackland AFB	3190
Laredo IAP	4137
Laredo AFB	4137
Laughlin AFB	3281
Lone Star Ordnance Plant	2245
Longhorn Ordnance Works	2459
Lubbock	1647
Lufkin AFS	2592
Midland	2250
Nederland ANG Station	2798
Oilton Msl Tracking Site	4137
Orange	2739
Paris/Cox Field	2247
Perrin AFB/Sherman	2337
Port Arthur	2798
Randolph AFB/San Antonio	2995
Red River Army Depot	2245
Reese AFB/Lubbock	1738
San Angelo/Mathis Field	2702
San Antonio IAP	2994
San Antonio AFS	2994
Sheppard AFB/Wichita Falls	2606
Tyler/Pounds Field	2388
Waco/James Connally Aprt	2878
Waco/Madison Cooper	2863
Webb AFB/Big Spring	2382
Wichita Falls MAP	2611
UTAH	
Bryce Canyon	41
Cedar City	615
Deseret Test Center	639
Dugway PG/Michaels AAF	1088
Hill AFB/Ogden	920
Hill AF Range	1051
Ogden MAP	814
Provo	892
Salt Lake City IAP	927
Tooele Army Depot	859
Utah Army Depot	814
Wendover AF Range	1137
VERMONT	
Burlington IAP	396
St Albans AFS	280
VIRGINIA	
Arlington Hall	1415
Bedford AFS	194
Cameron Station	1415
Camp A P Hill	1188
Camp Pickett/Blackstone AAF	1319
Cape Charles AFS	1509
Charlottesville	1263
Dahlgren NAVSURFWPNCEN	1348
Dam Neck	1485
Dulles IAP	940
Fort Belvoir/Davison AAF	1120
Fort Eustis/Felker AAF	1585
Fort Lee	1353
Fort Lee AFS	1353
Fort Monroe	1539
Fort Myer	1415
Fort Story	1485
Langley AFB/Hampton	1539
Little Creek NAVPHIBASE	1441
Lynchburg MAP	1100
Manassas/Davis Field	1188
Newport News/Patrick Henry	1539
Norfolk	1441
Norfolk NAS/Chambers Field	1707
Oceana NAS	1485
Portsmouth	1441
Quantico MCAS	1348
Radford Ordnance Works	755
Richmond/Byrd IAP	1353
Richmond Quartermaster Depot	1353
Roanoke/Woodrum Aprt	1030
Staunton/Shenandoah Valley	1030
Vint Hill Farms Station	940
Williamsburg	1345
Yorktown	1539
WASHINGTON	
Aberdeen	13
Bangor	89
Bellingham IAP	44
Blaine AFS	44
Bremerton NAVSHIPYD	89
Ephrata MAP	941
Everett	49
Fairchild AFB/Spokane	416
Fort Lawton	60
Fort Lewis/Gray AAF	110
Four Lake Comm Sta ANG	416
Keyport	89
Longview	135
Madigan Army Hospital	94
Makah AFS	0
Marietta	44
McChord AFB/Tacoma	94
Mica Peak AFS	109
Moses Lake/Grant Co	707
Olympia	101
Othello AFS	666
Paine AFB/Everett	60
Pasco/Tri-Cities Aprt	826
Seattle NSA	162
Seattle-Tacoma IAP	129
Spokane IAP	388
Tacoma	138
Tatoosh Island	0
Walla Walla Aprt	793
Whidbey Island/Ault Fld	6
Whidbey Is/Oak Harbor	24
Yakima Firing Center	479
Yakima MAP	479
WEST VIRGINIA	
Beckley/Raleigh Co Aprt	490
Charleston/Kanawha Aprt	1055
Elkins/Randolph Co Aprt	389
Fairmont	841
Huntington	1098

TABLE 4C—Cooling degree day data for sites in the United States. (*continued*)

STATE Station	Annual Cooling, Degree Days
Martinsburg MAP	922
Parkersburg	1045
Wheeling/Ohio Co Aprt	647
WISCONSIN	
Antigo AFS	318
Badger Ordnance Works	631
Camp McCoy	573
Green Bay/Austin-Straubel	386
La Crosse MAP	695
Madison/Truax Field	460
Milwaukee/Gen Mitchell Fld	450
Oshkosh/Wittman Field	547
Volk Field ANG/Camp Douglas	708
WYOMING	
Casper IAP	458
Cheyenne MAP	327
F E Warren AFB/Cheyenne	327
Lander/Hunt Field	383
Rock Springs	227
Sheridan	446

TABLE 4D—Cooling degree day data for sites outside the United States.

Area Country Station	Annual Cooling, Degree Days
Africa	
Algeria	
Alger	1453
Ethiopia	
Addis Ababa	507
Kenya	
Mandera	7004
Libya	
Benghazi	2322
Wheelus AB	2167
Morocco	
Kenitra/Port Lyautey	1044
Rabat-Sale	781
Somalia	
Mogadiscio	5551
South Africa	
Pretoria	1543
Sudan	
Khartoum	7576
United Arab Republic/Egypt	
Alexandria/Nouzha	2243
Cairo IAP	3089
Asia	
Aden	
Aden IAP	6945
Afghanistan	
Kabul IAP	1171
China	
Peking	1486
Shanghai	1816
Hong Kong	
Hong Kong IAP	3266
India	
Bombay	5886
Calcutta	5811
Hyderabad	5317
Madras	6855
New Delhi	5230
Iran	
Abadan IAP	5641
Esfahan	2005
Kerman	1736
Tehran/Mehrabad IAP	2286
Israel	
Jerusalem	1415
Tel Aviv	1932
Japan	
Atsugi NAS	1278
Futema MCAS/Okinawa	3141
Itazuke Aux Airfield	1566
Iwakuni MCAS	1555
Kadena AB/Okinawa	3168
Misawa AB	520
Nagasaki	1773
Nagoya/Komaki AB	1552
Osaki IAP	1497
Sapporo	427
Sasebo NB	1788
Tokyo IAP	1371
Yokosuka FWC	1315
Yokota AB	1192
Jordan	
Amman	1838
Korea	
Kangnung	892
Kunsan AB	1274
Kwangju AB	1479
Mosulpo	1381
Osan AB	1183
Pusan IAP	1200
Seoul/Kimpo IAP	1063
Taegu	1475
Kuwait	
Kuwait IAP	5625
Lebanon	
Beirut IAP	2183
Pakistan	
Karachi Aprt	5150
Peshawar	4190
Saudi Arabia	
Dhahran AB	5906

TABLE 4D—Cooling degree day data for sites outside the United States. *(continued)*

Area Country Station	Annual Cooling, Degree Days
Taiwan	
Ching Chuan Kang AB	3055
Tainan AB	3926
Taipei IAP	3269
Thailand	
Bangkok/Don Muang IAP	6602
Chiangmai	4675
Korat	5876
Nakhon Phanom	5122
Ubon	5718
Udorn	5647
U-Tapao	6371
Turkey	
Ankara/Esenboga	765
Cigli AB/Izmir	1720
Diyarbakir AB	2223
Incirlik AB/Adana	2391
Istanbul/Yesilkoy	979
Malatya	1552
Vietnam	
Saigon/Tan Son Nhut	6564
Atlantic Ocean	
Azores	
Lajes Field	621
Bermuda	
Bermuda NAS/Kindley AFP	2631
Iceland	
Keflavik NAS	0
Australia	
New South Wales	
Sydney IAP	923
Northern Territory	
Darwin	5714
Queensland	
Townsville	4209
South Australia	
Adelaide	644
Woomera	2262
Western Australia	
Northwest Cape	3952
Perth IAP	1189
Caribbean Sea	
Bahama Islands	
Grand Bahama AAFB	3634
Cuba	
Guantanamo Bay NAS	5537
Puerto Rico	
Ramey AFB/Aquadilla	4709
Roosevelt Roads NAS	5576
San Juan/Isle Verde	4982
Central America	
Canal Zone	
Albrook AFP	6003
Fort Kobbe	5851
Howard AFB/Balboa	5851
Rodman Naval Station	6003
Europe	
Austria	
Innsbruck	313
Belgium	
Brussels IAP	146
Ostend	63
Denmark	
Copenhagen/Kastrup	90
Finland	
Helsinki/Seutula	130
France	
Bordeaux/Merignac	309
Lyon/Bron	351
Marseille/Marignane	899
Nantes	172
Paris/Orly	193
Germany	
Ansbach	168
Augsburg	237
Bad Tolz/Greiling AAF	104
Berlin/Tempelhof AB	235
Bitberg AB	93
Bremen	203
Bremerhaven	112
Coburg	212
Feucht AAF	218
Frankfort/Rhein Main AB	191
Fulda/Sickels AAF	139
Gablingen	237
Giebelstadt AAF	157
Grafenwohr AAF	88
Hahn AB/Hunsruck	71
Hanau AAF	256
Hannover	203
Heidelberg AAF	311
Illesheim AAF	221
Kitzingen AAF	301
Muenster	221
Munich	139
New Ulm	206
Nurnberg/Furth AAF	157
Ramstein AB/Landstuhl	107
Rhein Main AB	191
Sembach AB	113
Spangdahlem AB	94
Stuttgart/Echterdingen AB	154
Tempelhof AB/Berlin	235
Wiesbaden AB	219
Wurzburg	338
Zweibrucken AB	131
Greece	
Athens/Hellinikon Aprt	2002
Iraklion AS/Crete	1550
Souda Bay/Crete	1474
Hungary	
Budapest/Ferihegy	602
Ireland	
Dublin IAP	68
Shannon IAP	92
Italy	
Aviano AB	629
Brindisi	1103
Cagliari/Elmas/Sardinia	1177
Firenze	955
Livorno/Leghorn	1008

TABLE 4D—Cooling degree day data for sites outside the United States. (*continued*)

Area Country Station	Annual Cooling, Degree Days
Milano/Linate	868
Monte Cimone	4
Monte Venda	546
Naples NAF	1024
Pisa/San Guisto	920
Rome/Ciampino	1116
Sigonella NAF/Sicily	1472
Venezia/Tessera	717
Verona/Villafranca	884
Netherlands	
Soesterberg AB	103
Norway	
Oslo/Fornebu	140
Poland	
Warsaw/Okecie	258
Portugal	
Lisbon/Portela	864
Spain	
Alicante/Santa Pola	1482
Cordoba	2059
Madrid	1022
Menorca/Mahon	1137
Moron AB	1667
Rota Naval Station	1195
Torrejon AB/Madrid	889
Zaragoza AB	1049
Sweden	
Goteborg/Torslanda	64
Stockholm/Bromma	159
Switzerland	
Bern	240
Geneva/Cointrin	334
United Kingdom	
Aberdeen/Dyce Scotland	22
Alconbury RAF Sta	39
Bentwaters RAF Sta	30
Edinburgh/Scotland	34
Flyingdales	8
Greenham Common	30
Lakenheath RAF Sta	53
Leuchars/Scotland	10
Liverpool Aprt	54
London/Heathrow Aprt	92
Londonderry/N. Ireland	9
Mildenhall RAF Sta	52
Prestwick Aprt/Scotland	25
Sculthorpe RAF Sta	33
Upper Heyford RAF Sta	36
Wethersfield RAF Sta	38
USSR	
Moscow/Sheremetievo	259
Yugoslavia	
Belgrade IAP	785
Indian Ocean	
Chagos Archipelago	
Diego Garcia NB	5854
North America	
Canada	
Argentia NAS/Placentia Nfld	7
Calgary Aprt Alta	105
Cambridge Bay Aprt NWT	0
Cape Dyer NWT	0
Cape Parry NWT	0
Churchill Man	0
Edmonton/Namao Aprt Alta	136
Fort Nelson BC	105
Fort Smith Aprt NWT	93
Frobisher Bay NWT	0
Gander IAP Nfld	74
Goose Bay AB Nfld	56
Grand Prairie Alta	83
Halifax IAP NS	80
Hall Beach NWT	0
Inuvik NWT	9
Melville AS Nfld	15
Montreal IAP Que	464
North Bay Ont	133
Ottawa IAP Ont	387
Port Hardy BC	0
Prince George BC	56
Resolute Aprt NWT	0
St. Johns/Torbay Aprt Nfld	14
Saskatoon Sask	256
Stephenville Aprt Nfld	25
The Pas Man	151
Toronto IAP Ont	445
Vancouver IAP BC	72
Whitehorse YT	16
Winnipeg IAP Man	339
Yarmouth NS	19
Greenland	
Easterly Ice Cap	0
Kulusak	0
Sondrestrom AB	0
Thule AB	0
Mexico	
Mexico City/Tacubaya	396
Pacific Ocean	
Carolina Islands	
Koror Is Aprt	6008
Ponape	5652
Truk	5888
Yap	5916
Johnston Island	
Johnston AFB	5086
Mariana Islands	
Guam/Agana NAS	5865
Guam/Anderson AFB	5398
Marshall Islands	
Eniwetok	6299
Kwajalein/Bucholz AAF	6164
Majuro	5904
Midway Island	
Midway Island NAVSTA	2752

TABLE 4D—Cooling degree day data for sites outside the United States. (*continued*)

Area Country Station	Annual Cooling, Degree Days
New Zealand	
Christchurch	57
Mount John	0
Wellington Aprt	117
Philippine Islands	
Baguio	750
Clark AB	5762
Cubi Point NAS	6285
Sangley Pt FWC	6340
Subic Bay NB	6285
Wake Island	
Wake Island AFB	5455
South America	
Argentina	
Buenos Aires	1342
La Quiaca	0
Brazil	
Rio de Janeiro Aprt	4145
Chile	
Santiago/Pupahuel	572
Columbia	
Bogota/Eldorado	37
Equador	
Quito/Mariscal Sucre	76
French Guiana	
Cayenne	5156
Paraguay	
Asuncion/Stroessner	4095
Peru	
Lima/Callao	1592
Surinam	
Zanderij/Paramaribo	5542
Uruguay	
Montevideo/Carrasco	1047
Venezuela	
Caracas/La Carlota	2868

TABLE 5—Cities with weather summaries in each volume.

TRY Data			WYEC Data
Volume I	Volume II	Volume III	Volume IV
Albany, NY	Atlanta, GA	Albuquerque, NM	Albuquerque, NM
Atlanta, GA	Birmingham, AL	Amarillo, TX	Bismarck, ND
Birmingham, AL	Bismarck, ND	Bismarck, ND	Boise, ID
Boston, MA	Chicago, IL	Boise, ID	Boston, MA
Buffalo, NY	Cincinnati, OH	Brownsville, TX	Brownsville, TX
Burlington, VT	Cleveland, OH	Cheyenne, WY	Charleston, SC
Charleston, SC	Columbia, MO	El Paso, TX	Chicago, IL
Cincinnati, OH	Detroit, MI	Fresno, CA	Cleveland, OH
Cleveland, OH	Dodge City, KS	Fort Worth, TX	Dayton, OH
Jacksonville, FL	Indianapolis, IN	Great Falls, MT	El Paso, TX
Louisville, KY	Jackson, MS	Houston, TX	Fort Worth, TX
Madison, WI	Kansas City, MO	Lake Charles, LA	Lake Charles, LA
Miami, FL	Lake Charles, LA	Los Angeles, CA	Las Vegas, NV
Nashville, TN	Louisville, KY	Lubbock, TX	Los Angeles, CA
New York, NY	Memphis, TN	Medford, OR	Madison, WI
Norfolk, VA	Minneapolis, MN	New Orleans, LA	Medford, OR
Philadelphia, PA	Nashville, TN	Phoenix, AZ	Miami, FL
Pittsburgh, PA	New Orleans, LA	Portland, OR	Nashville, TN
Portland, ME	Oklahoma City, OK	Sacramento, CA	New York, NY
Raleigh, NC	Omaha, NB	Salt Lake City, UT	Omaha, NB
Richmond, VA	St. Louis, MO	San Antonio, TX	Seattle, WA
Tampa, FL	Tulsa, OK	San Diego, CA	Tallahassee, FL
Washington, DC		San Francisco, CA	Washington, DC
		Seattle-Tacoma, WA	

TABLE 6A—TRY data.

JACKSONVILLE, FLORIDA
WBAN 13889
TABLE A:

TRY Data (1965)

Monthly Dry Bulb Temperature Frequencies With Mean
Coincident Wet Bulb Temperature (MCWB): First Quarter
(5 Degrees(F)/3Hr Bins)

Latitude 30.50 N
Longitude 81.70 E

		Number of Hours of Occurrence in time period Hour of Day										HEATING*		COOLING*	
	Dry Bulb Range(F)	1-3	4-6	7-9	10-12	13-15	16-18	19-21	22-24	Month Total	MCWB Temp(F)	hours below	degree hours	hours above	degree hours
Jan															
	80 to 84	0	0	0	0	1	0	0	0	1	68.0	744	20412	0	0
	75 to 79	0	0	0	5	14	9	1	0	29	64.6	738	16701	6	9
	70 to 74	1	0	0	10	9	13	7	1	41	64.1	697	13107	47	135
	65 to 69	3	3	8	17	26	19	10	10	96	59.6	640	9728	104	476
	60 to 64	20	12	10	13	11	13	15	18	112	57.3	516	6801	228	1269
	55 to 59	8	13	10	22	17	20	22	12	124	50.2	425	4451	319	2639
	50 to 54	23	19	22	12	9	10	15	19	129	48.0	290	2647	454	4555
	45 to 49	12	13	15	5	2	4	11	12	74	43.1	184	1511	560	7139
	40 to 44	11	11	8	3	2	4	5	10	54	38.6	105	785	639	10133
	35 to 39	6	10	5	4	2	1	6	4	38	33.2	68	349	676	13417
	30 to 34	5	5	9	2	0	0	1	7	29	29.4	33	97	711	16885
	25 to 29	4	7	6	0	0	0	0	0	17	25.9	4	2	740	20510
Feb															
	80 to 84	0	0	0	0	5	2	0	0	7	65.9	672	17298	0	0
	75 to 79	0	0	0	6	7	4	1	0	18	66.2	656	13971	16	33
	70 to 74	0	0	0	5	12	15	4	3	39	63.5	633	10732	39	154
	65 to 69	13	5	5	10	13	15	14	16	91	61.4	576	7687	96	469
	60 to 64	12	12	11	13	17	11	12	8	96	57.1	479	5045	193	1187
	55 to 59	9	17	16	25	20	24	18	14	143	52.3	377	2886	295	2388
	50 to 54	21	15	21	17	7	9	24	22	136	48.6	214	1415	458	4277
	45 to 49	12	15	17	2	2	4	8	14	74	42.3	103	658	569	6880
	40 to 44	9	9	5	6	1	0	3	5	38	37.8	48	281	624	9863
	35 to 39	5	2	4	0	0	0	0	1	12	31.8	25	113	647	13055
	30 to 34	3	9	5	0	0	0	0	1	18	28.6	12	14	660	16316
Mar															
	85 to 89	0	0	0	0	7	6	0	0	13	69.9	744	19293	0	0
	80 to 84	0	0	0	7	12	14	2	0	35	69.3	719	15631	25	58
	75 to 79	0	0	1	11	20	13	8	0	53	66.4	674	12136	70	283
	70 to 74	5	3	6	17	8	6	11	13	69	65.8	618	8898	126	765
	65 to 69	22	21	21	14	9	15	12	18	132	62.8	531	6012	213	1599
	60 to 64	14	18	16	12	19	20	15	14	128	57.7	373	3751	371	3058
	55 to 59	11	9	13	10	8	9	28	16	104	52.3	276	2132	468	5159
	50 to 54	15	13	14	13	4	4	9	16	88	48.6	163	1045	581	7792
	45 to 49	12	8	6	5	6	6	6	9	58	42.2	86	418	658	10885
	40 to 44	13	15	10	4	0	0	2	7	51	37.6	39	89	705	14276
	35 to 39	1	6	6	0	0	0	0	0	13	35.2	2	1	742	17908

FOOTNOTES: * The Cooling and Heating degree base is at the center of the dry bulb temperature range.

TABLE 6A—TRY data. *(continued)*

JACKSONVILLE, FLORIDA
WBAN 13889
TABLE A:

TRY Data (1965)

Monthly Dry Bulb Temperature Frequencies With Mean
Coincident Wet Bulb Temperature (MCWB): Second Quarter
(5 Degrees(F)/3Hr Bins)

Latitude 30.50 N
Longitude 81.70 E

Dry Bulb Range(F)	Number of Hours of Occurrence in time period Hour of Day 1-3	4-6	7-9	10-12	13-15	16-18	19-21	22-24	Month Total	MCWB Temp(F)	HEATING* hours below	HEATING* degree hours	COOLING* hours above	COOLING* degree hours
Apr														
90 to 94	0	0	0	0	2	2	0	0	4	69.3	720	15885	0	0
85 to 89	0	0	0	3	22	16	0	0	41	67.6	708	12304	12	19
80 to 84	0	0	0	23	31	22	7	0	83	67.5	651	8904	69	219
75 to 79	0	0	6	31	12	21	17	4	91	65.9	554	5896	166	811
70 to 74	21	16	29	19	14	11	32	30	172	65.4	453	3365	267	1880
65 to 69	29	24	27	10	5	12	22	27	156	62.4	268	1605	452	3720
60 to 64	22	23	13	1	2	6	7	19	93	57.9	135	649	585	6364
55 to 59	10	15	8	1	2	0	5	9	50	53.9	55	201	665	9516
50 to 54	8	12	7	2	0	0	0	1	30	49.5	19	25	701	12940
May														
95 to 99	0	0	0	0	0	1	0	0	1	72.0	744	15522	0	0
90 to 94	0	0	0	3	26	7	0	0	36	72.5	734	11811	10	9
85 to 89	0	0	0	33	47	27	2	0	109	70.4	684	8257	60	175
80 to 84	0	0	13	45	19	51	15	0	143	68.8	529	5212	215	850
75 to 79	8	3	31	12	1	7	50	34	146	68.8	407	2872	337	2230
70 to 74	49	25	26	0	0	0	26	47	173	67.2	233	1252	511	4330
65 to 69	21	27	10	0	0	0	0	11	69	63.8	98	458	646	7256
60 to 64	13	26	12	0	0	0	0	1	52	59.2	42	104	702	10622
55 to 59	2	12	1	0	0	0	0	0	15	55.3	4	3	740	14241
Jun														
90 to 94	0	0	0	2	6	3	0	0	11	73.7	718	11158	2	2
85 to 89	0	0	0	26	39	19	0	0	84	73.6	694	7609	26	53
80 to 84	0	0	19	42	21	33	19	0	134	72.5	568	4436	152	480
75 to 79	22	16	44	15	14	20	50	47	228	72.3	428	1929	292	1573
70 to 74	53	50	20	3	10	14	20	37	207	70.0	132	490	588	3734
65 to 69	7	12	7	2	0	1	1	5	35	65.0	39	130	681	6974
60 to 64	8	12	0	0	0	0	0	1	21	61.3	10	9	710	10453

FOOTNOTES: * The Cooling and Heating degree base is at the center of the dry bulb temperature range.

TABLE 6A—TRY data. *(continued)*

JACKSONVILLE, FLORIDA
WBAN 13889
TABLE A:

TRY Data (1965)

Monthly Dry Bulb Temperature Frequencies With Mean
Coincident Wet Bulb Temperature (MCWB): Third Quarter
(5 Degrees(F)/3Hr Bins)

Latitude 30.50 N
Longitude 81.70 E

		Number of Hours of Occurrence in time period										HEATING*		COOLING*	
	Dry Bulb Range(F)	Hour of Day 1-3	4-6	7-9	10-12	13-15	16-18	19-21	22-24	Month Total	MCWB Temp(F)	hours below	degree hours	hours above	degree hours
Jul															
	95 to 99	0	0	0	0	1	1	0	0	2	75.5	744	13199	0	0
	90 to 94	0	0	0	15	32	10	0	0	57	76.1	725	9504	19	25
	85 to 89	0	0	2	42	36	27	3	0	110	75.2	651	6040	93	281
	80 to 84	0	0	32	27	15	33	36	8	151	74.8	511	3123	233	1084
	75 to 79	59	33	50	9	9	18	46	69	293	73.2	335	949	409	2630
	70 to 74	30	54	8	0	0	4	8	15	119	71.0	38	86	706	5487
	65 to 69	4	6	1	0	0	0	0	1	12	65.3	6	9	738	9130
Aug															
	90 to 94	0	0	0	15	49	20	0	0	84	77.4	725	8962	19	18
	85 to 89	0	0	3	55	23	23	8	0	112	76.3	627	5593	117	369
	80 to 84	0	0	36	20	9	29	33	16	143	75.4	501	2788	243	1284
	75 to 79	70	54	45	3	9	18	49	65	313	73.7	306	701	438	2917
	70 to 74	23	39	9	0	3	3	3	12	92	71.7	9	7	735	5943
Sep															
	90 to 94	0	0	0	3	7	1	0	0	11	77.3	720	9731	0	0
	85 to 89	0	0	0	35	41	23	0	0	99	75.3	679	6191	41	60
	80 to 84	4	0	26	36	28	43	23	5	165	74.8	559	3086	161	555
	75 to 79	71	57	43	10	8	16	58	74	337	73.4	292	818	428	1887
	70 to 74	13	33	20	6	6	7	9	11	105	70.9	48	70	672	4739
	65 to 69	2	0	1	0	0	0	0	0	3	68.7	0	0	720	8269

FOOTNOTES: * The Cooling and Heating degree base is at the center of the dry bulb temperature range.

TABLE 6A—TRY data. *(continued)*

JACKSONVILLE, FLORIDA
WBAN 13889
TABLE A:

TRY Data (1965)

Monthly Dry Bulb Temperature Frequencies With Mean
Coincident Wet Bulb Temperature (MCWB): Fourth Quarter
(5 Degrees(F)/3Hr Bins)

Latitude 30.50 N
Longitude 81.70 E

	Number of Hours of Occurrence In time period										HEATING*		COOLING*	
	Dry Bulb Range(F)	Hour of Day 1-3	4-6	7-9	10-12	13-15	16-18	19-21	22-24	Month Total	MCWB Temp(F)	hours below	degree hours	hours above	degree hours
Oct															
	90 to 94	0	0	0	0	3	1	0	0	4	77.0	744	16949	0	0
	85 to 89	0	0	0	6	15	10	0	0	31	72.8	735	13246	9	17
	80 to 84	0	0	1	21	21	12	7	0	62	71.0	699	9672	45	163
	75 to 79	13	8	12	29	23	25	14	12	136	69.9	608	6384	136	595
	70 to 74	13	17	25	15	20	23	36	27	176	66.6	444	3737	300	1668
	65 to 69	37	34	24	12	5	12	13	27	164	63.7	268	1964	476	3615
	60 to 64	10	11	9	10	6	9	12	6	73	58.0	138	1004	606	6375
	55 to 59	5	6	13	0	0	1	8	7	40	53.5	80	483	664	9574
	50 to 54	7	8	4	0	0	0	3	13	35	48.9	46	169	698	12980
	45 to 49	8	7	4	0	0	0	0	1	20	44.9	15	29	729	16560
	40 to 44	0	2	1	0	0	0	0	0	3	42.3	0	0	744	20251
Nov															
	80 to 84	0	0	0	0	2	1	0	0	3	67.3	720	14184	0	0
	75 to 79	0	0	0	13	29	10	0	0	52	64.7	707	10600	13	16
	70 to 74	0	0	1	27	25	30	6	0	89	64.0	630	7247	90	263
	65 to 69	6	8	15	27	25	28	39	24	172	61.7	534	4329	186	945
	60 to 64	36	29	28	14	3	15	22	31	178	59.7	307	2195	413	2411
	55 to 59	24	24	21	5	4	4	15	19	116	53.7	184	1010	536	4826
	50 to 54	12	15	12	2	2	1	5	8	57	49.0	75	382	645	7798
	45 to 49	11	7	7	2	0	1	1	6	35	44.9	31	114	689	11130
	40 to 44	1	7	5	0	0	0	2	0	15	39.3	9	20	711	14636
	35 to 39	0	0	1	0	0	0	0	2	3	34.7	1	1	719	18217
Dec															
	75 to 79	0	0	0	0	2	1	0	0	3	63.7	744	17046	0	0
	70 to 74	0	0	0	6	18	7	0	0	31	61.8	729	13345	15	19
	65 to 69	1	0	0	15	29	25	3	4	77	59.3	676	9802	68	196
	60 to 64	7	6	8	27	22	26	24	5	125	56.7	591	6607	153	721
	55 to 59	21	19	22	19	11	20	24	27	163	54.1	434	4005	310	1839
	50 to 54	17	18	14	19	10	7	20	21	126	48.6	295	2200	449	3754
	45 to 49	20	14	16	5	1	7	13	16	92	44.6	174	1051	570	6325
	40 to 44	14	18	18	2	0	0	8	13	73	39.7	92	375	652	9369
	35 to 39	13	13	11	0	0	0	1	7	45	34.5	29	78	715	12792
	30 to 34	0	5	4	0	0	0	0	0	9	30.3	4	3	740	16437

FOOTNOTES: * The Cooling and Heating degree base is at the center of the dry bulb temperature range.

TABLES 6B AND 6C—TRY data.

JACKSONVILLE, FLORIDA
WBAN 13889
TABLE B:

TRY Data (1965)

Latitude 30.50 N
Longitude 81.70 E

Annual Dry Bulb Temperature Frequencies
With Mean Coincident Wet Bulb Temperature
(5 Degrees(F)/3Hr Bins)

Dry Bulb range(F)	Number of Hours of Occurrence in time period									Mean Coincident Wet Bulb Temperature (F)								
	Hour of day									Hour of day								
	1-3	4-6	7-9	10-12	13-15	16-18	19-21	22-24	Year	1-3	4-6	7-9	10-12	13-15	16-18	19-21	22-24	Year
95 to 99	0	0	0	0	1	2	0	0	3	0.0	0.0	0.0	0.0	75.0	74.0	0.0	0.0	74.3
90 to 94	0	0	0	38	125	44	0	0	207	0.0	0.0	0.0	76.3	75.8	75.3	0.0	0.0	75.8
85 to 89	0	0	5	200	230	151	13	0	599	0.0	0.0	77.0	74.7	72.5	73.3	75.2	0.0	73.6
80 to 84	4	0	127	221	164	240	142	29	927	76.8	0.0	74.7	71.8	70.7	71.7	73.9	75.2	72.4
75 to 79	243	171	232	144	148	162	294	305	1699	73.2	73.2	72.6	68.4	67.3	69.2	71.5	72.9	71.5
70 to 74	208	237	144	108	125	133	162	196	1313	69.7	70.4	68.7	64.0	63.6	65.1	67.2	68.3	67.7
65 to 69	145	140	119	107	112	127	114	143	1007	64.3	64.9	64.2	60.4	57.6	59.0	62.4	63.4	62.2
60 to 64	142	149	107	90	80	100	107	103	878	59.8	60.3	60.0	55.9	52.9	54.7	58.1	59.6	58.1
55 to 59	90	115	104	82	62	78	120	104	755	54.4	54.7	54.9	50.7	49.7	50.0	52.2	53.3	52.8
50 to 54	103	100	94	65	32	31	76	100	601	50.1	50.1	49.5	46.5	43.9	44.8	48.0	49.0	48.6
45 to 49	75	64	65	19	11	22	39	58	353	44.1	45.1	44.6	39.3	40.3	40.5	42.0	43.7	43.5
40 to 44	48	62	47	15	3	4	20	35	234	39.0	39.9	39.3	35.5	34.7	35.8	37.2	38.2	38.7
35 to 39	25	31	27	4	2	1	7	14	111	33.4	34.6	34.1	31.0	32.0	33.0	32.7	34.0	33.8
30 to 34	8	19	18	2	0	0	1	8	56	29.0	29.2	29.2	27.0	0.0	0.0	31.0	30.5	29.3
25 to 29	4	7	6	0	0	0	0	0	17	26.5	26.0	25.5	0.0	0.0	0.0	0.0	0.0	25.9

TABLE C: Annual and Monthly Temperature, Humidity and Windspeed Summary

Month	Dry Bulb Temperature (F)					Wet Bulb	Percent Relative Humidity					Average Humidity Ratio (lb moisture/lb dry air)					Average wind
				Daily Ave			Average										
	Ave	Max	Min	Max	Min	Ave	4AM	10AM	4PM	10PM	Day	4AM	10AM	4PM	10PM	Day	MPH
Jan	55.1	81	27	66	45	49.7	82	68	51	71	70	0.0064	0.0069	0.0067	0.0071	0.0067	9.3
Feb	56.8	82	30	67	48	51.7	83	72	56	73	72	0.0072	0.0074	0.0073	0.0076	0.0074	9.9
Mar	61.6	87	37	72	53	55.9	85	70	54	72	72	0.0088	0.0089	0.0087	0.0088	0.0088	10.4
Apr	70.4	91	50	81	61	62.8	86	63	49	68	69	0.0108	0.0109	0.0101	0.0107	0.0106	10.1
May	76.6	95	56	88	65	67.4	86	55	45	66	65	0.0122	0.0125	0.0119	0.0128	0.0124	8.8
Jun	77.0	94	61	86	70	71.2	89	67	66	79	77	0.0147	0.0151	0.0148	0.0155	0.0151	8.6
Jul	79.8	95	65	90	73	73.5	90	68	64	79	77	0.0162	0.0167	0.0163	0.0165	0.0164	8.2
Aug	80.5	94	71	90	74	74.6	91	68	66	81	78	0.0169	0.0174	0.0171	0.0173	0.0171	7.6
Sep	79.0	92	69	86	74	73.7	89	71	69	82	79	0.0166	0.0166	0.0165	0.0169	0.0167	9.9
Oct	69.7	90	43	79	62	64.2	89	69	60	77	76	0.0119	0.0122	0.0117	0.0120	0.0120	9.0
Nov	62.8	80	37	73	54	58.1	89	71	59	79	77	0.0091	0.0096	0.0094	0.0098	0.0094	7.6
Dec	54.6	76	31	65	46	50.4	86	75	60	81	77	0.0066	0.0074	0.0074	0.0075	0.0071	7.6
Year	68.7	95	27	79	60	62.8	87	68	58	76	74	0.0115	0.0118	0.0115	0.0119	0.0116	8.9

TABLE 6D—TRY data. *(continued)*

JACKSONVILLE, FLORIDA
WBAN 13889
TABLE D:

TRY Data (1965)
Annual Heating and Cooling Degree Hour Summary for All Degree Bases

Latitude 30.50 N
Longitude 81.70 E

BASE	BY TIME OF DAY																		24 HOUR SUMMARY			
TEMP	7-9AM**			10-12AM**			1-3PM**			4-6PM**			7-9PM**			10PM-6AM**			HEATING		COOLING	
(F)	Hrs Above Base	Deg-Hrs (100s)* Heat	Deg-Hrs (100s)* Cool	Hrs Above Base	Deg-Hrs (100s)* Heat	Deg-Hrs (100s)* Cool	Hrs Above Base	Deg-Hrs (100s)* Heat	Deg-Hrs (100s)* Cool	Hrs Above Base	Deg-Hrs (100s)* Heat	Deg-Hrs (100s)* Cool	Hrs Above Base	Deg-Hrs (100s)* Heat	Deg-Hrs (100s)* Cool	Hrs Above Base	Deg-Hrs (100s)* Heat	Deg-Hrs (100s)* Cool	Hrs Below Base	Deg Hrs 100s*	Hrs Above Base	Deg Hrs 100s*
96	0	338	0	0	247	0	0	213	0	0	240	0	0	300	0	0	1053	0	8760	2391	0	0
95	0	327	0	0	236	0	0	202	0	1	229	0	0	289	0	0	1020	0	8758	2303	2	0
94	0	316	0	0	225	0	10	191	0	4	218	0	0	278	0	0	987	0	8746	2216	14	0
93	0	305	0	0	214	0	30	180	0	7	207	0	0	267	0	0	955	0	8722	2128	38	0
92	0	294	0	2	203	0	55	170	1	15	196	0	0	256	0	0	922	0	8687	2041	73	1
91	0	283	0	8	192	0	82	159	1	25	186	0	0	245	0	0	889	0	8645	1955	115	2
90	0	272	0	24	182	0	110	149	2	37	175	1	0	234	0	0	856	0	8587	1868	173	3
89	0	261	0	48	171	1	141	140	4	52	165	1	0	223	0	0	823	0	8517	1783	243	5
88	0	250	0	73	161	1	175	130	5	66	154	2	1	212	0	0	790	0	8443	1698	317	8
87	0	239	0	112	151	2	224	121	7	93	144	2	2	202	0	0	758	0	8327	1614	433	12
86	0	228	0	163	141	3	284	113	10	138	134	4	5	191	0	0	725	0	8168	1531	592	17
85	3	217	0	214	132	5	335	105	13	180	125	5	10	180	0	0	692	0	8017	1451	743	23
84	10	206	0	267	123	8	375	98	16	221	116	7	18	169	0	0	659	0	7868	1371	892	31
83	26	196	0	320	115	11	410	91	20	272	107	10	30	158	1	0	626	0	7701	1293	1059	41
82	50	185	1	367	108	14	440	84	24	326	99	13	48	148	1	1	593	0	7526	1217	1234	53
81	77	175	1	407	101	18	471	78	29	375	92	16	80	137	1	6	560	0	7343	1143	1417	66
80	111	165	2	440	94	22	504	71	34	417	85	20	127	127	2	21	528	0	7137	1070	1623	81
79	153	155	3	475	88	27	535	66	39	456	78	25	188	118	4	58	495	0	6894	1000	1866	98
78	200	146	5	509	82	32	566	60	45	490	72	29	253	109	6	135	463	1	6606	932	2154	118
77	246	137	7	539	76	37	597	55	50	524	66	34	316	101	9	256	432	3	6280	868	2480	141
76	288	129	10	564	71	42	628	50	57	559	61	40	374	94	13	420	403	6	5925	807	2835	168
75	337	121	13	589	65	48	656	46	63	587	56	46	425	87	17	633	375	12	5531	749	3229	198
74	384	114	17	614	60	54	683	42	70	616	51	51	472	80	21	858	350	19	5131	696	3629	232
73	421	107	21	635	56	61	716	38	77	646	46	58	510	74	26	1030	326	29	4800	647	3960	271
72	450	100	25	657	51	67	745	34	84	673	42	64	540	69	31	1150	304	40	4543	600	4217	312
71	472	94	30	682	47	74	767	31	92	700	38	71	572	63	37	1252	284	52	4314	556	4446	355
70	494	88	35	702	43	81	785	27	99	722	34	78	600	58	43	1346	264	65	4109	514	4651	401
69	521	82	40	723	39	88	803	24	107	745	30	86	619	53	49	1432	245	79	3916	474	4844	448
68	546	76	45	746	36	95	826	22	115	771	27	93	634	49	55	1507	227	93	3728	435	5032	497
67	567	71	51	768	32	103	850	19	124	796	24	101	655	44	61	1586	209	109	3535	399	5225	549
66	588	66	56	787	29	110	872	17	132	823	21	109	684	40	68	1671	193	125	3333	365	5427	602
65	613	61	62	806	26	118	894	15	141	848	18	118	712	36	75	1767	177	142	3119	332	5641	657
64	640	56	69	828	23	127	914	13	150	870	16	126	739	32	82	1878	162	160	2890	302	5870	715
63	666	52	75	847	21	135	931	11	160	893	14	135	767	29	90	1971	149	180	2683	275	6077	775
62	691	47	82	866	18	144	945	9	169	913	12	144	790	26	98	2048	136	200	2505	249	6255	836
61	712	44	89	884	16	152	956	8	178	929	10	153	807	23	106	2126	124	221	2344	224	6416	900
60	727	40	96	900	14	161	974	7	188	948	9	163	823	20	114	2189	113	242	2198	202	6562	965
59	748	36	104	918	12	170	992	6	198	966	7	172	843	17	122	2246	102	265	2045	181	6715	1031
58	770	33	111	935	11	180	1005	5	208	981	6	182	866	15	131	2302	92	287	1899	161	6861	1099
57	790	30	119	953	9	189	1016	4	218	995	5	192	891	13	140	2360	83	311	1753	143	7007	1168
56	814	27	127	969	8	199	1027	3	228	1009	4	202	915	11	149	2422	74	335	1602	126	7158	1239
55	832	24	135	982	6	208	1039	2	239	1026	3	212	940	9	158	2487	65	359	1452	110	7308	1311
54	847	21	144	995	5	218	1049	2	249	1039	3	222	962	8	167	2558	58	384	1307	97	7453	1385
53	868	19	152	1009	4	228	1057	1	260	1045	2	233	983	6	177	2623	51	410	1172	84	7588	1460
52	894	17	161	1026	4	238	1067	1	270	1052	2	243	1000	5	187	2697	45	437	1023	73	7737	1537
51	913	15	170	1038	3	249	1073	1	281	1059	1	254	1013	4	197	2761	39	464	901	64	7859	1615

FOOTNOTES: * Heating and Cooling Degree Hrs are in Hundreds (eg. 565 x 100 = 56500 Deg Hrs)
** The Hours Below the Base Temp for any X-Hr period are calculated by subtracting the Hrs Above from X times 365

TABLE 6D—TRY data. (*continued*)

JACKSONVILLE, FLORIDA
WBAN 13889
TABLE D:

TRY Data (1965)
Annual Heating and Cooling Degree Hour Summary for All Degree Bases

Latitude 30.50 N
Longitude 81.70 E

BASE	BY TIME OF DAY																		24 HOUR SUMMARY			
	7-9AM**			10-12AM**			1-3PM**			4-6PM**			7-9PM**			10PM-6AM**			HEATING		COOLING	
TEMP (F)	Hrs Above Base	Deg-Hrs (100s)* Heat	Cool	Hrs Above Base	Deg-Hrs (100s)* Heat	Cool	Hrs Above Base	Deg-Hrs (100s)* Heat	Cool	Hrs Above Base	Deg-Hrs (100s)* Heat	Cool	Hrs Above Base	Deg-Hrs (100s)* Heat	Cool	Hrs Above Base	Deg-Hrs (100s)* Heat	Cool	Hrs Below Base	Deg Hrs 100s*	Hrs Above Base	Deg Hrs 100s*
50	926	13	179	1049	3	259	1077	1	292	1065	1	265	1024	4	207	2804	34	492	814	55	7946	1694
49	941	12	189	1056	2	270	1081	1	302	1071	1	275	1031	3	218	2852	29	520	726	48	8034	1774
48	958	10	198	1061	2	280	1085	0	313	1079	0	286	1040	2	228	2899	25	549	637	41	8123	1855
47	973	9	208	1065	2	291	1087	0	324	1084	0	297	1050	2	238	2936	22	578	563	35	8197	1936
46	985	8	218	1069	1	302	1089	0	335	1087	0	308	1059	2	249	2967	18	608	504	30	8256	2019
45	993	7	228	1073	1	312	1090	0	346	1089	0	319	1065	1	260	3003	15	638	446	25	8314	2102
44	1001	6	238	1075	1	323	1090	0	357	1090	0	329	1069	1	270	3042	13	668	390	21	8370	2185
43	1014	5	248	1079	1	334	1091	0	368	1091	0	340	1075	1	281	3081	11	698	327	17	8433	2269
42	1025	4	258	1083	0	345	1092	0	379	1091	0	351	1078	1	292	3116	9	729	273	14	8487	2354
41	1032	3	268	1086	0	356	1092	0	390	1092	0	362	1081	0	303	3143	7	761	233	11	8527	2439
40	1039	3	278	1088	0	366	1092	0	400	1093	0	373	1085	0	313	3162	6	792	199	9	8561	2524
39	1048	2	289	1089	0	377	1093	0	411	1094	0	384	1088	0	324	3181	5	824	166	8	8594	2610
38	1055	2	299	1089	0	388	1094	0	422	1095	0	395	1089	0	335	3199	4	856	136	6	8624	2696
37	1060	2	310	1091	0	399	1095	0	433	1095	0	406	1090	0	346	3210	3	888	117	5	8643	2782
36	1064	1	321	1092	0	410	1095	0	444	1095	0	417	1092	0	357	3218	2	920	103	4	8657	2869
35	1068	1	331	1093	0	421	1095	0	455	1095	0	428	1093	0	368	3230	2	952	84	3	8676	2956
34	1073	1	342	1093	0	432	1095	0	466	1095	0	439	1094	0	379	3242	1	985	67	2	8693	3042
33	1077	1	353	1093	0	443	1095	0	477	1095	0	450	1095	0	390	3249	1	1017	55	1	8705	3129
32	1080	0	364	1094	0	454	1095	0	488	1095	0	461	1095	0	401	3258	1	1050	42	1	8718	3217
31	1084	0	374	1094	0	465	1095	0	499	1095	0	472	1095	0	412	3267	0	1082	29	1	8731	3304
30	1087	0	385	1094	0	476	1095	0	510	1095	0	483	1095	0	423	3272	0	1115	20	0	8740	3391
29	1089	0	396	1095	0	487	1095	0	521	1095	0	494	1095	0	434	3277	0	1148	13	0	8747	3479
28	1090	0	407	1095	0	498	1095	0	532	1095	0	505	1095	0	445	3283	0	1181	6	0	8754	3566
27	1093	0	418	1095	0	508	1095	0	543	1095	0	515	1095	0	455	3285	0	1213	2	0	8758	3654
26	1095	0	429	1095	0	519	1095	0	554	1095	0	526	1095	0	466	3285	0	1246	0	0	8760	3741

FOOTNOTES: * Heating and Cooling Degree Hrs are in Hundreds (eg. 565 x 100 = 56500 Deg Hrs)
** The Hours Below the Base Temp for any X-Hr period are calculated by subtracting the Hrs Above from X times 365

TABLES 6E, 6F, AND 6G—TRY data.

JACKSONVILLE, FLORIDA
WBAN 13889
TRY Data (1965)
Latitude 30.50 N
Longitude 81.70 E

TABLE E:

Annual COOLING Wet Bulb Degree Hour Summary

Wet Bulb Temperature (F) Base:	50	53	56	59	62	65	68	71	74	77	80
Annual Wet Bulb hours ABOVE base:	7460	6984	6530	6040	5474	4691	3848	2982	1561	297	17
Annual Wet Bulb Cooling deg-hrs:	130013.	108084.	87577.	68492.	50904.	35212.	22051.	11343.	3725.	478.	18.

TABLE F:

Annual Humidification/Dehumidification Requirements
At various Indoor Conditions and Degree Day Bases
(Pounds of Moisture)

Maintained Indoor Humidity	HEATING HUMIDITY RATIO HOURS **											COOLING HUMIDITY RATIO HOURS **											Maintained Indoor Humidity
	Heating Degree Base											Cooling Degree Base											
Ratio*	30	35	40	45	50	55	60	65	70	75	80	30	35	40	45	50	55	60	65	70	75	80	Ratio*
.001	0	0	0	0	0	0	0	0	0	0	0	89	89	89	88	86	83	78	70	61	41	20	.001
.002	0	0	0	0	0	0	0	0	0	0	0	80	80	80	80	79	76	72	65	56	38	19	.002
.003	0	0	0	0	0	0	0	0	0	0	0	72	72	72	71	71	69	65	59	52	35	17	.003
.004	0	0	0	0	1	1	1	1	1	1	1	63	63	63	63	63	61	59	54	47	32	16	.004
.005	0	0	0	1	1	1	2	2	2	2	2	56	56	56	56	55	54	53	48	43	29	14	.005
.006	0	0	1	1	2	2	3	3	3	3	3	48	48	48	48	48	48	46	43	38	26	13	.006
.007	0	0	1	2	3	3	4	4	5	5	5	41	41	41	41	41	41	40	38	34	23	11	.007
.008	0	0	1	2	3	5	6	6	7	7	7	34	34	34	34	34	34	34	32	29	20	10	.008
.009	0	1	1	2	4	6	7	8	9	9	9	28	28	28	28	28	28	28	27	25	17	8	.009
.010	0	1	1	3	5	7	10	11	12	12	12	23	23	23	23	23	23	23	22	21	15	7	.010
.011	0	1	2	3	6	9	12	14	15	15	16	18	18	18	18	18	18	18	17	17	12	6	.011
.012	0	1	2	4	6	10	14	17	18	19	20	13	13	13	13	13	13	13	13	13	9	4	.012
.013	0	1	2	4	7	11	16	20	22	24	25	10	10	10	10	10	10	10	10	9	7	3	.013
.014	0	1	2	5	8	13	18	23	26	28	30	6	6	6	6	6	6	6	6	6	5	2	.014
.015	0	1	2	5	9	14	20	26	30	33	35	4	4	4	4	4	4	4	4	4	3	1	.015
.016	0	1	3	5	9	16	22	29	34	38	41	2	2	2	2	2	2	2	2	2	1	1	.016
.017	0	1	3	6	10	17	24	32	38	43	47	0	0	0	0	0	0	0	0	0	0	0	.017
.018	0	1	3	6	11	18	27	35	42	49	54	0	0	0	0	0	0	0	0	0	0	0	.018

FOOTNOTES: * Indoor Humidity Level is measured in pounds of moisture per pound of dry air. Indoor set points of 72 deg(F)-30$RH and 78 deg(F)-50$RH yield humidity ratios of .005 and .010 respectively.

** Heating (Cooling) Humidity Ratio Hours are defined as the summation of the differences between the maintained indoor humidity ratio and the observed outdoor humidity ratio when both the hourly dry bulb temperature and the humidity ratio are above (below) the base levels.

TABLE G:

Percent Diffuse Solar Radiation*
and Percent Possible Sunshine**

	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec	Year
$ Diffuse on surface													
HORIZONTAL	25	48	58	46	38	57	57	54	60	39	36	38	48
VERTICAL													
NORTH	100	100	100	98	89	90	92	97	100	100	100	100	96
WEST	42	60	67	62	58	77	75	77	72	55	49	52	64
SOUTH	25	49	66	70	79	93	91	80	74	44	34	33	59
EAST	42	61	71	67	56	69	69	65	71	53	51	51	62
$ Possible Sun	57	61	66	72	69	62	60	59	54	57	60	56	61

FOOTNOTES: * Corrected For Cloud Cover.

** Source: NOAA, Comparative Climatic Data for the United States Through 1978.

TABLES 6H AND 6I—TRY data.

JACKSONVILLE, FLORIDA
WBAN 13889
TABLE H:

TRY Data (1965)

Latitude 30.50 N
Longitude 81.70 E

Average Daily Solar Radiation on Vertical and Horizontal Surfaces
(BTU/DAY.SQFT)

Month	Under Clear Sky Assumption*											Corrected For Cloud Cover**											
	S	SSE/ SSW	SE/ SW	ESE/ WSW	E/ W	ENE/ WNW	NE/ NN	NNE/ NNW	N	S-45 ***	horiz	S	SSE/ SSW	SE/ SW	ESE/ WSW	E/ W	ENE/ WNW	NE/ NN	NNE/ NNW	N	S-45 ***	horiz	Obs ****
Jan	1812	1689	1391	1134	752	437	252	198	197	2066	1241	1182	1111	928	764	520	323	211	177	176	1330	830	900
Feb	1739	1632	1427	1241	912	589	366	247	235	2201	1520	886	847	761	679	534	398	307	260	253	1033	806	1164
Mar	1452	1442	1389	1326	1104	828	571	373	295	2239	1891	970	945	897	849	737	612	508	432	403	1217	1118	1522
Apr	1025	1152	1249	1317	1226	1045	806	572	391	2103	2183	917	954	977	989	918	808	681	568	489	1456	1535	1856
May	745	944	1137	1293	1314	1217	1007	773	562	1961	2377	824	973	1110	1221	1227	1146	983	804	648	1649	1972	1956
Jun	642	847	1077	1264	1332	1281	1100	875	678	1877	2441	755	855	969	1066	1096	1061	957	833	729	1314	1639	1885
Jul	691	890	1100	1274	1320	1252	1063	837	636	1901	2399	793	900	1012	1108	1129	1082	969	836	717	1359	1666	1802
Aug	897	1053	1184	1288	1244	1106	886	660	470	2000	2225	882	983	1051	1101	1060	963	824	684	568	1392	1546	1694
Sep	1267	1298	1300	1284	1116	882	646	446	341	2132	1964	911	926	916	897	810	699	593	501	446	1206	1200	1442
Oct	1619	1546	1395	1255	972	673	438	293	267	2177	1633	1081	1049	960	872	698	522	389	311	296	1339	1067	1223
Nov	1796	1684	1421	1179	823	500	294	217	214	2107	1327	940	881	753	636	464	313	222	189	187	1060	718	996
Dec	1806	1681	1369	1094	708	400	228	190	190	2007	1163	960	905	758	623	431	279	197	177	177	1034	656	818
Year	1288	1320	1286	1245	1069	852	640	475	374	2063	1865	926	945	926	902	804	686	572	482	425	1285	1232	1438

FOOTNOTES:
* Derived according to DOE-2.1 LOADS Algorithms.
** Derived according to DOE-2.1 LOADS Algorithms and TRY cloud cover data.
*** South exposure tilt 45 degrees.
**** Cinquemani, V., J. R. Owenby, Jr. and R. G. Baldwin. 1978. Input Data for Solar Systems. NCC, Ashville, NC.

TABLE I:

Average Daily Solar Heat Gain Through Single Pane Glass on Vertical
and Horizontal Surfaces
(BTU/DAY.SQFT)

Month	Under Clear Sky*									Corrected For Cloud Cover**								
	S	SSE/ SSW	SE/ SW	ESE/ WSW	E/ W	ENE/ WNW	NE/ NN	NNE/ NNW	N	S	SSE/ SSW	SE/ SW	ESE/ WSW	E/ W	ENE/ WNW	NE/ NN	NNE/ NNW	N
Jan	1546	1415	1161	939	608	331	187	161	161	1004	928	773	630	420	249	161	144	143
Feb	1443	1351	1184	1030	744	464	272	196	191	727	696	627	559	435	319	241	209	206
Mar	1117	1165	1144	1103	912	666	439	282	239	770	766	734	699	604	496	406	345	327
Apr	712	881	1009	1085	1017	852	638	435	307	692	751	789	806	750	653	544	451	393
May	501	678	898	1058	1089	1000	813	601	415	606	736	888	1000	1013	939	795	634	501
Jun	447	596	835	1030	1102	1054	888	686	495	586	657	772	870	901	870	777	667	571
Jul	474	633	861	1039	1093	1030	857	655	467	614	694	811	907	930	889	788	669	563
Aug	617	790	952	1059	1033	906	710	510	361	672	774	854	905	875	788	665	543	456
Sep	942	1033	1062	1061	922	715	503	339	276	712	745	748	737	666	571	477	398	362
Oct	1316	1272	1156	1045	796	532	330	228	217	880	862	794	722	571	416	303	248	240
Nov	1524	1407	1183	984	668	384	220	176	174	791	731	624	527	376	245	174	153	152
Dec	1550	1413	1143	905	571	300	173	155	154	814	756	630	514	348	216	155	144	144
Year	1013	1051	1048	1028	880	687	504	370	289	740	759	755	741	659	556	458	385	339

FOOTNOTES:
* Derived according to DOE-2.1 LOADS Algorithms.
** Derived according to DOE-2.1 LOADS Algorithms and TRY cloud cover data.

TABLE 7—Sample BIN data for Jacksonville/Cecil Field Naval Air Station, from reference 3.

JACKSONVILLE/CECIL FLD NAS FLORIDA

LAT 30 13N LONG 81 53W ELEV 80 FT

MEAN FREQUENCY OF OCCURRENCE OF DRY BULB TEMPERATURE (DEGREES F) WITH MEAN COINCIDENT WET BULB TEMPERATURE (DEGREES F) FOR EACH DRY BULB TEMPERATURE RANGE

Temperature Range	MAY					JUNE					JULY					AUGUST					SEPTEMBER					OCTOBER				
	Obsn Hour Gp			Total Obsn	M C W B	Obsn Hour Gp			Total Obsn	M C W B	Obsn Hour Gp			Total Obsn	M C W B	Obsn Hour Gp			Total Obsn	M C W B	Obsn Hour Gp			Total Obsn	M C W B	Obsn Hour Gp			Total Obsn	M C W B
	01 to 08	09 to 16	17 to 24			01 to 08	09 to 16	17 to 24			01 to 08	09 to 16	17 to 24			01 to 08	09 to 16	17 to 24			01 to 08	09 to 16	17 to 24			01 to 08	09 to 16	17 to 24		
100/104		0	0	0	74		0		0	80		0		0	78		0		0	81										
95/99		5	1	6	74		6	1	7	77		13	2	15	78		8	1	9	78		1		1	77					
90/94		24	6	30	72		43	9	52	76		68	14	82	77		63	9	72	77		28	3	31	76		3	0	3	75
85/89		63	17	80	71		81	23	104	75	0	85	25	110	77	0	86	25	111	76		76	15	91	75		29	3	32	73
80/84	0	75	35	110	70	6	68	48	122	74	12	56	54	122	76	7	58	51	116	75	1	76	42	119	74		65	14	79	71
75/79	12	47	55	114	69	50	28	83	161	73	92	19	98	209	74	79	25	98	202	74	45	40	95	180	73	7	64	40	111	70
70/74	68	24	78	170	68	133	12	65	210	70	132	8	53	193	71	145	6	59	210	71	140	15	68	223	70	50	44	76	170	68
65/69	90	7	41	138	64	42	1	10	53	66	12	0	2	14	67	17	2	4	23	68	41	4	14	59	66	74	26	61	161	64
60/64	55	2	13	70	60	9		1	10	61	0			0	63	0		0	0	64	10	0	2	12	60	51	12	33	96	59
55/59	17		2	19	55	1			1	57											2		0	2	55	35	4	14	53	54
50/54	5			5	50																0			0	48	16	1	6	23	49
45/49	0			0	47																0			0	46	11	0	2	13	45
40/44																										3		0	3	40
35/39																										0			0	38

Temperature Range	NOVEMBER					DECEMBER					JANUARY					FEBRUARY					MARCH					APRIL					ANNUAL TOTAL				
	Obsn Hour Gp			Total Obsn	M C W B	Obsn Hour Gp			Total Obsn	M C W B	Obsn Hour Gp			Total Obsn	M C W B	Obsn Hour Gp			Total Obsn	M C W B	Obsn Hour Gp			Total Obsn	M C W B	Obsn Hour Gp			Total Obsn	M C W B	Obsn Hour Gp			Total Obsn	M C W B
	01 to 08	09 to 16	17 to 24			01 to 08	09 to 16	17 to 24			01 to 08	09 to 16	17 to 24			01 to 08	09 to 16	17 to 24			01 to 08	09 to 16	17 to 24			01 to 08	09 to 16	17 to 24			01 to 08	09 to 16	17 to 24		
100/104																																0	0	0	76
95/99																																33	5	38	77
90/94																						0		0	66		5	1	6	72		234	42	276	76
85/89		2		2	70		0		0	70							1	0	1	70		8	2	10	70		30	8	38	70	0	461	118	579	74
80/84		20	2	22	69		7	0	7	68		3	0	3	67		8	2	10	69		22	7	29	68		52	19	71	68	26	510	274	810	72
75/79		42	9	51	66		19	3	22	65		12	3	15	65		16	5	21	66		35	14	49	64	1	61	32	94	66	286	408	535	1229	71
70/74	3	50	25	78	64	1	28	12	41	64	1	22	8	31	63	2	23	14	39	63	5	43	29	77	63	17	48	56	121	64	697	323	543	1563	68
65/69	25	44	50	119	62	11	35	25	71	61	4	30	18	52	61	12	25	22	59	60	25	38	42	105	61	52	24	57	133	63	405	236	346	987	63
60/64	53	34	56	143	59	22	41	38	101	57	18	38	36	92	58	21	33	31	85	56	41	38	49	128	57	72	15	43	130	59	352	213	302	867	58
55/59	44	23	40	107	54	29	38	41	108	53	31	37	41	109	53	23	41	36	100	52	49	32	46	127	53	54	4	18	76	54	285	179	238	702	53
50/54	45	14	30	89	49	46	38	52	136	49	39	41	43	123	49	38	35	46	119	48	50	19	31	100	48	30	1	7	38	49	269	149	215	633	49
45/49	33	6	16	55	44	40	22	35	97	44	42	28	40	110	44	37	22	33	92	44	35	8	18	61	44	11		1	12	45	209	86	145	440	44
40/44	19	3	8	30	39	37	12	23	72	39	40	22	33	95	39	39	13	25	77	39	25	4	9	38	39	3		0	3	40	166	54	98	318	39
35/39	11	1	3	15	35	33	5	13	51	35	34	9	17	60	35	32	5	7	44	34	15	1	1	17	35	0			0	38	125	21	41	187	35
30/34	6	0	1	7	31	20	2	4	26	30	26	5	7	38	30	15	2	2	19	30	4	0	0	4	30						71	9	14	94	30
25/29	1	0	0	1	25	7	1	1	9	26	9	1	2	12	25	5	1	0	6	25	0			0	29						22	3	3	28	25
20/24	1		0	1	21	1	0	0	1	21	3	1		4	21	0			0	20											5	1	0	6	21
15/19						0	0		0	15																					0	0		0	15
10/14						0			0	13																					0			0	13

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8

Moisture Sources

by Jeffrey E. Christian[1]

TO UNDERSTAND MOISTURE PROBLEMS IN BUILDINGS, one must correctly determine the moisture sources. This chapter discusses the major sources of moisture in buildings, the rates associated with those sources, and frequencies of moisture dissipation. Several key equations are presented to estimate moisture sources for unique site-specific conditions.

Excessive moisture within buildings can cause mold, mildew, and potentially damaging concealed condensation which, in time, distresses the building envelope's thermal and structural performance. Interior moisture sources are more important in colder climates, with more than 2222 heat degree days (HDD) base 18.8°C (4000 HDD base 65°F) and an average January temperature below 4.4°C (40°F) where the relative humidity within the building could be 45% [*1*].

In the summer, moist outside air is the most important moisture source. Moist air from the outside is generally an important moisture source of concern in regions meeting the ASHRAE definition of a humid climate [*2*]. A humid climate is defined as one in which one or both of the following conditions occur:

1. A 19.5°C (67°F) or higher wet-bulb temperature for 3500 h or more during the warmest six consecutive months of the year.
2. A 23°C (73°F) or higher wet-bulb temperature for 1750 h or more during the warmest six consecutive months of the year.

The region between these two climate regions represents where both heating and cooling are needed for significant periods of time during the annual cycle. In this region, moisture sources from both the interior and exterior can be significant contributors to moisture problems.

This chapter is divided into three major sections. The first discusses construction moisture sources. These can be substantial and are generally important only during the first two to three years of a new building's life. The second section focuses on interior moisture sources resulting from the activities inside the conditioned space such as cooking, showering, and respiration of the occupants. The final section covers exterior moisture sources that enter the building by air movement, vapor diffusion, capillary suction, and liquid flow.

CONSTRUCTION SOURCES

Newly constructed buildings give off significant quantities of moisture during their first year as a result of moisture trapped within materials: fresh concrete, green lumber, and wet-applied insulations.

For an "average" house, it has been estimated that the lumber used at 19% moisture content can release a total of about 200 L (423 pt) of moisture as it dries to average conditions [*3*]. Most framing materials for construction are kiln dried; however, dry materials do get wet prior to and during construction. Piles of materials are often covered on top to shed rain, but not placed on top of vapor retarders to restrict ground-source moisture from condensing under the rain cover during cool nights. Even during construction in good weather, top surfaces can be wet with dew since surface temperatures cooled by night radiant heat loss may be 5 to 9°C (9 to 16°F) below ambient.

For poured concrete, it is estimated that 90 L of water per cubic meter (146 pt per cubic yard) of concrete is released over the first two years after construction. In general, 1 m^3 of concrete requires 210 L of water (1 yd^3 requires 344 pt) during the mix but with hydration eventually retains slightly less than 120 L (256 pt) of water. A basement wall which is 2.5 m (8.2 ft) high and 0.25 m (10 in.) thick, and has 35 m (115 ft) of perimeter contains 22 m^3 (29 yd^3) of concrete. The basement floor contains about 4 m^3 (5.2 yd^3) of concrete, for a total of 26 m^3 (34 yd^3). This concrete releases 2340 L (4960 pts) of water during the curing process. Most of this is released during the first year. Assuming a uniform rate release for one year would amount to 6.4 L/day [13.5 pt/day].

For new houses in the first year, the total moisture input from construction sources may average 10 or more L/day (21 pt/day) during winter, 5 L (10 pt) the second year, and diminish to about 0 L/day [*4*].

INDOOR SOURCES

Common to All Types of Buildings

People

People generate moisture by respiration and perspiration. Figure 1 presents typical moisture release per hour at different levels of physical activity and surrounding temperature [*5*]. This plot is consistent with Ref *6*, which reports light activity from 0.03 to 0.06 L/h (0.06 to 0.013 pt/day), medium

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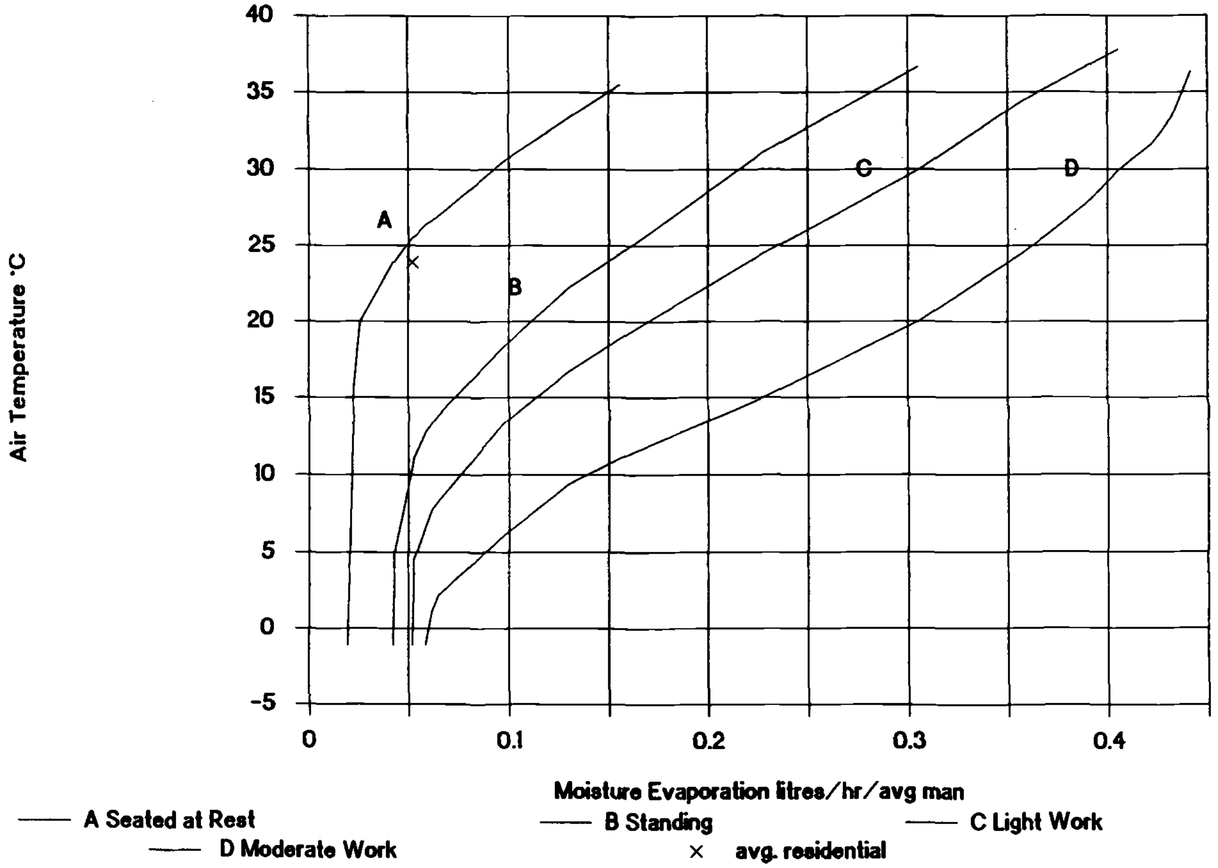

FIG. 1—The moisture released from respiration and perspiration as a function of activity level. One average value from a study of a family of four is plotted with the data assuming a uniform hourly release totaling 1.25 L/day per average-size man.

activity from 0.12 to 0.2 (0.25 to .42 pt/day) and hard work 0.2 to 0.3 (0.42 to 0.63 pt/day). The air temperature is not reported but assumed to be around 20°C (68°F). For residential housing, one older study found that the amount of water vapor produced by a family of four's metabolic process averaged 0.21 L/h [0.44 pt/h] or 5 L/day (10.5 pt/day), or 1.25 L/person/day (2.64 pt/person/day) [7].

Combustion

Burning 1 m^3/h of natural gas for cooking, heating, or any other application in an open and unvented mode results in 0.0026 L/h (1000 ft^3/h results in 0.16 pt/h) [5].

Bathroom

Table 1 indicates that 0.06 L (0.13 pt) of moisture are released from a standard size tub without specifying the duration of the "standard" bath [8]. A European reference indicates a rate of 0.7 L/h (1.5 pt/h) [6]. For these references to be consistent would mean a 5-min bath. Assuming the time it takes to fill and empty the tub, an average of 15 min is probably more reasonable. Table 1 shows the moisture load from a 5-min shower is 0.25 L (0.53 pt), which is very consistent with Ref 6, reported as 0.22 L (0.5 pt).

To estimate total daily moisture load, the incident frequencies are needed. One additional question to ask is how many baths and showers are taken per day. Reference 6 provides a daily moisture loading for personal hygiene per person of 0.6 L/day (1.3 pt/day).

A study performed on water migration in several hotels with extreme mold and mildew problems found that a hotel room generates a maximum of 2.3 L/day (4.9 pt/day). This includes people [1.53 L/day (3.2 pt/day)], showers [.38 L/day (0.8 pt/day)], plants, cleaning, and wet clothes [0.4 L/day (.85 pt/day)] [9].

Kitchens

The daily average kitchen moisture load for a family of four is listed as 2.4 L/day (5 pt/day) [6]. This compares well with the data in Table 1 if one adds the moisture loading for breakfast, lunch, and dinner for four, all prepared using a gas range, 2.35 L/day (5 pt/day). If cooking is prepared with electricity, the moisture load is around 1.0 L/day (2.1 pt/day) [8]. Dishwashing from three meals and for four people will contribute 0.5 L/day (1.1 pt/day) [8].

High levels of moisture can escape from hotel and restaurant kitchens into common areas. Open steam tables, uncovered cooking pots, and steam from dishwashers saturate warm kitchen air [10]. Boiling water in a covered 0.15-m (6-in.)-diameter pan for 10 min will emit 0.23 L (0.5 pt) of moisture [8].

TABLE 1—Residential moisture sources.

Moisture Source by Type	Estimated Moisture Amount, L
HOUSEHOLD PRODUCED	
Aquariums	Replacement of evaporative loss
Bathing: tub (excludes towels and spillage)	0.06/standard size bath
shower (excludes towels and spillage)	0.25/5-min shower
Clothes washing (automatic, lid closed, standpipe discharge)	0+/load (usually nil)
Clothes drying: vented outdoors;	0+/load (usually nil)
not vented outdoors or indoor drying line	2.2 to 2.92/load (more if gas dryer)
Combustion: unvented kerosene space heater	0.95/L per litre of kerosene burned
Cooking: breakfast (family of four, average)	0.17 (plus 0.28 if gas cooking)
lunch (family of four, average)	0.25 (plus 0.32 if gas cooking)
dinner (family of four, average)	0.58 (plus 0.75 if gas cooking)
simmer at 95°C, 10 min, 0.15-m pan (plus gas)	less than 0.005 if covered, 0.06 if uncovered
boil 10 min, 0.15-m pan (plus gas)	0.23 if covered, 0.27 if uncovered
Dishwashing: breakfast (family of four, average)	0.1
lunch (family of four, average)	0.08
dinner (family of four, average)	0.32
Firewood storage indoors (cord of green firewood)	190 (softwood) to 380 (hardwood)/6 months
Floor mopping	0.15/m^2
Gas range pilot light(each)	0.18/or less/day
Gas refrigerator	1.3/day
House plants (5 to 7 plants, average)	0.41 to 0.45/day
Humidifiers: 0 to 120+/day	(2.08 average/h)
Pets	Fraction of human adult weight
Respiration and perspiration (family of four, average)	0.21/h
Refrigerator defrost	1.03/day (average)
Saunas, steambaths, and whirlpools	0 to 1.08 +/h
Vegetable storage (large-scale storage is significant)	0 + (not estimated)
NONHOUSEHOLD PRODUCED	
Combustion exhaust gas backdrafting or spillage	0 to 3200 +/year
Desorption of materials: seasonal	3.0 to 8.0/average day
New construction	4.7+/average day
Ground moisture migration	0 to 50/day
Plumbing leaks	0+ (not estimated)
Rain or snowmelt penetration	0+ (not estimated)
Seasonal high outdoor absolute humidity	30 to 120+/day

SOURCE: W. Angell and W. Olson, Cold Climate Housing Information Center, University of Minnesota [*8*].

Plants

Almost all of the water used to water plants enters the air. At most, only 0.2% of this water can be used for growth. Five to seven small plants require around 0.5 L/day (1.1 pt/day) [*8*]. Although Ref *8*'s plant moisture loading appears to be on the low side compared to Ref *6*, which indicates a small potted violet emits between 0.12 and 0.24 L/day (0.25 and 0.51 pt/day). A medium single size plant such as a fern emits between 0.17 and 0.36 L/day (0.36 and 0.76 pt/day). A single medium size rubber plant can emit up to 0.5 L/day (1 pt/day). With a large number of house plants, this moisture load can be quite significant. Malls commonly have a considerable number of large plants. A young tree that is 2 to 3 m (6.5 to 10 ft) tall (beech) emits 50 to 100 L/day (106 to 212 pt/day) [*6*].

Evaporation from Wet Surfaces

Examples of wet surfaces in buildings are periodically washed floors or products, swimming pools, and standing water in crawl spaces. A large quantity of water is used in cleaning, particularity in commercial buildings like grocery stores where the floors are wet mopped every day. Any water left on shower, sink, floor, or walls will evaporate and add moisture to the conditioned space.

Evaporation is directly proportional to: (1) the difference in vapor pressure between the wet surface and the air, which provides the driving force to carry the water from the liquid surface into the air and (2) the heat transfer rate to the water surface film with heat providing the energy necessary for evaporation and the difference in vapor pressure. The evaporation from wet surfaces can be estimated by Fig. 2 and Eq 1. Figure 2 is used to estimate H and H_L. In some situations, it may be possible to measure air velocity and direction above the wet surfaces. If air is moving, then H increases, as shown in Fig. 2. Transverse flow refers to an air stream directed perpendicularly into the surface.

$$Me = \frac{H \times A \times (VP_s - VP_a) \times 0.454}{H_L} \tag{1}$$

where

Me = evaporation load from a wet surface, L/h,
H = latent heat transfer rate (Btu/h/ft^2/in. Hg) from Fig. 2,
A = wet surface area, ft^2,
VP_s = water vapor pressure of air saturated at the water temperature, in. Hg,
VP_a = water vapor pressure in the air above the surface, in. Hg,

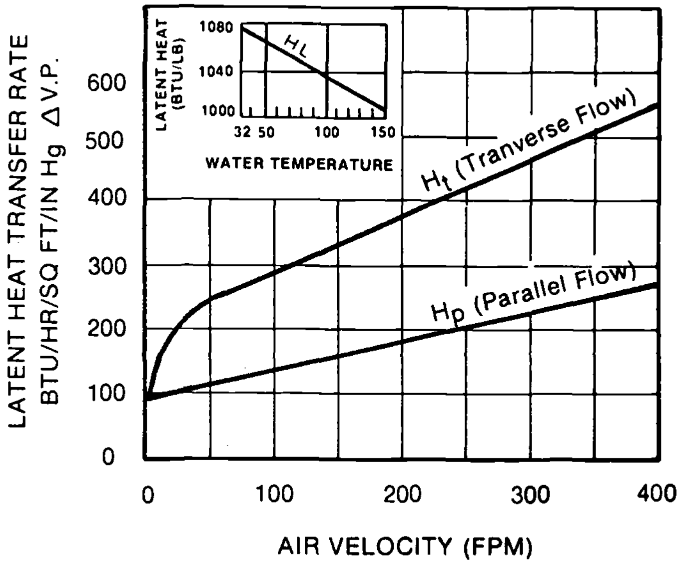

FIG. 2—Used to predict moisture load from wet surfaces.

H_L = latent heat of vaporization at the water temperature (Btu/lb) from Fig. 2, and

0.454 = conversion factor (liters of water in a pound of water).

Moisture evaporates from wet surfaces quite slowly, even when the surrounding air is very dry. The rate increases, as shown in Fig. 2, when air is blown at the surface and when the wet surface water is warm. Equation 1 originated from Dr. Willis Carrier in the 1920s [5].

For estimation of water evaporation from recreational facilities such as swimming pools, an approximation can be made by using Eq 2.

$$Me = C \times A(P_w - P_a) \qquad (2)$$

where

C = 0.000145 dimensionless,

A = area of exposed water, m^2,

P_w = saturation vapor pressure taken at the surface water temperature, Pa, and

P_a = saturation pressure at room air dew point temperature, Pa.

Values of P_w and P_a may be obtained from the *ASHRAE Handbook of Fundamentals* or from the simplified Table 2. The recommended relative humidity level in many parts of health care facilities and areas with swimming pools is in the 50 to 60% range, although this relative humidity can only be maintained with high air change rates.

For example, an indoor swimming pool measuring 4.9 × 9.8 m (16 × 32 ft) has a water surface area of 48 m^2 (520 ft^2) and indoor conditions of 50% relative humidity at 20°C (68°F), (P_a = 1169) with a water temperature of 25°C (77°F) (P_w = 3169). The surfaces will produce [0.000145 × 48 × (3169 − 1169)] or 13.9 L/h (29.4 pt/h) of water vapor.

Open Water Surface

Precise calculation of moisture evaporation from open water surfaces, such as ponds in shopping malls and landscaped interior spaces, depend on water temperature and air temperature, relative humidity, and movement. A rough value to use is 0.04 L/m^2 h (0.008 pt/ft^2 h) [*6*].

Rain Leakage

Rain leakage into the structure can turn the roof, wall, and foundation cavities into larger humidifiers.

Residential Buildings

The *ASHRAE Handbook of Fundamentals* states that "a typical family of four may produce as much as 11.4 L/day (25 lb/day) of water vapor or more if humidifiers, automatic washers, and clothes dryers are used" [*2*]. Total moisture loading is a strong function of the size of the family. A major variable for determining moisture emission rates is the number of household members. Table 3 shows a compilation of rates of daily moisture loads in European dwellings [*11*]. Table 1 provides some typical total moisture loads in North American residential buildings. One source suggested that you can correct for family size by assuming each member contributes an additional 2.1 L/day 4.4 pints/day [*21*]. In order to obtain daily moisture loadings, daily incidents are needed. An older study conducted in 1948 suggested that the average moisture input from occupants' respiration and perspiration, bathing, showering, and other internal moisture sources for a typical family of four averaged 7.6 L/day (16 pt/day) [7]. From the assorted references gathered for this chapter, the range of internal moisture loads from single-family residences can vary from a low of 4.3 to 23 L/day (9 to 50 pt/day) [*11*]. The upper range can be significantly exceeded by unvented clothes drying, extensive use of unvented kerosene heaters, attached greenhouse or swimming pool, and interior firewood storage.

TABLE 2—Simplified table for use with Eq 3 to estimate moisture evaporation from swimming pools.

Air or Water Temperature,°C	P_w (Pa)	P_a (Pa) at room RH					
	100%	80%	70%	60%	50%	40%	30%
0	611	489	428	367	306	244	183
5	873	698	611	524	436	349	262
10	1228	982	860	737	614	491	368
15	1706	1364	1194	1023	853	682	512
20	2339	1871	1637	1403	1169	936	702
25	3169	2535	2219	1902	1585	1268	951
30	4246	3397	2972	2548	2123	1698	1274
35	5628	4502	3940	3377	2814	2251	1688
40	7384	5907	5169	4430	3692	2954	2215

TABLE 3—Compilation of rates of daily moisture loads in dwellings (L/day).

Author	Reference	Households with Children			
		None	1	2	3
BM Bau	[11]		10		
BRE	[12]			5–10	
BS 5250	[13]				14.4
Dotz/Le Marie	[14]	7	20		
Erhorn/Gertis	[6]			14.6	
Lubke	[15]	13.2	19.9	23.1	
Meyringer	[16]		11.5		
Panzhauser et al.	[17]		5–12		
Pfeiler	[18]		6–10.5		
Stehno	[19]	4.3		13.7	
Average[a]		8.2	12.1	14.1	14.4

[a] Average values indicating a range are based on lower limiting values.

Unvented clothes dryers and/or the line drying of clothes indoors can be major sources of moisture, regardless of climate or season—2.2 to 3 L (4.6 to 6.3 pt) per load for electric dryer or line drying [8]. With gas dryers, the moisture load [0.0026 L/m^3 (0.16 pt/1000 ft^3)] of gas burned is an additional contribution. Clothes drying in a normal household in one day doing a week's laundry for a family of four can produce 12 L (25 pt) of water. This can usually be vented to the outside. Wet laundry that has been spin-dried at full speed emits between 0.01 and 0.04 L/kg (0.01 and 0.04 pt/lb) of dry laundry when hung in a room to dry [6]. Although Table 1 indicates no moisture load from clothes washing and drying when the dryer vent is to the outside, other sources do indicate a positive moisture load can result. Reference *21* suggests a family of four with an electric dryer vented to the outside can obtain a moisture load of 0.6 L/day (1.3 pt/day) from the washer and another 0.5 L/day (1.1 pt/day) from the vented dryer.

Another source of moisture during heating periods is combustion products from unvented space heaters. The two major by-products of combustion are carbon dioxide and moisture. An unvented kerosene space heater generates 0.95 L per liter (0.95 pt per pint) of kerosene burned.

Firewood storage indoors can also be a major source of moisture. A 10% reduction in moisture content of one cord of softwood is estimated to generate 130 L (275 pt) of moisture, for hardwoods 250 L (530 pt). Seasonal storage of a winter's worth of green hardwood firewood indoors can be equivalent to the moisture produced by a family of four through respiration during the same period, 5 L/day (10.5 pt/day) [4].

In cooling climates, the improper draining of condensate from air conditioning systems which allows for the re-evaporation of moisture and subsequent migration back into conditioned spaces has proven to be a major contributing factor to moisture-related building problems. Condensate should be drained to the exterior, not into crawl spaces, or plumbed directly into the waste water system. Standing water should be avoided in condensate pans. Detailed measurements of the latent moisture load on a building with half of the floor space dedicated to offices and the other half dormitory living quarters with a total of 372 m^2 (4000 ft^2) of floor area conditioned by a 3-ton unitary heat pump in Oak Ridge, Tennessee, found condensation quantities of 5 to 6.5 L (10.5 to 14 pt)/cooling degree day base 18.8°C (65°F) [22]. With 6 CDD (celsius degree days) (11 at 65°F), the total condensate to be properly drained to the outside of the building is 39 L/day (82 pt/day).

OUTDOOR SOURCES

Rain/Fog/Dew/Blowing Snow

Rain-Soaked Walls and Roofs

One of the primary functions of the above-grade envelope is to keep rainwater out. The moisture load from this source is mentioned because if the envelope leaks this can overshadow all of the internal loads discussed in the last section. The actual loads can vary from zero to the annual rainfall multiplied by the roof area. One analysis indicated that approximately 273 L (600 lb) of water could be absorbed by the wood siding and sheathing of a house with a floor area of 84 m^2 (900 ft^2) before the moisture content would reach 26%, assuming a uniform distribution of moisture [23].

Flooded Basement

Liquid water flows downward due to the effect of gravity. Hydrostatic pressure can develop and force water through openings in below-grade walls or floors. High hydrostatic pressure is caused by snowmelt water or a high water table with poor subsurface drainage surrounding the building foundation.

Sixty square meters (646 ft^2) of exposed water at 5 to 10°C (9 to 18°F) lower than the ambient air temperature would vaporize at the rate of 6 L/h (12.7 pt/h), assuming that the air above was vented rapidly enough to maintain relative humidities below 40%. The ventilation required is about 5 air changes/h during a typical winter period. In such cases, however, the rate of evaporation is reduced by higher humidity levels in the house, which usually results in serious condensation problems.

Damp Basement

Another physical process that permits moisture to enter foundations is by capillarity. Capillarity is the movement of water which is wicked by fine pores (due to surface tension forces) in soil, concrete, brick, mortar, and other foundation materials. It can transport water accumulated underneath a foundation up and into the basement space.

Sources of moisture entering foundations are:

- surface run-off due to poor grading
- lack of or effective eaves troughs and downspouts
- blocked drainage at base of house's exterior wall
- defective or missing footing drainage system
- improperly drained window wells
- flooding of nearby stream or drainage swale
- melting snow adjacent to foundation walls
- high water table
- defective storm drainage system
- inadequately draining backfill around basements
- humid outside air used for summertime ventilation
- defective basement wall moisture and air/vapor retarders

A building in Oak Ridge with 195 m^2 (2100 ft^2), used for detailed envelope measurements in which a dehumidifier was installed to control humidity, was found to produce on average 18.8 L/day (40 pt/day) of condensate during a warm day in July 1991. This value was above and beyond the latent load removed by the thermostatically controlled air conditioner set at 24°C (75°F). A substantial portion of this building was below grade. The measured values are believed to be representative of a dehumidifier operating in a large residential basement. There were no internal moisture sources in this building; the majority of the moisture came from infiltration and capillary suction from the surrounding soil.

Humid Air

In cooling climates, a major source of moisture is the exterior ambient air. The outside air is typically warm and humid. The greater the air change or exchange of interior air with exterior air in cooling climates, the greater the rate of inward-airborne moisture migration.

This moisture source depends on the air leakage rate and/or controlled ventilation. For an existing building, the air leakage rate can be measured by a tracer gas analysis of the building or implied by using a blower door to check the ability to sustain both positive and negative internal air pressures. The best-known procedure for estimating air leakage rates for buildings that have not yet been constructed is provided in Chapter 23 of the *1989 ASHRAE Handbook* [*2*].

Ventilation is required for people, for most exhaust hoods or fans, and to maintain positive air pressure in the building compared to surroundings. ASHRAE Standard 62-89, "Ventilation for Acceptable Indoor Air Quality," requires a minimum fresh air requirement of 0.425 to 0.71 m^3/min (15 to 25 ft^3/min) per person and larger if smoking is allowed [*24*]. Fume hoods generally require an air velocity of 46 m (150 ft) per minute across the open hood area. The amount of make-up air needed to maintain positive pressure depends on the open area through which air will leak out of the room, the shape of the openings, and the specific static pressure difference between the inside and ambient. Equation 3 can be used to estimate airflow rate (cubic metres per minute) required to maintain a specified positive air pressure [*25*]

$$Q = 945 \times 0.60 \times A \times SP^{0.65} \qquad (3)$$

where

945 = calculation factor (dimensionless),
0.60 = coefficient of entry for air entering a square-edged opening (dimensionless),
A = area of the opening, m^2, and
SP = specified static pressure differential centimetres of water in a water column.

A is derived by assuming an estimated linear crack-like opening for the conditioned space. Once the total ventilation is known, the moisture load from all exterior sources can be calculated by Eq 4.

$$M_e = Q \times d \times 60 \times (M_o - M_i) \qquad (4)$$

where

M_e = moisture load from fresh air, kg/h,
Q = sum of outdoor airflows necessary for people, pressurization, and exhaust air make-up, m^3/min,
d = density of air, kg/m^3,
60 = minutes per hour,
M_o = moisture level of the fresh air, kg/kg of air,
M_i = moisture level inside the building, kg/kg of air.

In more northern climates, a typical house vented during the summer partly absorbs moisture by building materials and furnishings. This moisture is released later when the ambient humidity level starts to drop. Three to eight L/day (6.3 to 17 pt/day) may be released in the early fall.

Ground

One of the largest sources of moisture in building enclosures is the migration of moisture from the surrounding soil into foundations, basements, and crawl spaces, and subsequently into conditioned spaces.

A crawl space, especially under houses on hillsides, without a ground cover over exposed dirt can release as much as 40 to 50 L/day (85 to 106 pt/day) of moisture into conditioned space [*3*]. A second reference indicates this could be well over 72 L (150 pt) of water [*26*]. To bring in large quantities of moisture through the crawl space requires a water table within 5.5 m (18 ft) of the crawl space floor and a soil other than porous sand or rock. The soil capillary rise can be reduced by 90% by installing a ground cover [*27*].

Moist air does leak into the basement from around the basement floor perimeter wall joints, through cracks, and around drains. This air may also contain a significant amount of moisture. The moisture input rate would be at a maximum during the coldest part of winter. This was found during a study of radon gas emissions in basement areas. Under a low pressure difference of 10 Pa, water vapor was entering the basement along with radon gas in the leakage air. During the winter, when a stack effect is at work, the basement area would be under a slight negative pressure with respect to the outside. Thus, outside air may seep down through the soil or around the exterior part of the foundation through window sills or by drain pipes from an eaves trough and finds its way into the perimeter drain tile, becomes wet, and enters the basement as cold saturated air. If this finding is generalized, saturated cold moist air could be trickling into the house all winter [*5*]. For three basement homes tested in Canada, soil gas entry was 1.1 to 3.8% of the entire home air infiltration [*28*]. Each liter per second of soil gas, at 10°C (50°F) and 100% relative humidity, brings in 0.67 L/day (1.4 pt/day) more moisture than is in outdoor air of −10°C (50°F) and 80% relative humidity [*29*].

In typical basement houses in Canada, one research project reported 2 to 3 L/day (4.2 to 6.3 pt/day) of moisture may be diffusing inward through the walls and floor [*5*]. Hollow concrete block walls, when visibly wet for several feet above the basement floor all around the perimeter of an average-size basement, may have as much as 8 to 10 L (17 to 21 pt) of moisture evaporating from this surface area per day with a 40% or less indoor relative humidity. If there is visible water on the floor near the wall, this rate will be larger.

SUMMARY

Moisture in buildings comes from only five general sources: construction material, interior activities, immediate surrounding exterior, above-grade environment, and adjacent soil. In properly constructed and operated residential buildings, the largest single moisture source is from people's respiration and perspiration, for a family of four, 5 to 6 L/day (10.5 to 13 pt/day). The other activities such as cooking and cleaning about double the moisture load to around 10 L/day (21 pt/day). Construction sources, such as the moisture trapped within fresh concrete and green lumber materials, double the total residential moisture load in the first year to about 20 L/day (42 pt/day).

The other major potential moisture sources should be controlled in properly constructed and operated buildings. Firewood storage inside the basement would add about 5 L/day (10.5 pt/day). Clothes drying inside conditioned spaces or using a dryer which is not vented to the outside can add around 12 L/day (25 pt/day) for the typical family of four. A plant room or attached greenhouse will add 0.1 to 100 L/day (0.2 to 200 pt/day) per plant, depending on the size of the plant. Wet mopping a large kitchen 6 by 10 m (20 by 33 ft) every day would add about 9 L/day (19 pt/day). Standing water in a 144 m^2 (1550 ft^2) basement for a full day would add about 140 L/day (296 pt/day). Although properly constructed foundations with good subdrainage and dampproofing should keep moisture loads from foundations below 3 L/day (6.3 pt/day), there are reported foundations which contribute 20, 30, 50, up to 72 L/day (40 to 150 pt/day).

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Part 2: Applications

9

Effect of Air Infiltration and Ventilation

by David T. Harrje[1]

VENTILATION AND MOISTURE TRANSPORT

THE EMPHASIS IN THIS CHAPTER is on moisture transport via ventilation and air infiltration. When calculations are made as to the relative importance of the various moisture transport mechanisms, air movement normally heads the list. In the case of convection versus diffusion, a 10 to 1 ratio (or even higher) is not surprising. Therefore, it is necessary to understand what air movements are present in our buildings and what moisture problems are a direct result of these air movements. In the following sections, the relationship between ventilation requirements, natural flows of air, and key building locations will be discussed with regard to how they influence building moisture problems.

VENTILATION REQUIREMENTS FOR BUILDINGS

In North America, the standard that covers ventilation requirements in buildings is the American Society for Heating, Refrigeration and Air Conditioning Engineers Standard 62 [*1*]. The ASHRAE goal is for standards to be updated every five years to meet the ANSI (American National Standards Institute) requirement. The latest update of Standard 62 occurred in 1989. The standard takes into account moisture-related factors, but its primary concern is maintaining the quality of indoor air and control of odors. Enforcement is through local building codes using the standard.

ASHRAE Standard 62–1989 approaches building ventilation requirements in two ways: (1) using the Ventilation Rate Procedure, in which building spaces with various functions have been assigned minimum ventilation rates (using professional consensus as the basis for the assigned ventilation values); and (2) using the Air Quality Procedure, in which the emphasis is placed on maintaining air contaminants below prescribed concentrations. The Ventilation Rate Procedure is based upon the maintenance of carbon dioxide levels in each room below 1000 ppm. This results in a minimum ventilation rate of 15 ft^3/min (7 L/s) per occupant. Using CO_2 as a "surrogate" pollutant, this approach assumes that other pollutants present will also be kept at acceptable levels. Where special conditions exist in the building, such as moisture generated in bathrooms and kitchens, elevated ventilation rates have been prescribed. Detailed tables are provided in Ref *1*. The alternative Air Quality Procedure is actually to measure the pollutant concentrations to assure that the indoor environment is acceptable; otherwise, ventilation rates must be raised accordingly. Depending on the special conditions for an individual space, one might choose one approach over the other.

Other countries have their own standards for ventilation, e.g., Scandinavian countries have created the Nordic Standard, which has many similar ventilation requirements as found in ASHRAE 62-89. The Air Infiltration and Ventilation Centre, maintained by the International Energy Agency (IEA), has aided in cross comparisons of the various international ventilation standards [*2*], has held a workshop on airborne moisture transfer [*3*], and has served as the organization formulating calculation [*4*] and measurement [*5*] methods as well as providing requirements for air infiltration data collection [*6*]. Since the United States (through the Department of Energy) and Canada are two of the fourteen countries supporting the AIVC, the majority of the information collected by the AIVC, including detailed airflow-related moisture references, are free to U.S. and Canadian users. This information source can prove very useful to the building designer concerned with achieving adequate ventilation and freedom from airflow-related moisture problems.

STRATEGIES FOR PROVIDING AND CONTROLLING VENTILATION

Control of ventilation has been achieved in a variety of ways. Mechanical ventilation using fans and blowers is used to fully control the amount of air reaching each building zone. At the other extreme, natural ventilation is relied upon, often completely. This can mean a deliberate opening and closing of windows, vents, and doors, or it can rely upon air infiltration (through unintentional openings) to supply the required airflow. It is not difficult to guess which of these two approaches provides the best control; however, there is still resistance in the U.S. building industry to even require exhaust fans in every new bathroom to control the local ventilation rate and minimize moisture problems. Some countries have completely committed themselves to mechanical ventilation in new residences, while others resist mechanical systems, relying on natural ventilation and mild climates to satisfy their ventilation needs and to control moisture.

The desirability of mechanical ventilation tends to be widely recognized as necessary for commercial buildings, although architects from Great Britain still make the case for the naturally ventilated office building. Most disagreement

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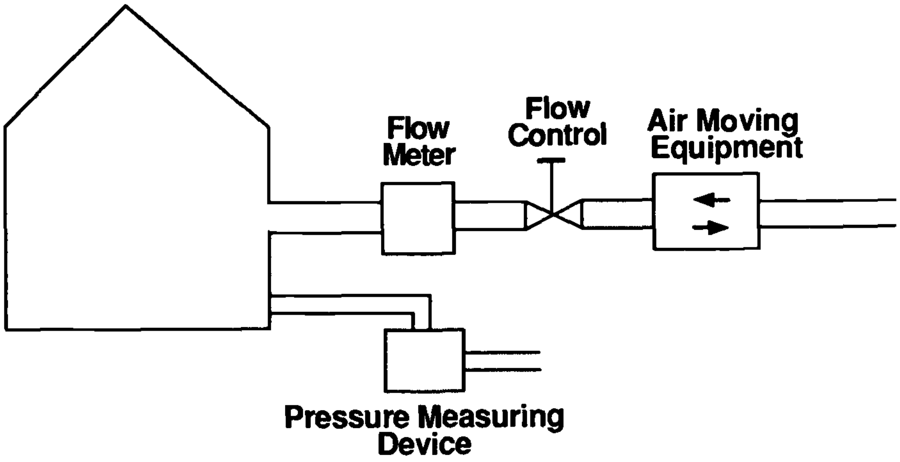

FIG. 1—Schematic of a whole building airtightness test from Ref *5*. A blower door is the typical airflow equipment used in these tests in residences. Large blowers are used in commercial buildings, or the HVAC systems can be used to supply the required pressure.

occurs in the residential arena. It is clear from a number of studies [*7*] that using mechanical ventilation to achieve the goal of controlled ventilation to each room requires that the building envelope be tight. Unless air infiltration is controlled, the mechanical ventilation goals will be compromised and zones will end up over- or underventilated.

One measure of building envelope tightness is the number of air changes per hour that take place when the pressure within the building is raised to 50 Pa. The method used is based on fan pressurization [*8*] (for example, use of a blower door in residences, or the use of building ventilation systems or huge blowers in larger buildings), which is illustrated schematically in Fig. 1. The tightness goal should be set at approximately one air change per hour (1 ACH) based upon the Swedish experience [*7*] if the mechanically ventilated residential building is to achieve the goal of providing the desired ventilation rates free of undesirable weather influences due to air infiltration. Larger buildings require even tighter construction standards [*7*].

A Scandinavian design strategy for a house using mechanical air exhaust is shown in Fig. 2 [*7*]. This is a ventilation system with the air exhausted from the bathrooms and kitchen (sources of moisture and odor), with appropriate amounts of outside air entering the house at locations where there are ventilation needs. The design must keep occupant comfort as a principal goal in that the entering air must not create drafts;

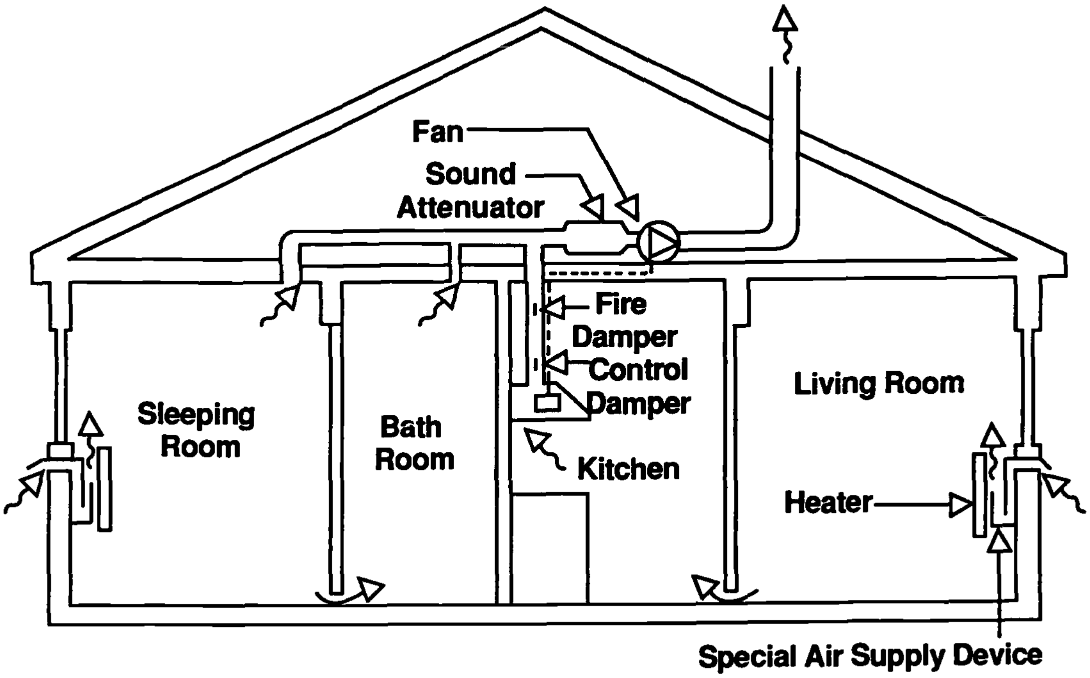

FIG. 2—Schematic of mechanical exhaust system in a modern residence. Air enters at zone locations with ventilation needs and exits at the kitchens and bathrooms. From Ref *7*.

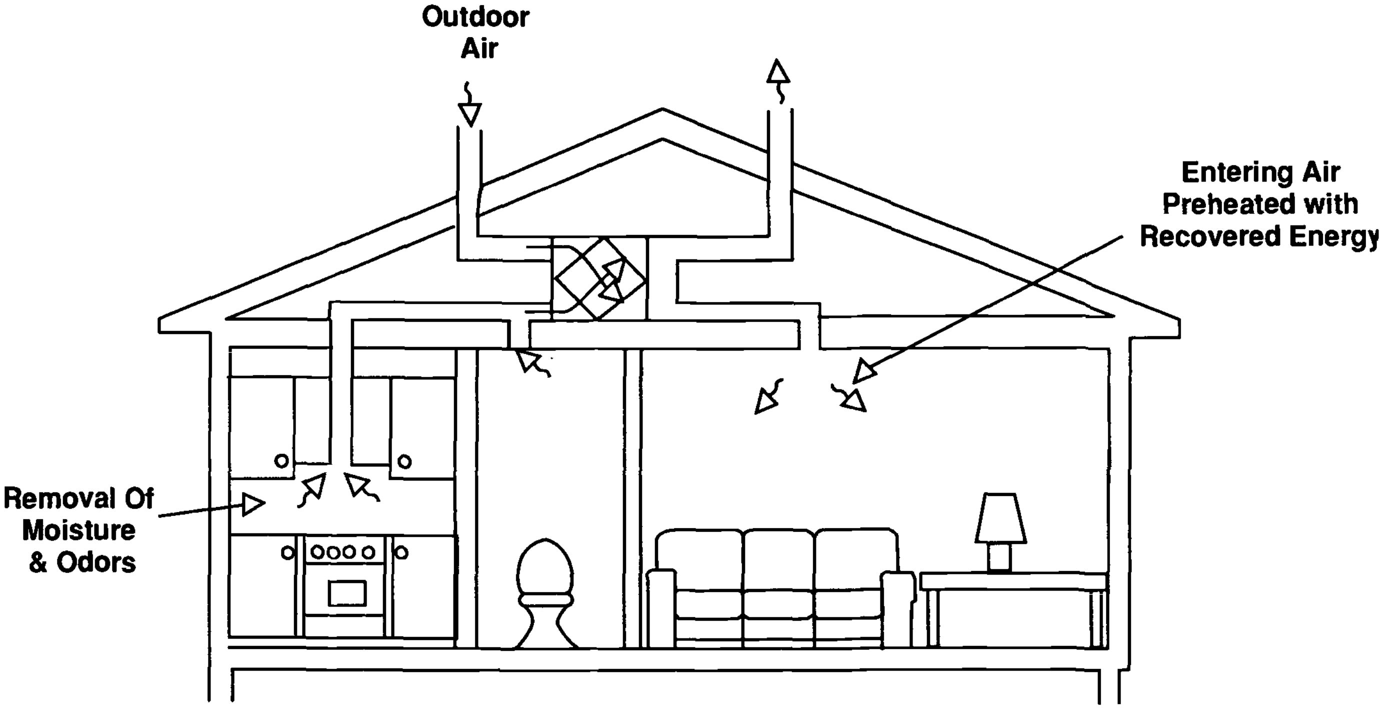

FIG. 3—Schematic of balanced system with controlled supply and exhaust airflow. Heat recovery from the exhaust air allows the energy to be added to the supply air. Moisture can be added or removed from the supply air to reach the desired interior levels. From Ref *7*.

hence, the fresh air entry locations are linked with the space conditioning equipment (e.g., in Sweden, slot vents are used behind the radiators to preheat the incoming air).

A completely balanced system may also be used, i.e., a mechanical air supply as well as a mechanical exhaust as shown in Fig. 3 [7]. The R-2000 homes in Canada use variations of such ventilation systems, and such systems are beginning to appear in new U.S. residential construction. These more complex systems lend themselves to energy recovery measures such as recovering energy from the exhaust air and reintroducing it to the supply air (or possibly heating domestic water). Moisture control through humidification or dehumidification is greatly aided when a mechanical ventilation system is employed. However, one must be careful that the system is indeed "balanced." If there are pressurized rooms, then the moisture-laden interior air will be forced into walls, ceilings, and floors, causing possible major condensation problems unless vapor/air retarders can prevent such flow. The worst case history of houses which used positive interior pressure (where a design goal was to eliminate drafts) was in Sweden; the result was extreme moisture damage in the wall systems. The other concern is that the return air system is inadequate; then the mechanical system seeks the required airflow from other sources, often from the basement or from crawlspace locations where moisture (or radon gas) may be ingested into the return.

AIR INFILTRATION

Air infiltration is present to a greater or lesser extent in every building. Ongoing studies by researchers at the National Institute of Standards and Technology (NIST, formerly the National Bureau of Standards) [9] point out that even in commercial buildings with full mechanical ventilation systems, air infiltration often plays a major role in determining the total amount of airflow actually moving through the building. Such airflows normally have not been fully taken into account in the initial building systems design calculations, yet they may double airflow rates and continue to be present even when the mechanical systems have been turned off [9]. At the other extreme, residential buildings often depend completely upon air infiltration for meeting ventilation requirements. Here the question becomes "how dependable is the ventilation rate?," and from a moisture standpoint "where does the air come from?," and"how much moisture does it bring to the individual rooms?" To answer these questions, we need to review the subject of air infiltration and the moisture environment of typical buildings.

The subject of air infiltration has been treated exhaustively in the 14 yearly conference proceedings of the AIVC [*10*], the numerous reports and manuals published by the AIVC (such as Refs *4* and *5*), Chapter 23 on air infiltration and ventilation in the *ASHRAE Handbook of Fundamentals* [*11*], and special publications [*12–14*] and standards [*8,15,16*] by ASTM, to name just some of the information available. The reader is referred to these publications for detailed information on the subject. What will be discussed here is how air infiltration relates to moisture transport in buildings.

Other chapters have discussed the vital subject of moisture sources. One source of great concern is moisture from the soil under and surrounding each building. The surest way for that moisture to interact with the building interior is for an upward flow of air to be present and thus supply the means of

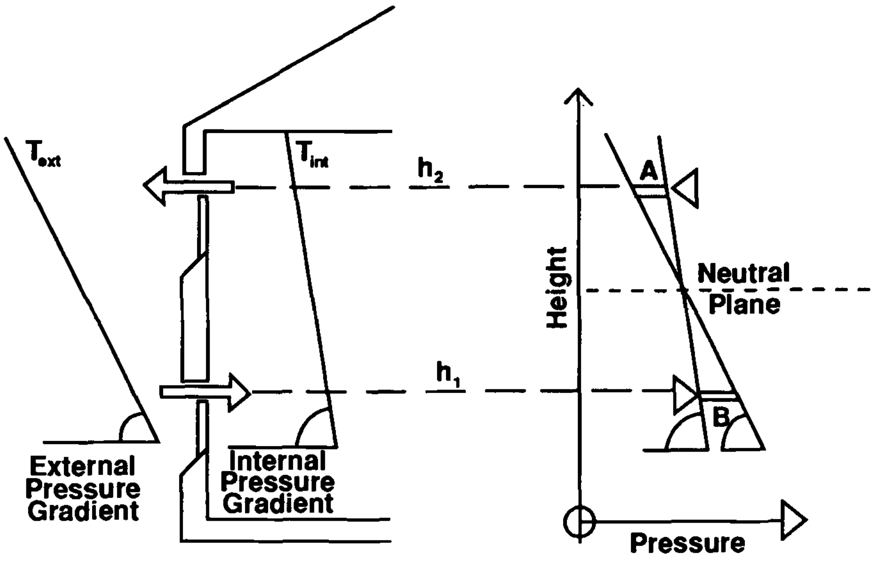

FIG. 4—Stack-induced pressure between two vertically placed building openings. The neutral plane, where there is no pressure, is also indicated. From Ref *4*.

moisture transport. The stack effect, i.e., the upward flow of air due to air density differences within the building is often that transport mechanism. In most locations in the United States, heating is required for more than half the year. During the heating season, the heated interior air is less dense than the outdoor air, causing the indoor air to rise within the building [*11*]. This rising air is replaced by outdoor and basement air. High basement moisture levels thus can translate into high interior moisture levels. A diagram of the pressure differences caused by the stack effect is shown in Fig. 4. Using tracer gases to document the extent of vertical airflows in buildings, as well as the results of extensive radon testing (in those cases, the radon gas acts as the tracer), one discovers that typical tracer concentrations on the first floor are often half that of the basement. This is evidence of very effective air (and hence, moisture) transport, and the transfer process continues as we move upward through the building. Eventually, much of the moisture contained in the building air finds its way into attic or loft areas, where rapid cooling condenses the moisture on building components such as roof sheathing and roof support elements.

To calculate the pressure resulting from the vertical displacement of two openings, A and B, in a building envelope (Fig. 4), we use the relationship [*4*]

$$p = -dg\,273\,(h1 - h2)\,(1/\text{Text} - 1/\text{Tint})\,(\text{Pa})$$

where

d = air density at 273 K, kg/s/m^3,
g = acceleration due to gravity, m/s^2,
T = absolute temperature of air, K (exterior, exterior and interior, interior), and
h = height of opening, m.

If we are dealing with different interior temperatures at the opening locations, the relationship becomes more complex [*4*]. As the height difference increases, the stack effect becomes even more dominant. High-rise buildings provide large pressure differentials which must be controlled floor to floor if stack effects are to be minimized. However, moisture sources of proportional magnitudes are necessary if high rise and other large buildings are to experience airflow-related moisture problems comparable to residential buildings.

It must be remembered that outdoor air entering the building is capable of transporting less and less moisture as the outside temperature drops (see Chapter 6 of Ref *11*). Therefore, although the relative humidity may still be high outside, the absolute moisture content drops dramatically with temperature. For example, at 20°C, the air at saturation conditions carries four times the amount of water vapor as compared to saturated conditions at 0°C [*11*]. This means that under winter heating conditions, with higher driving pressures, even though air infiltration will increase, the amount of outside moisture entering the building via air infiltration will actually decrease. This lowering of the moisture level inside will cause the interior wood to shrink and possibly crack and cause the occupants to experience respiratory effects and discomfort from the dry air. Adding moisture via air humidifiers must be closely controlled or major condensation problems will occur on any cool interior surface. One should seek to pro-

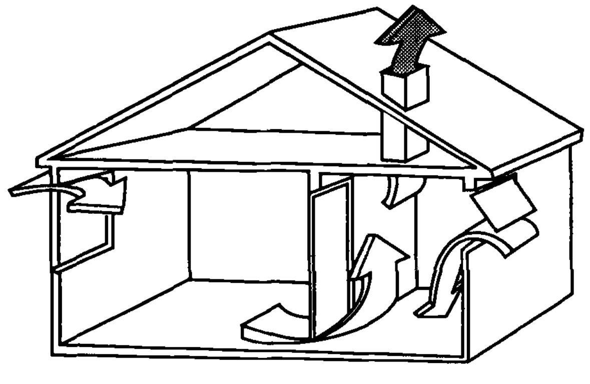

FIG. 5—Multi-zone network simplified case. From Ref *4*.

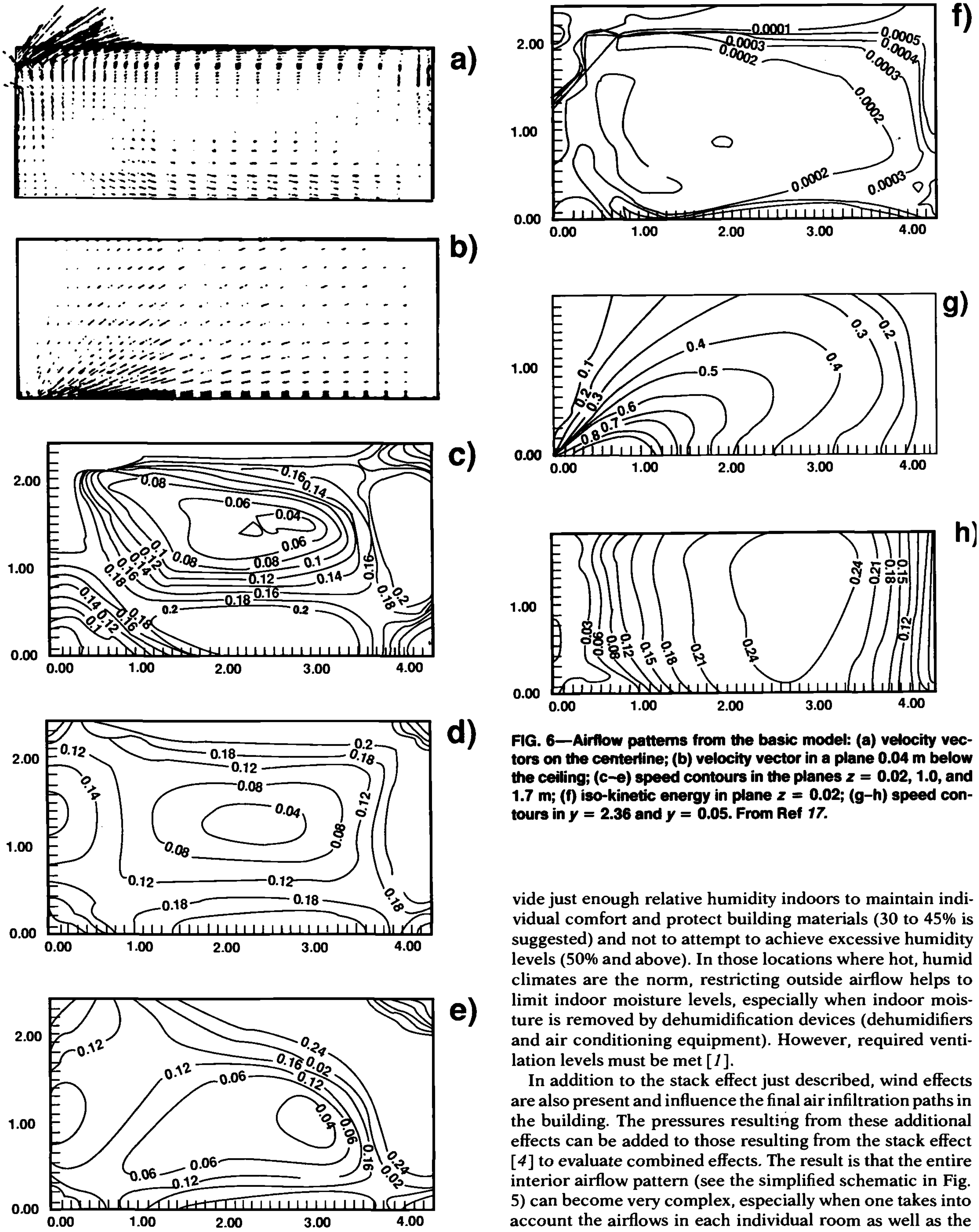

FIG. 6—Airflow patterns from the basic model: (a) velocity vectors on the centerline; (b) velocity vector in a plane 0.04 m below the ceiling; (c–e) speed contours in the planes z = 0.02, 1.0, and 1.7 m; (f) iso-kinetic energy in plane z = 0.02; (g–h) speed contours in y = 2.36 and y = 0.05. From Ref *17*.

vide just enough relative humidity indoors to maintain individual comfort and protect building materials (30 to 45% is suggested) and not to attempt to achieve excessive humidity levels (50% and above). In those locations where hot, humid climates are the norm, restricting outside airflow helps to limit indoor moisture levels, especially when indoor moisture is removed by dehumidification devices (dehumidifiers and air conditioning equipment). However, required ventilation levels must be met [*1*].

In addition to the stack effect just described, wind effects are also present and influence the final air infiltration paths in the building. The pressures resulting from these additional effects can be added to those resulting from the stack effect [*4*] to evaluate combined effects. The result is that the entire interior airflow pattern (see the simplified schematic in Fig. 5) can become very complex, especially when one takes into account the airflows in each individual room as well as the flows between rooms (e.g., even the flow through large openings, such as doorways, becomes a special item of concern). A multi-nation task group (IEA Annex 20, Airflow Patterns Within Buildings), has been conducting investigations of airflow patterns in single rooms as well as multi-room flows. That work has been reported extensively at the Twelfth AIVC Conference [*17*] and has also appeared in a series of Annex 20 reports [*18,19*]. A typical single-room airflow pattern that occurs when air is introduced to the room by a diffuser is illustrated in Fig. 6 on page 189. Such patterns are documented in highly instrumented special test rooms and/or by the use of computational fluid dynamics (CFD). The airflow pattern is further complicated when furniture and occupants are added to the room. A handbook covering the experimental methods used to document the airflow in multi-room buildings was published by the AIVC in the fall of 1991 in conjunction with Annex 20 [*18*]. The AIVC previously published the companion applications guide, Air Exchange Rate and Airtightness Measurement Techniques [*5*]. Both documents will prove extremely useful to the building designer interested in verifying that ventilation and moisture goals have been achieved.

THE LOCATION OF THE BUILDING

The location of the building can make a major difference in the moisture problems to which it is exposed. In every region of the country, one can find microclimates where moisture effects are elevated. Examples are: near bodies of water; on soil that has high moisture content; in valleys where fog and moisture condensation are prevalent; and those locations where relative humidities are high, especially where temperatures are also high so that the outside air is then able to transport large amounts of moisture into the building.

The case of high moisture content in the outside air poses special problems. No longer does increased ventilation rate help the situation; rather, it can make matters worse. Add to that equation air conditioning, which generates cool interior surfaces, and it is not hard to visualize a whole class of condensation and moisture problems. The hotel industry has encountered just such problems, not limited to, but especially prevalent in such locations as Florida and the Gulf Coast. The American Hotel and Motel Association has reported that mold and associated musty odors cost their members $68 million every year in lost revenue and repair costs [*20*]. Reference *20* points out that such mold and moisture problems have tended to be neglected in building research.

Above and beyond the mold-related costs, there is the cost of air conditioning the warm, moist air to acceptable indoor comfort levels. Reference *20* points out that under summer conditions in the warm, moist areas of our country, air conditioning cost associated with the latent load is comparable to, or even exceeds, the sensitive load. With this in mind, only that outside air actually required should be allowed to enter the building. Again, this means a tightly constructed building envelope is necessary, with appropriate measurements to insure that the goal has been achieved.

Returning to mold and mildew, Ref *21* describes two case studies in Florida buildings. These studies point out the various paths of airflow and locations in the structure where problems often are present. One common practice that causes problems is the use of vinyl wallpaper, which is an excellent interior vapor retarder. Unfortunately, the backside of the wallpaper is the point where the infiltrating moisture, borne initially by the outside air, is condensed. This becomes the site for mold growth and odor generation. Seven patterns of external airflow are described in the reference, which were mapped by infrared methods and tracer gas techniques. Reference *21* concludes that problems result when a formula-type approach is used in the building design rather than taking into account regional differences, operational variations, and the interrelationships between mechanical systems and the building envelope. In the case studies, both buildings were excessively depressurized, encouraging outside air to enter the structures.

Similar exterior moisture problems have been analyzed in the Gulf Coast region of Texas [*22*]. A test building has been used to model various design approaches in the treatment of the outside walls of residential construction. The conclusion is that, as a general rule, vapor retarders should be placed on the side of the structure which will be the warmest during the longest season. For the warm, moist Gulf Coast areas, this means an exterior vapor retarder [*22*]. An interior vapor retarder produces repeated seasonal condensation that can result in mold growth, wood rot, loss of insulation quality, and corrosion problems in piping and electrical systems and therefore is not appropriate in that climate. Since moisture control is the key to arresting the mold growth, limiting vapor transmission and providing appropriate ventilation to prevent condensation are vital for design success.

BUILDING AREAS OF SPECIAL INTEREST

The documentation of the airflow patterns in buildings, which are the principal mechanism of moisture transport, can help pinpoint building locations that are of special interest from a moisture standpoint. Linked closely is the necessary information on where moisture condensation can take place within the building. Here we need to know the location of cold surfaces, such as glass areas and thermal bridges [*23*] (from a moisture problem standpoint, those locations on the building envelope where interior surfaces are cool enough to cause condensation, often the result of insufficient insulation and the presence of building envelope structural elements), and convective loop phenomena [*24*] (airflows within the building cavities which can result in cool interior surface temperatures). Some of the locations of concern are: basements, attics, corners, closets, kitchens, bathrooms, etc.

Basements

The sources for moisture in the basement include groundwater, which can evaporate from exposed soil or enter through the floor and wall surfaces that have not been treated with moisture retarders, exhaust from clothes dryers and washers, clothes drying on lines in the basement, and other moisture-related equipment located there, as well as from humid outside air entering via infiltration or through vents. A significant fraction of the building air enters the living space from the basement or crawlspace zones. This air path up through the building can be limited by additional basement/crawlspace vents (to provide an easier exit path for the air) or by emphasizing good sealing methods between the substructure and the floors above.

How much to vent the basement/crawlspace zone is dictated by local and state building codes. In a number of crawlspace homes in New Jersey, it was shown that once the moisture entry was eliminated via a vapor retarder covering the moist dirt floor, there no longer was a need for vents, and wood moisture levels in the crawlspace were no higher than the previous vented arrangement, while energy savings resulted [*25*]. Moisture source removal should always be the first priority! In this case, moisture from the soil was minimized, but closing off vents also limits moist air infiltration into the crawlspace during that part of the year when outdoor moisture levels are excessive (humid summer conditions).

Attics

A principal source of moisture entering the attic is air from the building moving upward from the occupied zone [*26*]. Unless ventilation rates in the attic can rapidly dilute this moisture-laden air and remove it from the attic space, as shown in Fig. 7, condensation is to be expected when cool surfaces are present. The critical moisture season for the attic is the winter. When it is cold enough, condensation will take

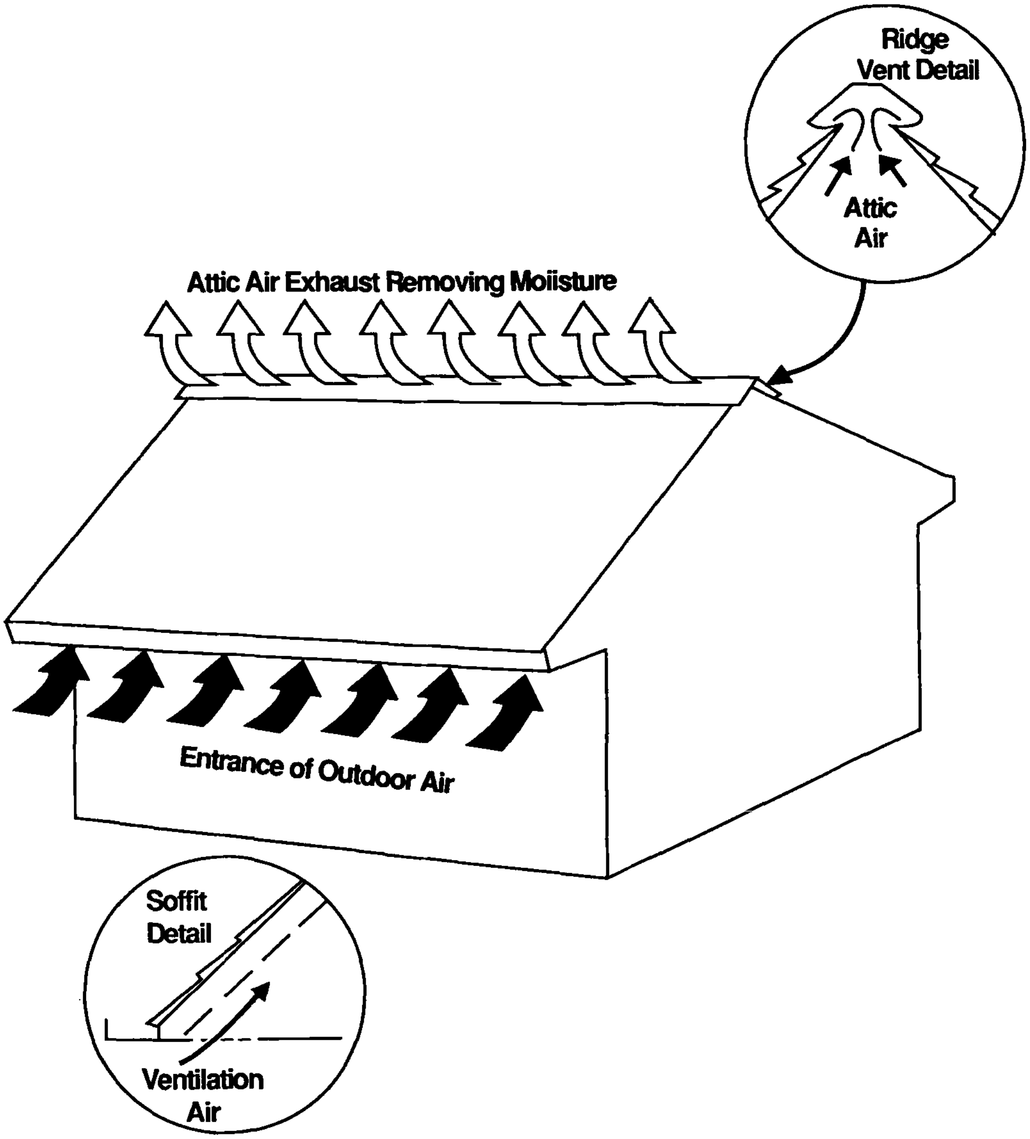

FIG. 7—Attic soffit vents and ridge vents are ideal to provide evenly distributed ventilation for the attic space and over the sheathing. Outside airflow is necessary to provide the dilution of the moist indoor air that has exfiltrated to the attic space. The recommended minimum vent area is 1 ft^2 (1 m^2) of vent area to 300 ft^2 (300 m^2) of attic area. Vent area should be evenly matched between intake (vents in the eaves or near the attic floor) and exhaust, high in the attic space.

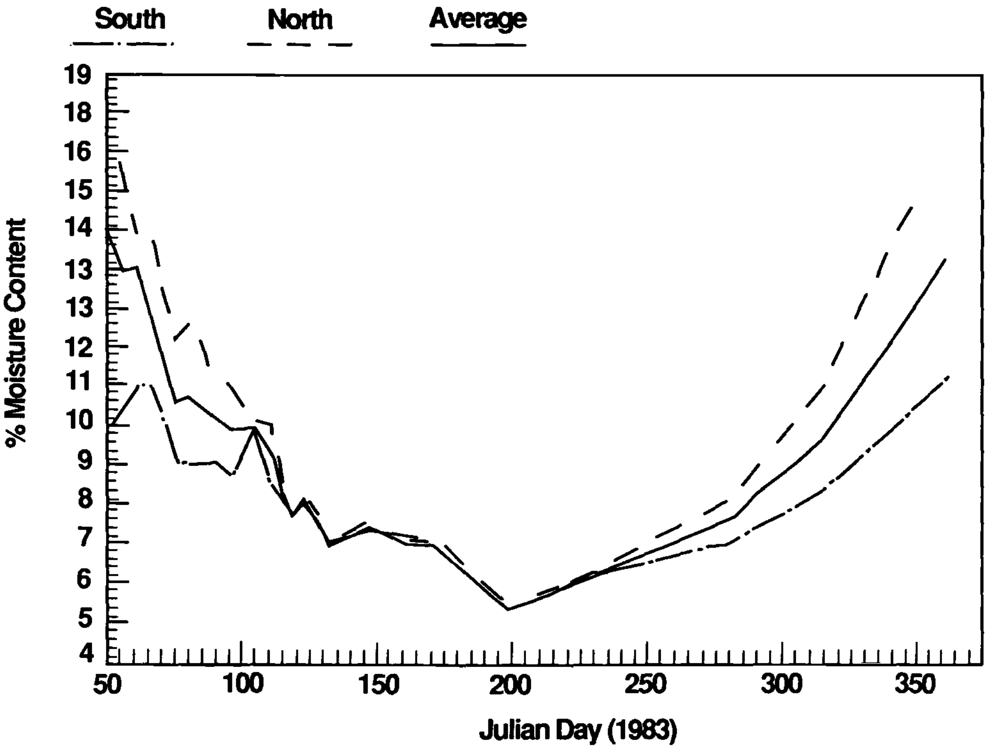

FIG. 8—Yearly moisture cycle of wood sheathing where low moisture levels are reached in the summer period when temperatures are elevated and moisture levels are high when attic temperatures are low. Both conditions limit the growth of destructive fungi, but for brief periods the fungi can grow. From Ref *27*.

the form of frost and ice buildup on the underside of roof sheathing and on roof support members. When attic temperatures rise, the frost will melt and may result in water dripping on the ceiling (or insulation), causing possible water damage. Even when no dripping occurs, the water will be absorbed into the wood, raising its moisture level and causing possible wood damage. Two examples of damage are the growth of destructive fungi, so called dry rot, that causes the wood to crumble. The appropriate combination of moisture level and temperature speeds up this destructive process. Another example of roof moisture damage is delamination of plywood sheathing. Here the condensed moisture enters the bottom layer of ply, but the glue layer acts initially as a moisture retarder, causing the entire moisture burden to be handled by a single layer of ply. Repeated cycles cause that layer to swell and delaminate, and the process can then move on to the next layer [*27*]. The older practice of using solid wood sheathing allowed the entire wood thickness to take on the moisture burden, with the wood moving through a yearly moisture cycle and avoiding dry rot by passing rapidly through the zone of dangerous combination of wood moisture and temperature as shown in Fig. 8 [*27*]. New choices of roof construction material must take into account the moisture-related events taking place in this zone or face similar disasters brought about by airborne moisture.

We must remember that venting of the attic space is critical for all seasons. Too little ventilation in the summer period means excessive temperatures in this space, with shortened life for the roofing materials. In the winter period, moisture contained in the indoor air venting through the attic will cause major condensation problems in the attic if sufficient ventilation is not provided. House inspections have revealed attic vents sealed off under the mistaken idea that energy would be saved (the "keep that warmer air in the attic" approach) without realizing that in the process, the materials in the attic were placed in extreme moisture danger!

Corners

The way buildings are constructed often places a high concentration of building support materials at the corners of the building. The materials tend to be relatively heat conductive when compared to wall insulation, e.g., steel beams, concrete, or even wood construction. This means one should anticipate thermal bridging in these corner locations. Add to that problem the fact that interior airflow tends to make corners into "dead zones" (zones where recirculation patterns are encountered, limiting communication with other room air) and one can recognize all the ingredients for condensation problems. Together with the condensation is the possibility of mold growth. Even in the best maintained residence, corner mould growth may be present. This is especially true of bedroom locations, where temperature settings may reduce corner temperatures further (e.g., lower temperature settings maintained during the day when bedrooms are not used) or where moisture generated by the sleeping occupants at a time when the airflow is low (during the night setback period) tends to promote corner condensation and mold growth.

Under conditions of excessive interior moisture generation with poor air circulation, the problem of moisture condensation and mould growth can get out of hand. In New York apartments, where clothes were being dried indoors and concrete thermal bridges existed in the corners of the rooms, dark mould covered these surfaces. Great Britain has numerous horror stories of excessive condensation and rampant mould growth. Whole housing developments have been torn down because authorities felt more confident to build new than repair the existing buildings to alleviate the moisture, mold problems.

Closets

Closets only compound the problems of corners. If proper air circulation is a problem in other parts of the room, just think of the additional problem to adequately ventilate a closet with a closed door. Closets filled with clothing or other items that impede airflow only make matters worse. Under the reduced lighting levels in closets, certain types of mold and mildew growth also may be encouraged.

This same limited airflow effect can also be observed in the room itself behind furniture and drapes, where discoloration and mold growth first appear.

Bathrooms and Kitchens

These rooms have already been mentioned as having special ventilation requirements due to moisture generation and possible sources of odor. Appropriate airflow patterns associated with key items, such as the exhaust above the range top, can make the difference in maintaining desired humidity levels and air quality. Unfortunately, many of these exhaust arrangements are very inefficient (only a fraction of the pollutant is removed), and studies are currently in progress to aid in improving exhaust equipment designs. Bathrooms and kitchens often have abundant closet space and air leakage paths associated with the plumbing that aid in producing potential moisture problems associated with airflow.

Each of the cases just cited points out the interrelationship of airflow and moisture in the building environment. These examples have been primarily residential; however, the same moisture-related situations can be present in commercial construction, especially when major sources of moisture are present (processes that involve water sprays, indoor swimming pools, etc.). Care must be taken to avoid the building problems that will inevitably result if these airflow moisture problems are ignored in critical building locations.

DATA REQUIREMENTS AND CALCULATION METHODS

In calculating the airflow in a building we are faced with a wide spectrum of approaches ranging from relatively simple estimates of important flows, such as the stack flow (see section entitled "Air Infiltration"), to attempting to quantify detailed room airflow patterns or multi-room flows (even more complex than depicted in Figs. 5 and 6). When it comes to the more detailed documentation, the AIVC has begun the process of establishing a database and providing the necessary reporting guidelines [*6*]. The detailed documentation and the prediction of airflow and contaminant dispersal in buildings requires the use of high-speed computers as well as a knowledge of building physics on the part of the user. References *28* and *29* outline a typical approach to this challenging problem. This is a topic of current research.

Typical data requirements [*6*] are as follows: general information on the building and site including the time of year is represented in the data, geographic information relating the building to the terrain and prevailing weather factors, climate information, a building description including specifics of construction materials and HVAC design, pollutant sources including moisture sources, details on the way the building is operated (including occupant factors), and documentation on the measurements taken such as weather, air infiltration, inter-room airflow, pollutant (moisture) concentrations, building tightness, and duct and vent flow rates.

The reader is referred to the AIVC Applications Guide on Air Infiltration Techniques [*4*] or Chapter 23 of the ASHRAE Handbook [*11*] as preferred approaches to simple but pertinent calculations of the airflows.

Still another approach to moisture problem solution is the"expert system." Reference *30* describes that approach bringing together airflow and moisture source information to seek solutions for building moisture problems. Additional efforts are needed to update any expert system with the latest research findings if the approach is to prove useful.

Finally, the general question of moisture-related problems and indoor air pollution should not be overlooked in the analyses. Health perspectives should be a first concern in any building, and moisture can play a major role, such as in the microbiologic contamination in HVAC systems. Through moisture control, one can prevent the conditions that lead to fungal and bacterial growth and an unhealthy building environment [*31*]. This is a major concern since duct systems have been shown to be a principal site of moisture-related indoor pollution.

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10

Heating and Cooling Equipment

by Russell M. Keeler[1]

HOW AIR CONDITIONING IMPACTS BUILDING MOISTURE

AIR CONDITIONING IS TYPICALLY ASSOCIATED with cooling, but the conditioning of air to provide comfortable conditions for building occupants or processes can apply either to heating or cooling applications. Moisture generation as a by-product of air conditioning is more frequent in cooling due to the condensing of water vapor in the cooling and dehumidification of supply air. In this chapter, references are to cooling rather than heating unless identified as a heating season phenomenon.

Space cooling is as a process whereby heat is removed from the space. The heat transfer medium from the space to the air conditioning unit is typically air; space heat is absorbed by the conditioning air. Heat in the air consists of two components: sensible (temperature related) and latent (moisture content). Sensible heat is absorbed through a rise in the supply air temperature. Latent heat is absorbed through a rise in the humidity ratio of the supply air. The conditioning air is then returned to the air conditioning unit, where the absorbed heat is removed at the cooling coil and transferred to a second heat transfer medium (refrigerant) in the cooling coil. Ultimately, in this secondary process, the heat is transferred to the general environment, either to the atmosphere or to water.

When considering the impact of air conditioning systems on the formation of mold and mildew, consider how an air conditioning system maintains the humidity of a space within predetermined limits; moisture must be removed at the same rate as it is introduced. If the moisture is thus controlled, little chance will exist for the formation of liquid water through condensation of airborne water vapor. The lack of liquid water within the space will eliminate an essential ingredient for mold and mildew formation.

The component of an air conditioning system that removes moisture is the cooling, or dehumidification, coil [*1*]. Cooling coils are heat transfer devices which employ either chilled water or a direct expansion refrigerant to lower the surface temperature of finned surfaces. The fins, which are at a lower temperature than the air supplied to the space, are the medium whereby the heat of the air is transferred to the colder medium within the coil. Figure 1 shows a simple air conditioning system.

An air conditioning system's ability to control space humidity is a function of the humidity ratio of the conditioned air supplied to the space compared to the humidity ratio within the space. Dry supply air is able to absorb moisture from the space, lowering the overall humidity level within the room. When this air is returned to the air handling unit or exhausted, some of the space-generated moisture is removed. New air that passes through the cooling coil dehumidification process repeats the cycle of potential space moisture absorption.

The main factors which impact the efficiency of the dehumidification process are the number of rows of coil and fin spacing on the coil, coil discharge temperature and degree of saturation, potential for reheat, and air distribution.

Deeper coils (those with more tube rows) yield a closer approach between chilled water and conditioned air temperature because the air is in contact with the cold fins for a longer period of time and less air will bypass, or not contact the heat transfer surface. Cooling coils are available in various depth configurations with two through eight rows being the most common. Deeper coils are available for special dehumidification applications.

Higher fin densities (fins per foot of tube length) will also decrease the bypass factor and will improve the heat transfer efficiency for shallow coils. Increases in fin density frequently allow for more shallow coils with the same performance as deeper coils with less fins. Care should be taken to limit fin density, however, as too great a density of fins will result in a tendency toward clogging air passages with dirt: 168 fins per foot is a practical upward limit on fin density, with 132 fins per foot a preferred compromise between coil depth, efficiency, and ease of cleaning.

To obtain the greatest potential for dehumidification, air should leave the cooling coil at close to saturation (100% relative humidity). The degree of saturation or relative humidity of air leaving a cooling coil is a function of the bypass factor of the coil and the refrigerant temperature. Typically, the coil discharge air should be more than 90% saturated. Such a state maximizes the moisture-absorbing potential of the conditioned air.

If the coil configuration limits the discharge air temperature to a relatively high level, say 60°F (15.6°C), dehumidification is difficult. This is because even fully saturated air at this temperature has little or no capacity to absorb moisture (latent heat) as it warms to human comfort temperatures (72 to 75°F) (22.2 to 23.9°C). Figure 2 shows a typical shallow coil discharge air condition [58°F, 20°C dry bulb (DB)/90% relative humidity (RH)] and compares the air state to that of a

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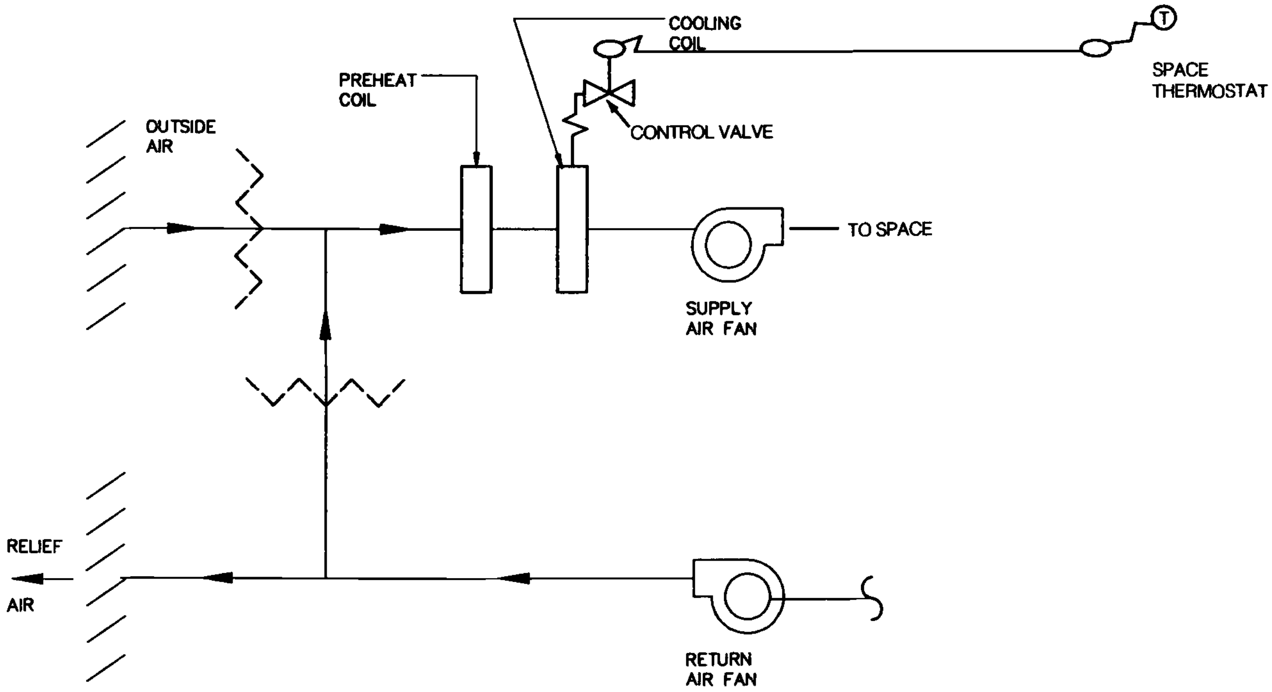

FIG. 1—Simple air conditioning system.

room condition (75°F, 23.9°C DB/50% RH) selected to be within the human comfort zone. A computation of the supply air's ability to absorb moisture in the form of latent heat is shown in Table 1.

For coils with discharge air temperatures at 60°F (15.6°C), moisture cannot be absorbed from a room at 75°F (23.9°C) DB/50% RH. The supply air does not have dehumidification potential. During periods with low sensible load and high humidity, such as on humid nights, a system without reheat is ineffective in reducing space humidity. Moisture removal can only take place by depressing the dry bulb temperature of the space, creating unreasonably low space temperatures.

On the other hand, lowering the supply air temperature alone is of little help, as the sensible load in the space is soon satisfied, the unit shuts down, and control of humidity never achieved except perhaps on the design day (highest expected temperature, full sun). Excessive cycling of the refrigeration system is especially common in unitary air conditioning systems, such as those found in residences. It is generally best to undersize smaller residential systems (those with simple controls and less than 10 tons of capacity) so that these systems will "work harder," that is, operate more or less continuously at part load.

For example, if the calculated peak cooling load is 3 tons, a reasonable equipment selection may be 2 tons. Few operating hours at the 3-ton condition will arise during the year, but a substantial part of the cooling duty will be experienced at the 2-ton level. During the more frequent times, the system will run most of the time, assuring dehumidification capability. During the few peak hours, slightly elevated temperatures may be experienced, but the relative level of cooling compared to the outdoors will minimize the impact of a higher space temperature. The "undersizing" equipment selection approach is quite common in the residential air conditioning market.

TABLE 1—Shallow coil moisture absorption.

	Absolute Humidity	
Location	Grains/lb Dry Air	Grams/kg Dry Air
Room air (75°F (23.9°C)/50% RH)	64	9.14
Coil discharge [58°F (14.4°C)/90% RH]	64	9.14
Absorbing potential	0	0

Small, simply controlled systems cannot easily differentiate between sensible and latent cooling load and typically are supplied with sensible load control sensors. During part load, these systems will cycle rapidly and are nearly useless for control of moisture removal, as the dry bulb thermostat which controls the systems is generally satisfied at part load. To maintain any control of space humidity, it is necessary to undersize the equipment. Smaller refrigeration capacity will cause longer run times, which yield more dehumidification.

An inability to control space humidity with temperature cycling of supply air control schemes was described above. Reheat systems overcome cycling and the resultant loss of dehumidification by maintaining a constant coil discharge temperature no matter how the space sensible cooling load varies. As the sensible load varies, the temperature of the supply air is varied. Figure 3 shows a process where the full cooling load requires a supply air temperature 20°F (11.1°C) lower than the space temperature set point; the room condition could be satisfied with supply air 5°F (2.78°C) lower than the space temperature set point when the cooling load is reduced by 75%. In a cycling control scheme, the system would be shut down approximately half the time. The reheat system includes either a single heating coil or multiple zone heating coils downstream of the cooling coil. The reheat is

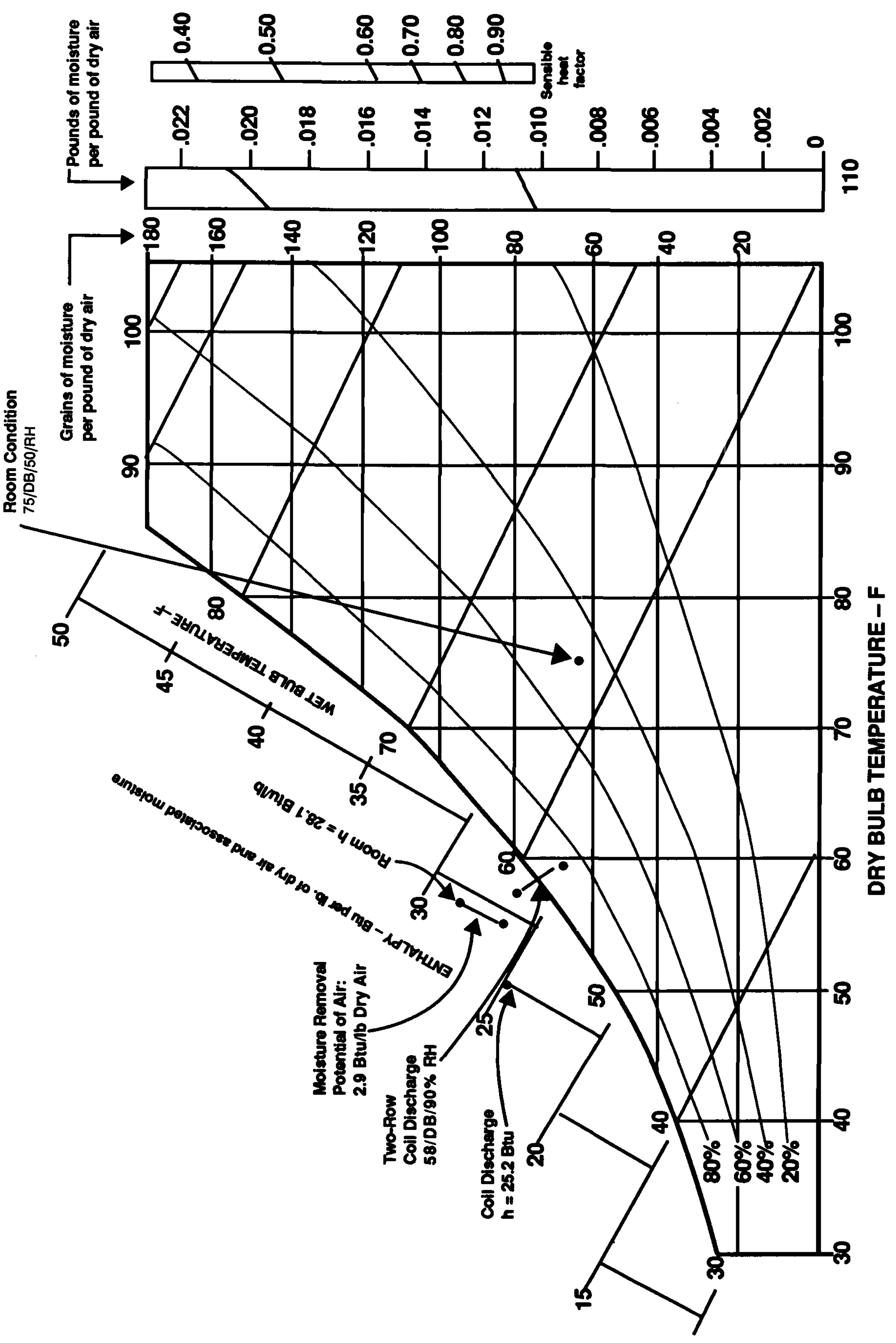

FIG. 2—Psychometric chart.

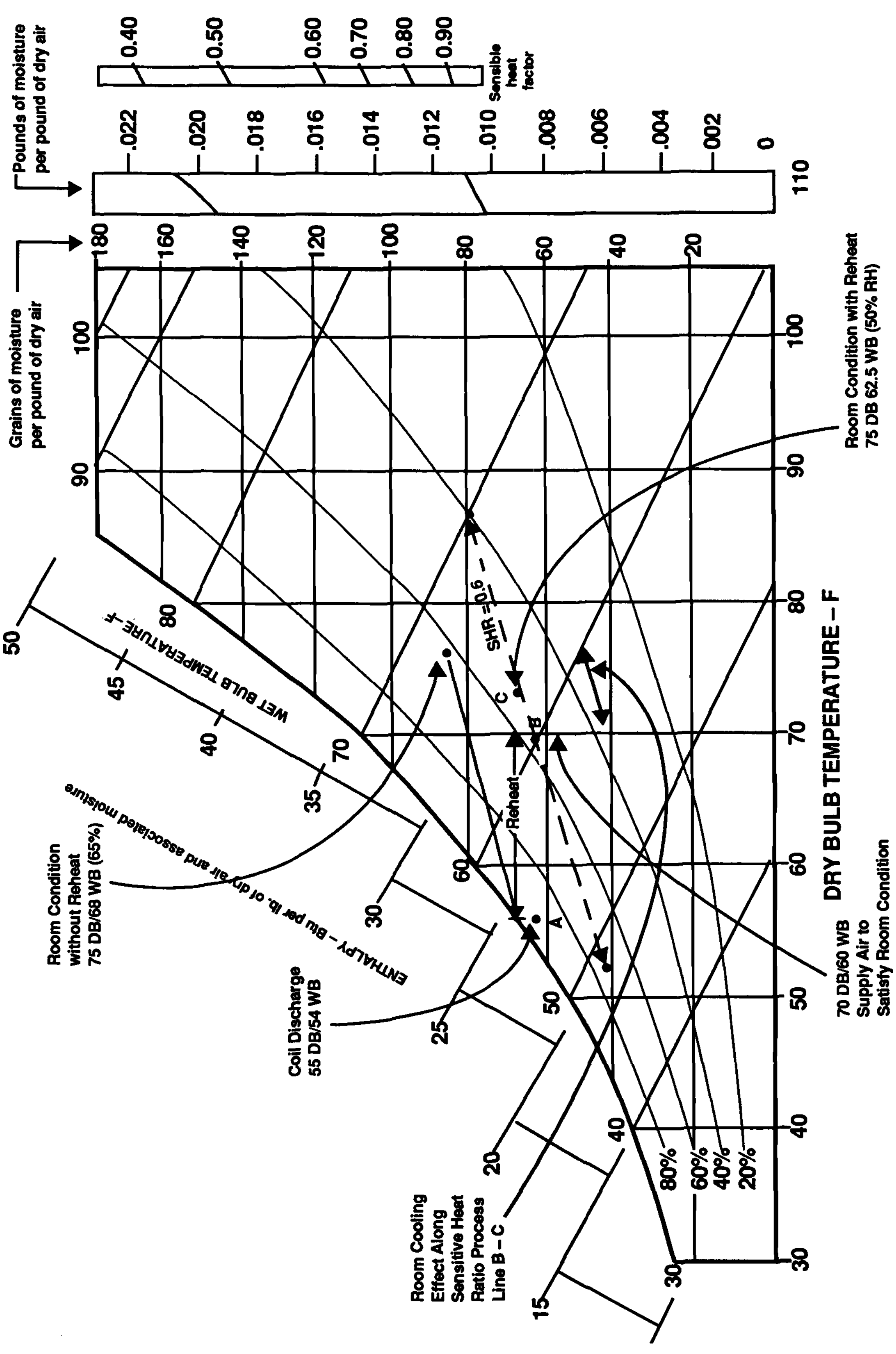

FIG. 3—Psychrometric chart.

controlled by the room thermostat(s) to raise supply air temperature when load is reduced.

Reheat systems provide much greater control of space humidity because the dehumidification coil operates continuously, independent of sensible cooling requirements. Although effective in the control of humidity, the use of reheat systems is discouraged because the systems are not energy conserving, but rather require the simultaneous expenditure of heating and cooling energy.

The way conditioned air is introduced to the space is a potential source of condensation. Many construction materials are hygroscopic (moisture retaining). When cold air comes into contact with these moisture laden materials, the potential for the water vapor entrained within the materials to condense exists. It is very important that the conditioned air become mixed with room air before the airstream sweeps the surfaces.

Cooling Coils

Depending on the coil configuration and refrigerant temperature, a specific amount of heat transfer can take place at the cooling coil. For purposes of this discussion, chilled water ranging from 40 to 50°F (4.44 to 10°C) is used as the coil heat transfer medium. Other coil heat transfer mechanisms, such as direct expansion refrigeration, can also be employed.

Cooling coils are configured in terms of rows of coil (depth) and in density of finned surface, normally measured in fins per inch. Coil density is achieved through a combination of the number of rows of coil and the fin spacing on the rows. Any number of rows of coil are available, with one to eight rows most common. Fin densities are somewhat more restricted, with an upward limit on density due to pressure drop and dirt restrictions being about 14 fins per inch (six fins per centimetre). Typically for air conditioning applications, fin spacing ranges from eight to fourteen per inch (three to six per centimetre).

For a given chilled water-entering temperature and flow rate, coils with greater density will result in the greatest amount of heat transfer, with the smallest difference between entering chilled water temperature and leaving air temperature (approach). The system design and equipment selection process should optimize the performance of the equipment in terms of desired coil discharge conditions and first operating cost of the system.

As an example of the capabilities of various coils, consider the example of air entering a cooling coil at the condition 80°F (26.7°C) DB and 67°F (19.44°C) wet bulb (WB) (see Table 2). Performance of two coils are shown, both with chilled water entering at 42°F (5.6°C) with a 10°F (5.6°C) rise. Water velocities through the coils and air velocities over the coils are held constant. Coil 1 is configured with four rows and eleven fins per inch, while Coil 2 has six rows with eleven fins per inch (see Table 2). Leaving conditions for these coils are markedly different.

TABLE 2—Coil performance comparison.

Coil Number	Rows/Fins	Entering Air, °F	Leaving Air, °F
1	4/11	80°DB/67°WB	56.6°DB/55.6°WB
2	6/11	80°DB/67°WB	52.2°DB/51.9°WB
Coil Number	**Rows/Fins**	**Entering Air, °C**	**Leaving Air, °C**
1	4/4	26.7°DB/19.44°WB	13.7°DB/13.11°WB
2	6/4	26.7°DB/19.44°WB	11.22°DB/11.05°WB

It is clear that the depth of the cooling coil has a significant impact on the amount of cooling work performed. All other factors being equal, the deeper coil is capable of removing a greater amount of heat, both sensible and latent, from the airstream. Using higher water velocities through the coil or higher air velocities across the coil do not change the general differentials of leaving air conditions.

Not only is the amount of sensible cooling greater on deeper coils, but the amount of latent cooling performed is greater. Note the differentials between dry and wet bulb temperatures for the leaving air. A deeper coil will yield air closer to saturation than a more shallow coil. Care should be taken in the selection of a coil. A deeper coil's performance can be approached using more fins per inch on a shallower coil. In a clean condition this less expensive configuration will deliver the desired performance, but the more densely packed fins tend to become clogged with dirt and are hard to clean. Over time, the coil performance will suffer, mostly from a reduced airflow. Eventually, poorly maintained coils will become blocked with dirt; airflow will become so restricted as to render the coil all but useless.

Coil depth is of special significance in humid climates. In high humidity climates, the latent performance of a coil is of the greatest importance, as there is significantly more dehumidification required than in dry locales. Deep coils have lower bypass factors than more shallow coils of the same fin density, so dehumidification efficiency is maximized. Observe a typical part load performance of the coils which were previously examined at design conditions. Note that the coils perform somewhat differently at this new condition. Performance is based on an entering air condition of 70°F (21.1°C) DB/60°F (15.6°C) WB. Results are tabulated in Table 3.

As could be predicted, the coil discharge temperature and degree of saturation is lower with cooler and drier entering air. The discharge air is so much cooler that the system will quickly satisfy the space temperature requirement. In a cooling-only system, the result will be a shutdown of the system or the cooling coil, depending on the control configuration.

TABLE 3—Coil performance comparison—humid climate.

Coil Number	Rows/Fins	Entering Air, °F	Leaving Air, °F
1	4/11	70°DB/60°WB	52.6°DB/51.5°WB
2	6/11	70°DB/60°WB	49.5°DB/49.3°WB
Coil Number	**Rows/Fins**	**Entering Air, °C**	**Leaving Air, °C**
1	4/4	21.1°DB/15.6°WB	11.44°DB/10.83°WB
2	6/4	21.1°DB/15.6°WB	9.72°DB/9.61°WB

Impact of Sensible Heat Ratio on Condensation

Operational histories with many air conditioning systems in a variety of climates indicate that achieving simultaneous control of temperature and humidity is not always easy to achieve. A variety of factors, in addition to the coil's cooling performance, enter into the problem of simultaneous control of temperature and humidity.

Of greatest interest in system control is the definition of the sensible heat ratio (SHR) for the conditioned space. SHR is defined as

$$\text{SHR} = \frac{\text{sensible load}}{\text{sensible load} + \text{latent load}}$$

In situations with a cooling load consisting almost entirely of sensible load (high SHR), a space thermostat controlling the air temperature entering the space will provide satisfactory control of temperature and keep humidity levels within reasonable tolerances. Where high latent loads are encountered (low SHR), control of cooling coils from room thermostats will prove unsatisfactory in maintaining reasonable levels of space humidity. For purposes of this discussion, it will be assumed that low SHR are those less than 0.65.

Even where the design SHR is high, a part load condition, such as during nighttime hours and/or during mid-range temperatures with high ambient humidity (fog or light rain), space control may be difficult to maintain.

The reason that conditions of low sensible/high latent load create difficulties for many air conditioning systems is that the systems are not configured for or do not have appropriate controls to deal with high latent/relatively low sensible load episodes. Causes of these problems include:

1. Shallow coils are employed in many applications.
2. Systems do not employ reheat.
3. Control is by dry bulb thermostat.

It should be remembered that for cooling-only systems which respond to sensible temperature changes, cooling (dehumidification) ceases when the room thermostat has been satisfied. Such an event will result in a high relative humidity space condition when the room temperature is satisfied.

These systems can control either temperature or humidity, but not both at the same time. If a humidistat is substituted for the thermostat, the cooling effect will continue until the humidistat is satisfied, creating lower and lower coil discharge temperatures to the limit of the cooling coil and/or chilled water temperature. Unfortunately, the space temperature will have fallen in the meantime to well below that acceptable for human comfort. The humidistat may or may not be satisfied, due to the lower space temperature caused by the continuously operating coil.

A related factor in the generation of condensation in the conditioned space is the impact of air distribution for reductions of surface temperatures. In some systems, such as fan coil and packaged terminal air conditioners (PTAC), equipment location is seldom ideal. Airflow sweeps surfaces such as walls and ceilings. At system design discharge temperatures, typically around 55 to 60°F (12.7 to 15.6°C), this continuous airflow over room surfaces lowers the surface temperatures. It is not unusual for the surface temperatures of these spaces to be below the dew point of the air, especially in conditions where high outdoor humidity, excessive infiltration, high ventilation rates, or all three in combination are present. When the cooling air contacts the surfaces, which are below the dew point of the air, condensation is inevitable.

Clearly, an air conditioning system, to be successful in a humid condition, must be able to remove the moisture generated in the space and deliver the conditioned air back into the space without creating condensation. Such performance requires adequate cooling coil capacity, proper air distribution, and appropriate controls.

Special care should be given to the selection of cooling coils so that latent capacity is maximized even if such a selection results in a somewhat oversized total heat capacity coil. Bypass should be minimized by increasing the coil depth rather than by increasing the fin density. This approach to cooling coil selection is not consistent with manufacturer's computer-aided coil selection programs, which optimize coil performance by first cost. The designer is urged to take this factor into account when designing for locales which exhibit periods of high latent load compared to sensible load.

Air distribution is critical to avoid the contact between conditioned air and room surfaces that have dew points below that of the air. Attention must be paid to the location of outlets, throw of outlets, and mixing between conditioned and room air.

Temperature controls should be designed to avoid the "on-off" cycling of compressors, which allows the introduction of ventilation air that has not been dehumidified. A common problem when employing packaged terminal air conditioners is the factory-installed control systems, which allow a "fan only" operation. In this mode, humid ventilation air is introduced directly to the space without being dehumidified. Thus, the system tends to defeat itself; alternate cycles of condensing water vapor from the air are followed by replenishment of the high level of humidity when the compressor is not operating. Fan-only cycles should interlock with outside air dampers on the room unit. When in a fan run-only mode, the outside air damper should be closed.

Under most load conditions it may be necessary to depress the air temperature below that required for sensible cooling to accomplish the requisite dehumidification. The space will then overcool unless the air is reheated up to the temperature differential appropriate for sensible cooling.

Reheat

If temperature and humidity cannot be controlled simultaneously, how can this idea be achieved? Control of temperature and humidity is a two-step process. First, the HVAC system cooling coil *dehumidifies* the conditioned air by cooling it to a temperature approaching the air's dew point. How close to saturation the coil discharge air becomes is a function of the coil bypass factor, discussed elsewhere. This process is independent of the amount of sensible cooling required by the space; the coil discharge is controlled by a coil discharge control. Second, the conditioned air is warmed back up so that the air temperature entering the space is cool enough to absorb the space sensible load, but not so cool as to overcool the space.

Air that leaves the cooling coil will warm and absorb moisture along a slope defined on a psychometric chart by the SHR. If a SHR line drawn through the room condition does not intersect with the humidity curve of the cooling air (coil discharge), the space temperature set point can be satisfied, but at a higher level of room humidity than is desired.

The challenge is to supply air that is cool enough (dry bulb temperature) and dry enough to absorb both the sensible and latent loads. Typically, it is difficult to design dehumidifying coils which closely approximate these conditions. Refer back to Fig. 3. In this case, the design room condition is 75°F (23.9°C) DB/50% RH. Air is cooled through a cooling coil to a leaving temperature of 55°F (12.7°C) DB/54°F (12.2°C) WB. The room SHR is 0.60 (high latent load). Following the SHR line, the room condition follows the SHR line A-C to a room condition of 75°F (23.9°C) DB/62% RH. Space relative humidity has risen!

To achieve dehumidification, the discharged air must be heated until it intersects the SHR slope that intersects the desired room condition. The required air condition is 70° DB/60° WB (21.1°C/15.6°C), or approximately 57% RH. Although the sensible cooling is only 5°F (2.8°C), the full dehumidifying capability of the air leaving the cooling coil is maintained. Specifically, the enthalpy of the air is still 22.5 Btu/lb.

Moisture which could potentially condense is removed from the space; condensation takes place, but at a controlled location, the coil. Because the air is introduced to the space at a somewhat higher temperature, the chance for cooling of surfaces and resultant condensation is minimized. Air distribution patterns are less critical. Of greatest importance, the dehumidifying action takes place on a continuous basis; there is little or no chance for the space to become overly humid.

A simple reheat system (Fig. 4) consists of a cooling coil and a heating coil in series, with associated fan and air distribution. The air—whether all recirculated, all outside, or a mixture—enters the cooling coil and is cooled and dehumidified down to a set temperature and humidity ratio. This condition is generally the design air temperature and humidity ratio required to satisfy the worst simultaneous sensible and latent load of the space. Typically, the design air condition for supply air is in the range of 55 to 57°F (12.8 to 13.9°C) DB and 54 to 56°F (12.2 − 13.3°C) WB, with a relative humidity of about 90 to 94%. Design dry bulb temperature rise is normally 18 to 20°F (−7.8 to −6.7°C).

In the case where the sensible load is less than that of design, delivery of supply air at the design dry bulb temperature will result in an overcooling of the space if the system runs wild or a throttling of the cooling function if a thermostat is used for control. In the first case, the absolute humidity may be reduced but at the price of a cold space. If cooling is throttled to maintain space temperature, the space relative humidity will rise.

Reheat allows the cooling coil to continue to dehumidify (provide full cooling) even when the sensible load is low or nonexistent. For example, at the worst condition, that of negligible sensible load and high latent load, such as during episodes of fog, drizzle, or high ambient relative humidity (such as a rainy evening with an outside temperature of 70°F) the cooling coil can continue to operate, cooling the air down to design. With a not-sensible load, the coil discharge air at say 56°F DB/55°F WB (13.3/12.8°C) is then reheated up to perhaps 70°F DB/55°F WB (21.1/12.8°C). The latent load can be removed without danger of condensation within the space, as the supply air temperature is well above the room dew point.

The use of reheat may appear to be inconsistent with energy efficiency, as the air is subjected to two treatments of energy expenditure. It is proposed here that the humid climate challenge is so severe that dehumidification becomes a necessary *process* application; the reheat is not being employed as an inefficient comfort control strategy, but rather as a necessity to limit property damage. ASHRAE Standard 90 permits reheat in cases where the discharge air temperature is raised to the highest level which will satisfy a zone [*2*]. From the examples above, it should be clear that reheat air conditioning is the only means available to limit the formation of liquid water within a space under humid climate conditions.

Source heat to raise the supply air temperature can be

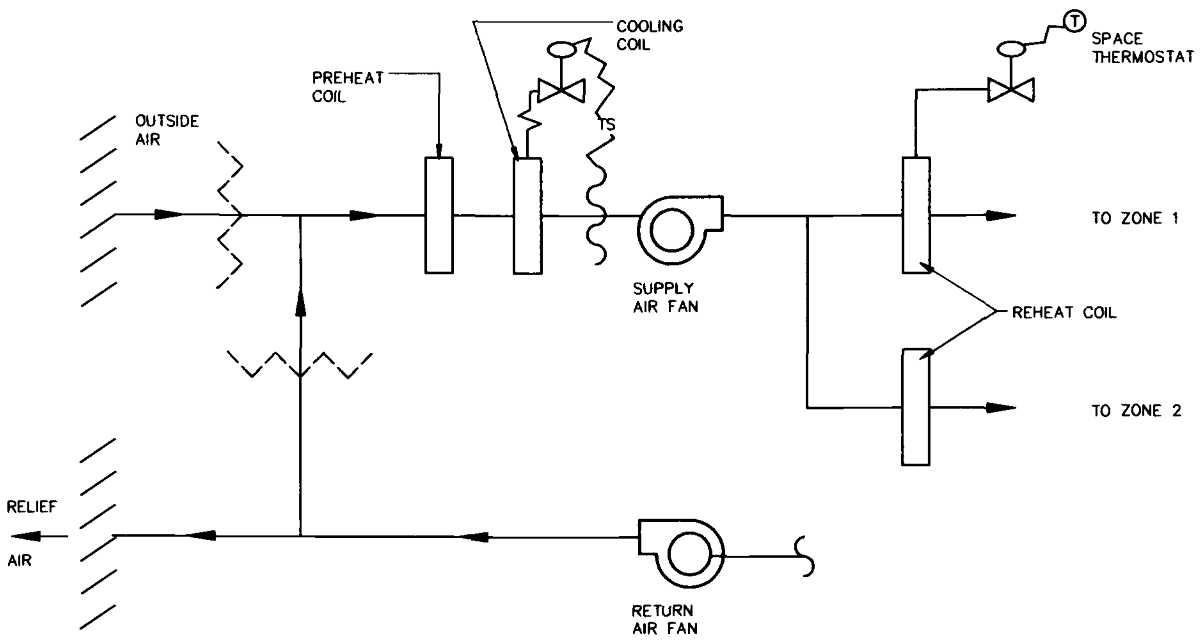

FIG. 4—Constant volume reheat system.

obtained either as newly purchased energy such as electricity, hot water, or steam as produced in a boiler by fossil fuels or, most energy efficient, a reclaimed form of heat produced as a by product of other building processes.

The most common means to obtain the recycled form of heat is from double bundle condensers which are part of a water chiller package. In this equipment configuration, the condenser is selected so as to produce rejected heat in the form of condenser water at relatively high temperatures (100 to 125°F) (37.8 to 51.7°C), which are suitable for use as reheat water. Other common means of capture such as heat pipes and other fixed heat exchangers can be employed, but are usually limited to single zone or several limited zone applications where the heat exchange between the exhaust and supply is in close proximity.

A reasonable question is: "Can the warmer return air be used directly as the heat source for reheat?" Unfortunately, the addition of return air to the off coil conditioned air will have no effect on the room condition as the resultant mixture is simply a new temperature and humidity point on the SHR line. The location of the new point is proportional to the percentage of the mix between conditioned and return air. A somewhat worse case results from the direct use of outdoor air as the reheat medium. In this situation, the effect is to directly introduce untreated outside air into the space, an undesirable strategy discussed above in the controls section [*3*].

A wide variety of reheat-type systems are available for use in the control of space humidity levels without condensation of water vapor. The most widespread application of the concept is the constant volume terminal reheat system described above. Other reheat systems include double duct, multizone, and fan-powered induction systems.

Air Distribution

To the extent possible, conditioned air should be distributed within the space in such a way that drafts are not created. Conditioned air should not contact surfaces until the air has properly mixed with room air and has risen in average temperature. In no case should supply air contact room surfaces at less than the anticipated room dew point. All possible means should be employed to avoid cooling of room surfaces to the point where the surfaces become potential condensation locations.

The distribution system should deliver conditioned air to all rooms and return air from all rooms to avoid too great a temperature difference from the center of the room to colder exterior wall surfaces. Trechsel [*4*] has shown it is possible to have a satisfactory relative humidity at the center of a room and have mildew forming in the cold corners because of inadequate air circulation and/or inadequate insulation in exterior walls.

COLD CLIMATE ISSUES

As described above, the interplay of temperature and moisture level within a space has a significant impact on the formation of liquid water through condensation, the contact of air with surfaces at or below the dew point of local air. In a cold climate, the issues are not as simple as those in cooling situations.

In a cold climate, the ambient air has a low humidity ratio even at high relative humidities. Cold air simply cannot absorb and retain water in the form of vapor in amounts similar to that of warmer air. For example, saturated air at 60°F (15.6°C) can retain 0.015 lb of water for each pound of dry air. At 20°F (−6.7°C), the same pound of dry air can hold only about 0.002 lb of water. 20°F (−6.7°C) air is only about 13% as absorbent of moisture as 60°F (15.6°C) air! As temperatures lower, the effect becomes even more pronounced.

Under cold climate conditions, the internal generation of latent heat (moisture) becomes significant. Eventually, as moisture migrates through the walls of the space toward the cold side of the wall (area of lower vapor pressure), the moisture can become trapped within the building construction and condense. The condensed water can then saturate insulation, rendering the insulation ineffective. As the insulating value of the construction decreases due to saturation with water, heat loss increases. In extreme cases, ice can form within the wall cavity with potential structural damage to the construction.

Eventually, the insulating value of the wall will be significantly reduced, and heat losses will increase due to the reduced insulating value of the envelope. With the loss of insulating value, condensation will form on the interior surface, with mold and mildew formation soon to follow. Refer to Chapter 1.

HVAC EQUIPMENT

An ideal HVAC system will be capable of maintaining the space temperature set point independently of requirements for dehumidification. Of greatest utility for this demanding task is a system that employs some form of reheat. A discussion of appropriate HVAC system types for "humid" climates could encompass most system types if the systems were fitted with a means to accomplish reheat. ASHRAE defines humid climates as those where the wet bulb temperature reaches either (1) 67°F (19.44°C) or more for 3500 h per year or (2) 73°F (22.8°C) or more for 1750 h per year [*1*]. Worldwide areas where these conditions exist are discussed in Chapter 7.

Many arrangements of HVAC equipment have been developed that accomplish the dehumidification and reheat of air. Systems generally are classified as either central station or unitary, based on the complexity and size of the air handler casing. Typically, unitary equipment has less than 10 tons of cooling, is self contained, and uses direct expansion cooling, although the size and amount of factory-installed components may sometimes vary. Unitary equipment normally does not include a factory-installed reheat coil, but employs a separate duct-mounted reheater. Central station equipment can include fan systems with separate coils, filters, and controls and is almost always ducted.

A source of heat to raise supply air temperature must be provided throughout the operational cycle of the system. The heat source can be a boiler, electric resistance, condenser heat from an air conditioning system heat rejection cycle, or other heat sources. Some of these devices require "new" energy. New energy is that energy expended directly for the process. For example, heating water for reheat in a boiler with a fossil fuel is new energy. In the best energy-efficient scenario, the thermal energy for the reheat would be recaptured from the process itself through a heat exchanger. Because the least first cost source of reheat has been through a purchased energy, the concept of reheat is viewed as being ecologically unsound. When employed solely for comfort control, reheat is not a responsible strategy for air conditioning system control.

Various schemes have evolved to accomplish the reheat necessary when dehumidification processes are needed. The most frequently encountered schemes include:

1. Constant volume terminal reheat.
2. Multizone.
3. Double duct systems.
4. Variable air volume with reheat.

Constant Volume Terminal Reheat

The constant volume terminal reheat system is the simplest form of a dehumidifying system. Although many adaptations of the reheat concept are available, the simplest is known as "constant volume terminal reheat" or a "reheat system." Until the oil embargo of 1973, reheat systems were the most common central air conditioning systems specified for commercial buildings.

Reheat systems have the additional benefit that the space can be subdivided into more than one occupancy zone. By providing each zone with a separate reheat coil controlled from an individual thermostat located within the zone, variations in occupancy requirements for both temperature and humidity can be easily accommodated.

Multizone

Multizone systems combine the simple reheat and dual duct concepts within the air-handling unit. The system uses a blow-through arrangement, with the air discharged from the supply fan into a bank of coil—a heating coil (hot deck) and cooling coil (cold deck). Immediately upstream of the coils is an array of dampers, arranged proportionally as zones, which meter the amount of hot or cold air that can enter each zone (Fig. 5). As an example of how the system regulates temperature, a system with a hot deck discharge of 90°F (32.2°C) and a cold deck discharge of 55°F (12.8°C), a one third hot deck, two thirds cold deck damper setting would yield a supply air temperature of approximately 66°F (18.9°C). Note that control of space humidity is only a by-product of the temperature control scheme.

Multizone systems are notorious for imprecise control due to the poor proportioning of air quantities caused by a limited number of damper sections and the limitations of the damper proportioning of air quantities. While multizone is a reheat system, it is not normally employed for close control of space humidity.

Dual Duct

Dual duct systems consist of, at minimum, a cooling coil, a supply air fan, and a heating coil. The difference between dual duct and straight reheat is that the air is separated into two air streams at the discharge of the apparatus, a cold air source and a hot air source (Fig. 6). Zoning is accomplished by mixing the two air streams in a terminal at the zone via a thermostat which operates dampers to mix the air. For example, if a zone requires 70°F (21.1°C) air to satisfy the space load, with a cold deck discharge of 55°F (12.77°C) and a hot deck

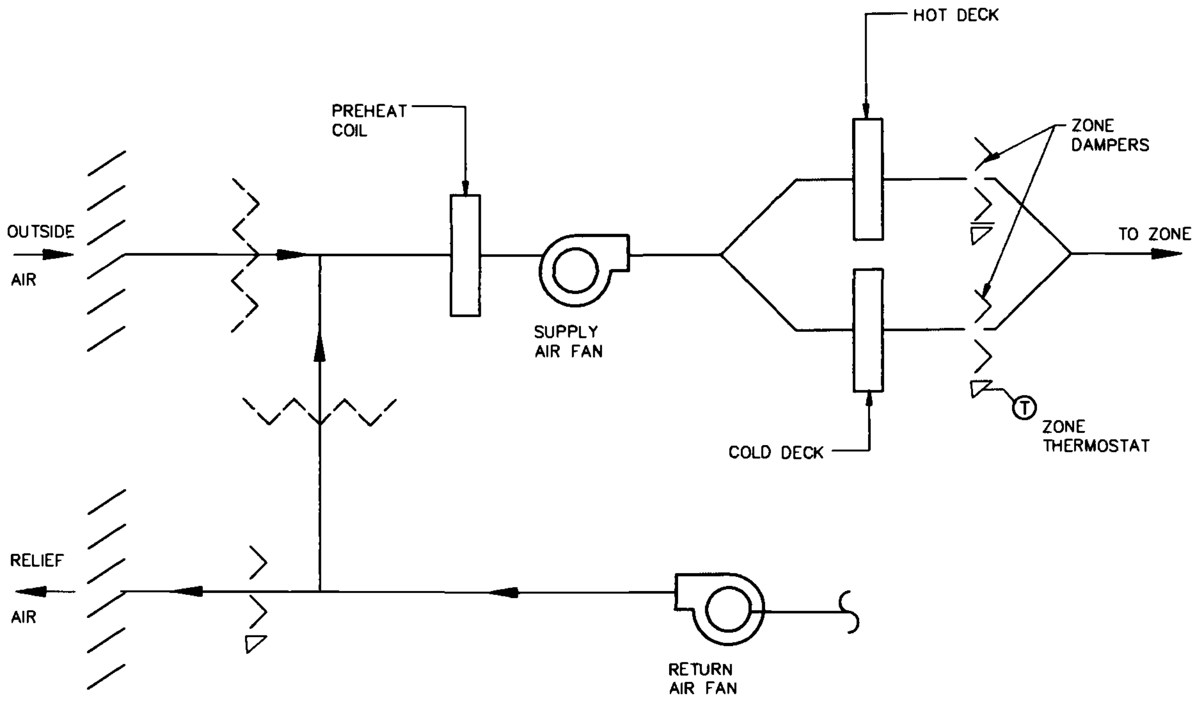

FIG. 5—Multizone system.

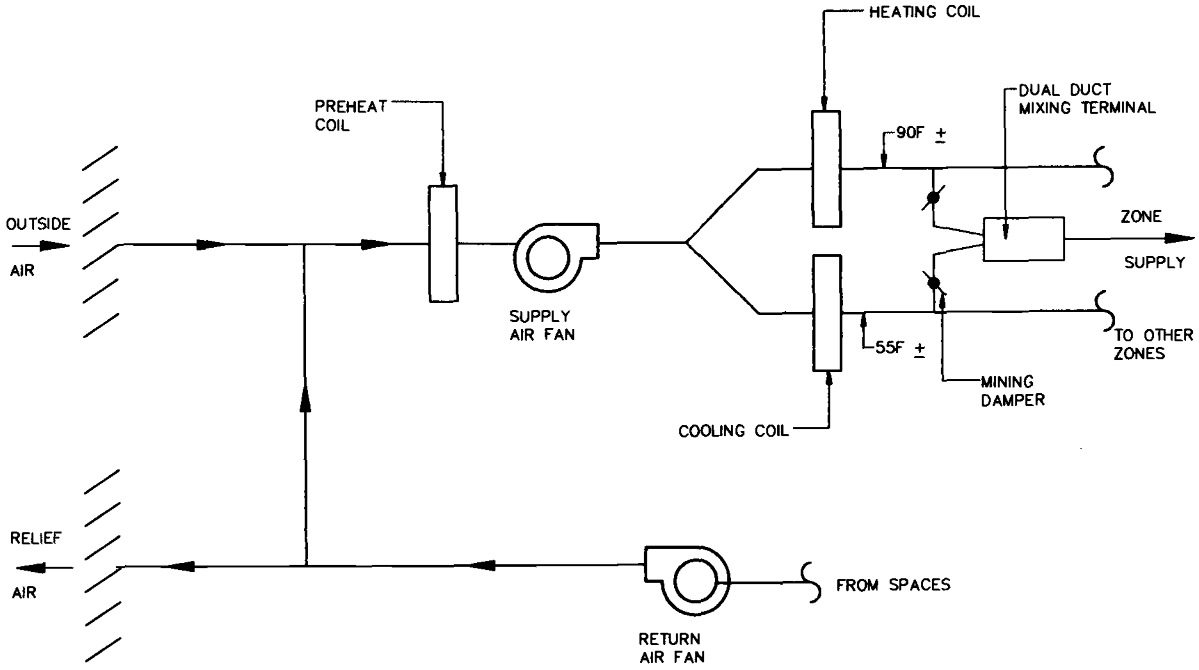

FIG. 6—Dual duct system (single fan).

discharge of 90°F (32.2°C), the proportions of cold and hot air will be

$$70 = 55x + 90(1 - x)$$
$$x = 0.5714$$

Enhancements of dual duct have been proposed to reduce the energy penalty imposed by use of a reheat coil. One example is that return air be employed, through a dampering arrangement, to accomplish the temperature elevation. A schematic diagram of this approach is shown in Fig. 7. In order to insure that the required dehumidification is achieved, it is suggested that the cold deck temperature be adjusted if necessary. For example, in a space with a relatively low SHR, it may be desirable to use a lower cold deck temperature to provide sufficient latent cooling capacity.

Variable Air Volume (VAV) Reheat

VAV is an energy efficient way to control space temperature. As a means to accomplish dehumidification, much of the benefit of reducing airflow is lost if the lower mass flow rate

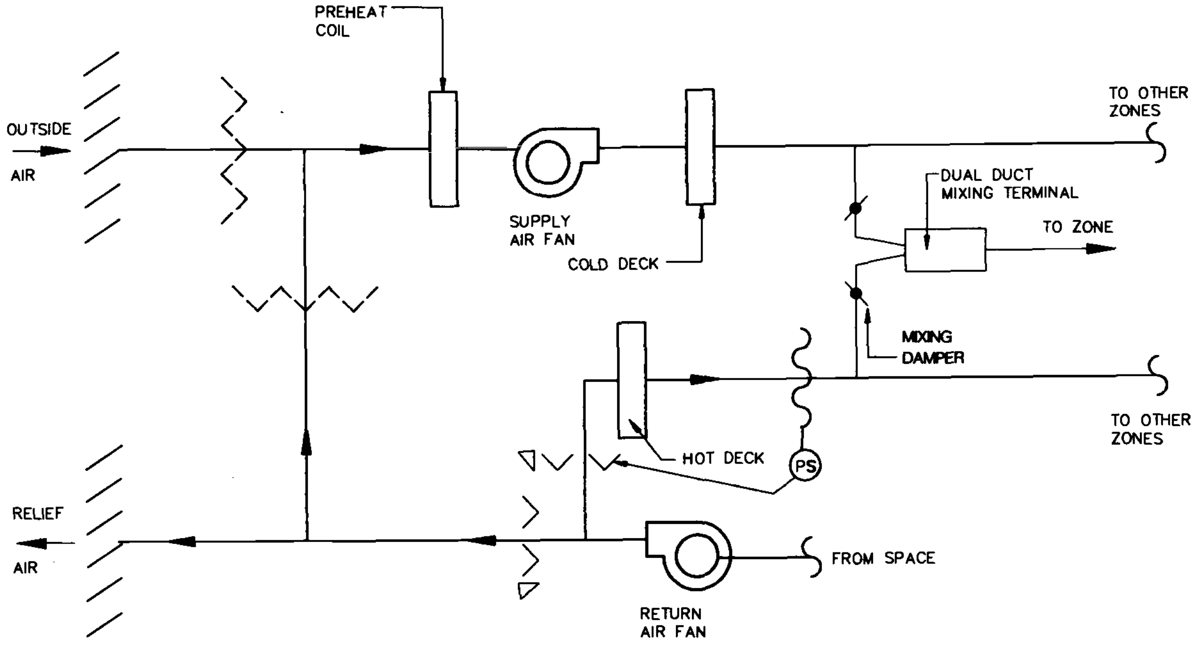

FIG. 7—Dual duct system with return air as hot deck.

is insufficient to remove the latent load generated by the space. VAV with reheat should be used only after an evaluation of the minimum cooling prior to reheat is undertaken. It may be necessary to lower the dehumidification coil discharge to allow for a VAV reheat system. It is suggested that this system only be employed where the latent loads are minimal.

SYSTEM SELECTION

Humid climate air conditioning varies from temperate climate air conditioning in one significant aspect, applications in which the exterior envelope and the ventilation air loads have major impacts on cycling of refrigeration. To illustrate, the refrigeration system for a high-rise office building in Miami, is driven by solar heat gain, people load, lighting load, and other *internal* heat gains to a much greater extent than from the ventilation load. It is highly likely that the high-rise building will feature some type of central air distribution system and a controls array capable of monitoring and maintaining a desired humidity level.

A beach front house or hotel room in the same area, if air conditioned, will probably be cooled using a refrigeration system that includes a reciprocating compressor. This small system is typically characterized by a factory-installed control system and includes fans, coils, and filters all enclosed in a single casing. There appears to be little choice in how such a system is deployed, other than where to locate the equipment.

The high-rise building that features a central system and the types of cooling loads described is relatively independent of the local climate as climatical load issues comprise a relatively minor part of the overall cooling load. In a small building [one in which the exterior wall to the center of the floor plan is less than 15 ft (4.5 m)], all areas of the building are influenced by the outside environment. Fifteen feet has been chosen because that distance from the outside wall has been found, by experience, to be the limit of impact for outdoor temperature and humidity conditions on the building's air conditioning system [*2*].

An interesting dilemma is thus presented: major buildings within the humid zone are likely to feature types of air conditioning systems that can dehumidify the conditioned space, but do not normally exhibit the extreme sensible heat ratio conditions that lead to the formation of moisture-laden environments. Small structures, however, are usually equipped with small decentralized air conditioning components that are characterized by an on/off control scheme, the very cooling approach that fosters the formation of conditions (condensation of water vapor to liquid water) which contribute to mold and mildew growth. Incidentally, reheat is almost never available as an option in unitary equipment (such as through-the-wall air conditioners) offerings.

How then can the designer select a system for the smaller, worst-case applications? Generally, the most difficult applications are for systems of less than 5 tons. Unfortunately, the small system comprises the vast majority of installations.

In general, any type of HVAC system that can vary the amounts of sensible and latent cooling independently is useful in a humid climate. On this basis, various configurations of reheat and variable air volume offer potential for use in these applications. When considering system selection and component design, the main factors to weigh are the number of rows of the coil, coil discharge temperature, potential for reheat, and air distribution.

Outside air also has an impact on system performance. Depending on the ambient condition and the ability of the system to vary the outside air quantity, coil performance is affected. Uncontrolled entry of outside air will also have an undesirable impact, as the frequently moist outdoor air becomes an additional source of water vapor through condensation. In warm weather, it is important to maintain the building at a slight positive pressure to minimize infiltration. Less uncontrolled entry of humid air decreases the potential for condensation within the space. Pressure controls cannot, however, counteract the effect of high winds.

During cold weather, infiltration is more difficult to control, especially in tall buildings due to stack effect. Stack effect is the tendency for air to rise based on temperature differential, with the warm interior air less dense than the colder outdoor air. In tightly sealed buildings, the moisture generated internally by occupants and processes tends to rise with the stack effect and collect near the top of the building. If air recirculation does not mitigate this condition, there will be a tendency for condensation to take place in the colder parts of the uppermost floors, as observed by Trechsel[2].

Criteria for selecting air conditioning components can vary widely, depending on construction budget, local climate, availability of maintenance personnel, and type of building. Rather than attempt to proscribe a specific system choice for each conceivable building type, some general rules are listed. It is, as always, up to the designer of the air conditioning system to make the final selections. Desirable air conditioning system features for the control of indoor moisture levels include:

Equipment

1. The system should not allow untreated outside air to enter the space when in the refrigeration mode. In a heat pump or PTAC installation, the outside air damper should be closed when the compressor is inoperative.
2. When using fan coil units, the selection should be for the four-pipe version, with reheat water available at all times.
3. Self contained, through-the-wall equipment should be equipped with a reheat option, either an electric coil or a way to recycle the heat rejected from the condenser.
4. Centrally ducted systems should include zoned reheat capabilities, with the reheat operated by humidistats. A central control should disable the reheat option whenever the outdoor air is below a predetermined humidity ratio. In this way, the reheat will only be employed for humidity control and will not be used for zone temperature control. Zone temperature control can be accomplished by variable air volume terminals and/or supply air temperature reset.
5. Cooling coils should be selected on the basis of minimizing bypass rather than for the lowest first cost. Generally select the deeper option for the coil.

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[2] Private communication with Heinz Trechsel regarding observations of public housing high-rise buildings.

6. Avoid coil face and bypass arrangements in air handling equipment.

Operations

1. The air systems should be carefully balanced to maintain a slight positive pressure [±0.05 in. water gage (WG) (0.093 Hg)] so that infiltration of humid air is minimized. This applies only for warm and humid conditions.
2. Exhaust systems should only operate when the cooling apparatus is energized.
3. Ventilation dampers should be interlocked with the refrigeration system so that untreated outside air is not introduced to the system unless the ventilation air is at or below a set humidity ratio.
4. Cooling coil discharge temperatures should be controlled in a set manner to maximize the dehumidification ability of the coil. Supply air temperature should be controlled via a space thermostat.
5. Air distribution patterns must be designed to avoid the contact between low dew point air and room surfaces. Avoid the location of fan coil equipment in corners. Diffusers should be selected so that the throw is no more than two thirds the distance to a wall.

Reheat System Control

To control a reheat system, independent controls are required for room temperature and for cooling coil discharge temperature. To be assured of humidity control, a room humidistat may be employed to operate to override the cooling coil discharge controller. The system is shown in Fig. 4. This is an example of a simultaneous heating and cooling system. Applications which use "new energy" for the reheat are not energy efficient and should be avoided where possible. In many cases, use of new energy reheat is against local and national energy codes.

Although new energy reheat is to be avoided, reheat can still be employed in many cases by using the rejected space heat. Examples of rejected heat application are the use of a double bundle condenser for enhanced condenser water temperature and return air as a reheat medium. In self-contained computer room air conditioning systems, rejected heat from the compressor is routinely used as the source heat for reheat.

Special Situations

To this point, the discussion has centered on typical air conditioning applications, that is, ones in which normal levels of moisture as generated by human metabolism and outdoor conditions are the major sources of humidity. It is assumed that the buildings are relatively tight, infiltration of outdoor air is a function of building cracks, and that doors and windows are closed. Other factors contribute as well to the formation of liquid water within the space.

Influence of the Construction Process

Observations at resort hotels and other major structures in humid climate areas show that formations of mold and mildew are widespread and appear in buildings with various types of air conditioning systems. In fact, an entire industry has grown up in these locales that does nothing but remove mildew from surfaces!

We conclude that the extensive mold and mildew formation within these buildings is a function of the way construction is scheduled. Coincidentally, coastal humid climates are also ideal locations for resorts. Economic factors of development strongly influence the construction schedule of new buildings; it is important to begin generating a return as soon as practical. Generally, the humid climate areas within the United States offer the most attractive weather during the spring and fall.

For humid climate resort hotels, it is desirable to complete new construction in February or early March, then begin renting rooms. Other satellite businesses that support the tourism industry have a similar cycle. Unfortunately, this construction schedule provides an ideal incubator for the condensation of water vapor.

Construction is a very wet business. From the water entrained in concrete to the final cleaning operations, water is everywhere in a building under construction. In addition, the unfinished structure is subjected to the weather up until the building is closed in. A new building is saturated with water.

Now the building must dry out. An ideal drying period would be the first heating season when dry outdoor air combined with higher heating temperatures provide the greatest ability for conditioned air to absorb moisture. Sad to say, the heating cycle is seldom the first action of the air conditioning system. A spring opening also guarantees that the first conditioning cycle which the building will be exposed to is cooling. Moist spring air combined with a cooling cycle provide the ideal condition for the moisture entrained in the structure to condense on surfaces. The way the facility is started up almost guarantees that condensation will form.

Unless a building utilizes a heating and drying cycle at the beginning of operation, very little can be done to control condensation during the first season of operation.

Process-Generated Moisture

Special applications where high levels of humidity are generated by a process require their own approaches. Examples of these conditions include laundries, swimming pools, and possibly kitchens. In moisture-laden circumstances such as these, opportunities exist to reclaim the latent heat removed from the return air.

Generally, it has been the norm to deal with high levels of internally generated humidity by using increased exhaust. Rather than remove the moisture from the recycled air, the moisture laden air is removed from the space.

Frequently, the high humidity spaces are part of a larger facility and would normally employ the same central refrigeration system as the rest of the building. Use of the main systems for dehumidification will result in less energy efficient operation of the main refrigeration because of the part loading required during many times of the year.

A more energy efficient option is to provide a separate heat pump system for the high humidity area to develop its cooling. The rejected heat from the moisture removal process is recycled to preheat the swimming pool water or the fresh laundry water. In a kitchen (dish wash area) a similar unit might be applied to heat domestic hot water.

Residential Buildings

Heating and cooling systems used in residential buildings, except high-rise construction, are often less elaborate in design than those used in hotels, office buildings, institutional buildings, and other commercial buildings. In residential buildings, the level of occupancy, the occupant's living habits, and the sources of moisture generation must be carefully evaluated. Outdoor ventilation air must be adjusted to be sufficient to remove the indoor moisture load, especially during the heating season.

The principal sources of moisture tend to occur in the living room, kitchen, and dining room during the daytime and tend to shift to the bedrooms at night. Typically, zoning is minimal in residential buildings; control is generally via local thermostats with no consideration to humidity levels. In single family residences, or in multi-family residences with separate air handling systems per occupant, it is unusual to include any zoning except for very high-priced installations.

Simplified return air systems, if used, must be located to provide recirculation from all spaces. Recirculation from bedrooms is especially important at night, if night setback is used, to avoid conditions for mold and mildew growth during the winter season. To the extent that circulation mixes the air from the various spaces, control of airborne moisture can be maintained.

SUMMARY

Condensation of water vapor within air conditioned structures can be reduced significantly by careful design. Some rules which must be applied are as follows:

1. Select cooling coils to minimize bypass.
2. Take care in the introduction of ventilating air when the compressor is inoperative.
3. Provide positive pressurization of the building at all times.
4. Employ reheat to control humidity, but not as a temperature control device.
5. Develop a way to dry out new construction before occupancy.
6. Design airflow patterns with care; avoid sweeping of surfaces with air below the dew point of the surfaces.
7. Look for opportunities to recycle the heat generated by moisture removal.
8. Zone air distribution systems to maximize recirculation.

REFERENCES

[1] *ASHRAE Handbook of Fundamentals*, ASHRAE, Atlanta, GA, 1991.

[2] ASHRAE Standard 90–89: Energy Conservation in New Building Design, ASHRAE, Atlanta, GA.

[3] *Trane Air Conditioning Manual*, 1965, pp. 105, 109.

[4] Trechsel, H. R. and Achenbach, P. R., "Field Studies of Moisture Problems in Exterior Walls of Family Housing Units at Naval Air Station, Pensacola, FL," contract report to Naval Civil Engineering Laboratory, Port Hueneme, FL, 1984.

11

Design Tools

by Anton TenWolde[1]

THERE ARE TWO FUNDAMENTAL APPROACHES to design for moisture control. One approach focuses on the thermal and moisture properties of the building envelope (exterior walls, roofs, and ceilings) needed to withstand the interior and exterior conditions. The second approach attempts to adjust the indoor climate to the thermal and moisture characteristics of the building envelope. This chapter deals with design tools for the exterior envelope only. Recommendations for indoor climate control can be found elsewhere in this handbook.

The traditional tools currently available for design of the exterior building envelope all have severe limitations, and the results are difficult to interpret. However, for lack of better tools, these methods are used by design professionals and form the basis for current building codes dealing with moisture control and vapor retarders. The proper use and limitations of these methods are discussed in the first section of this chapter, Manual Design Tools. A few relatively simple numerical methods that are not included in Chapter 2 are discussed briefly in the section on Numerical Tools.

MANUAL DESIGN TOOLS

The three best-known manual design tools for evaluating the probability of condensation within exterior envelopes (exterior walls, roofs, floors, or ceilings) are the dew point method, the Glaser diagram, and the Kieper diagram. All three methods compare vapor pressures within the envelope, as calculated by simple vapor diffusion equations, with saturation pressures, which are based on temperatures within the envelope. If the calculated vapor pressure is above the saturation pressure at any point within the envelope, condensation is indicated. The dew point method, used in North America, and the Glaser diagram, commonly used in Europe and elsewhere, are almost identical. They differ slightly in the formulation of the vapor diffusion equation for flow through a building material and in definition of terms; the main difference lies in the graphical procedures. These methods are often misused, especially when condensation is present. Like the dew point method and Glaser diagram, the Kieper diagram is based entirely on vapor diffusion theory.

Some people advocate abandoning these design tools because of their severe limitations. Perhaps the greatest limitation is that their focus is restricted to prevention of sustained surface condensation. Many building failures, such as mold and mildew, buckling of siding, or paint failure, are not necessarily related to surface condensation. Conversely, limited condensation can often be tolerated, depending on the materials involved, temperature conditions, and the speed at which the material dries out. Another weakness is that these methods exclude all moisture transfer mechanisms other than vapor diffusion and neglect moisture storage in the building materials. This severely limits the accuracy of the calculations, especially in the case of wet materials. There are no widely accepted criteria for using manual design methods. Recommendations for use and interpretation provided in this chapter are therefore primarily based on the opinions of the author.

Dew Point Method

The dew point method [1] is based on the following diffusion equation and definitions

$$w = -\mu\, \Delta p/d \qquad (1)$$

where

w = vapor flow per unit of area, kg/m^2·s (grain/ft^2·h),
μ = water vapor permeability, kg/m·s·Pa or s (perm·in.)[2],
p = vapor pressure, Pa (in. Hg), and
d = flow path or thickness of the material, m (in.).

Water vapor permeability of a material is the permeance of 1 in. (United States) or 1 m of that material. The permeance of a sheet of material is assumed to be inversely proportional to its thickness; e.g., the permeance of 0.5-in. gypsum board is twice that of 1-in. gypsum board.

Water vapor resistance, Z, is the inverse of permeance and is expressed in reps (1/perm) or m/s

$$Z = d/\mu \qquad (2)$$

Thus, Eq 1 can also be written as

$$w = -\Delta p/Z \qquad (1a)$$

The dew point method is best explained and demonstrated with example calculations. As an example, we will use a frame wall construction with gypsum board (painted), glass fiber insulation, plywood sheathing, and wood siding (Table 1). We will assume 21°C (70°F), 40% indoor relative humidity, and −6.7°C (20°F), 50% outdoor relative humidity. The wall in the

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[2] 1 perm = 1 grain/ft^2·h·in. Hg; 1 grain = 1/7000 lb; 1 rep = 1/perm.

TABLE 1—Example wall with approximate thermal and vapor diffusion properties.

	Thermal Resistance			Diffusion Resistance	
Air Film or Material	$(h \cdot ft^2 \cdot {}^\circ F/Btu)$	$(m^2 \cdot K/W)$	Permeance,[a] perm	$Z = d/\mu$, 1/perm	$Z = d/\delta$, 10^9 m/s
Air film (still)	0.68	0.12	160[b]	0.0063	0.11
Gypsum board, painted	0.45	0.08	5	0.2	3.5
Vapor retarder	...	...	0.06	17	290
Insulation	11	1.9	30	0.033	0.6
Plywood sheathing	0.62	0.11	0.5	2	35
Wood siding[c]	1	0.18	35	0.029	0.5
Air film (wind)	0.17	0.03	1000[b]	0.001	0.02
Total	13.92	2.42	...	18.94[d]	329.73[d]
				2.27[e]	39.73[e]

[a] 1 perm = 1 grain/ft²·h·in. Hg.

[b] Approximate values; permeance of surface air films is very large compared to that of other materials and does not affect results of calculations.

[c] Approximate values; permeance reflects limited ventilation of back of siding.

[d] Total diffusion resistance of wall with vapor retarder.

[e] Total diffusion resistance of wall without vapor retarder.

first example has a vapor retarder on the warm side of the cavity; the wall in the second example is identical except for the omission of the vapor retarder.

EXAMPLE 1: WALL WITH VAPOR RETARDER

Step 1—The first step is to calculate the temperature drop across each material. The temperature drop is proportional to the R value as follows

$$\Delta T_{material}/\Delta T_{wall} = R_{material}/R_{wall} \tag{3}$$

Table 2 lists the resulting temperature drops and resulting temperatures at each surface.

Step 2—The next step is to find the saturation vapor pressures [Pa (in. Hg)] corresponding with the surface temperatures. These values can be found in psychrometric tables or charts (e.g., Ref *1*, Chapter 6). Table 2 lists the saturation vapor pressures for this example.

TABLE 2—Calculation of temperatures and saturation vapor pressures.[a]

	Temperature, °C (°F)		Saturation Vapor
Air Film or Material	Drop	Surface	Pressure, Pa (in. Hg)
Indoor air			
		21.1 (70)	2503 (0.7392)
Surface air film	1.3 (2.4)		
		19.8 (67.6)	2305 (0.6807)
Gypsum board	0.9 (1.7)		
		18.9 (65.9)	2174 (0.6419)
Vapor retarder	0		
		18.9 (65.9)	2174 (0.6419)
Insulation	22.0 (39.5)		
		−3.1 (26.4)	486 (0.1434)
Plywood sheathing	1.2 (2.2)		
		−4.3 (24.2)	443 (0.1309)
Wood siding	2.0 (3.6)		
		−6.3 (20.6)	381 (0.1124)
Surface air film	0.4 (0.6)		
		−6.7 (20)	371 (0.1096)
Outdoor air			

[a] Temperature drop across the air film or material. Surface temperatures and saturation vapor pressures are taken at the interface for each set of air films or materials.

Step 3—Vapor pressure drops across each material can be calculated in much the same way as are temperature drops

$$\Delta p_{material}/\Delta p_{wall} = Z_{material}/Z_{wall} \tag{4}$$

where p is the vapor pressure [Pa (in. Hg)] and Z the vapor diffusion resistance [m/s (1/perm)]. In the example, the total resistance of the wall with the vapor retarder is as follows (see Table 1)

$$Z_{wall} = 329.73\ 10^9 \text{ m/s } (18.94 \text{ perm}^{-1})$$

The total vapor pressure drop across the wall is calculated from indoor and outdoor relative humidities and the indoor and outdoor saturation vapor pressures (see Table 2).

$$\begin{aligned} \Delta p_{wall} &= p_{indoor} - p_{outdoor} \\ &= (40/100)2503 - (50/100)371 \\ &= 1001 - 186 = 815 \text{ Pa } (0.2409 \text{ in. Hg}) \end{aligned}$$

As with temperatures, the vapor pressures at the surfaces of each material can be easily determined from the vapor pressure drops. Table 3 lists the results for the example wall with vapor retarder.

As with temperatures, the vapor pressures at the surfaces of each material can be easily determined from the vapor pressure drops. Table 3 lists the results for the example wall with vapor retarder.

Step 4—Figure 1 shows the saturation and calculated vapor pressures. It reveals that none of the vapor pressures exceeds the saturation vapor pressure, and therefore no condensation is indicated. Vapor flow is uniform throughout the wall and can be calculated easily as follows

$$w = \Delta p_{wall}/Z_{wall} \tag{5}$$

For this example, $w = 815/(329.73\ 10^9) = 2.5\ 10^{-9}$ kg/m²·s (0.013 grain/h·ft²). This is a very small amount of water vapor flow.

EXAMPLE 2: WALL WITHOUT VAPOR RETARDER

Example 2 uses the same wall but without the vapor retarder. The vapor retarder has a negligible effect on tem-

TABLE 3—Calculation of vapor pressures in wall with vapor retarder.[a]

Air Film or Material	Saturation Vapor Pressure, Pa (in. Hg)	Vapor Pressure [Pa (in. Hg)]	
		Drop	Surface
Indoor air (40% RH)[b]			
	2503 (0.7392)		1001 (0.2957)
Surface air film		0.3 (0.00008)	
	2305 (0.6807)		1001 (0.2956)
Gypsum board		8.6 (0.0025)	
	2174 (0.6419)		992 (0.2930)
Vapor retarder		717.9 (0.2120)	
	2174 (0.6419)		274 (0.0810)
Insulation		1.4 (0.0004)	
	486 (0.1434)		273 (0.0806)
Plywood sheathing		86.2 (0.0254)	
	443 (0.1309)		187 (0.0552)
Wood siding		1.2 (0.0004)	
	381 (0.1124)		186 (0.0548)
Surface air film		0.04 (0.00001)	
	371 (0.1096)		186 (0.0548)
Outdoor air (50% RH)			

[a] Vapor pressures are taken at the interface for each set of air films or materials.
[b] RH is relative humidity.

peratures (as long as air movement is not considered), and temperatures and saturation vapor pressures are therefore the same as in the wall in Example 1. Skip directly to Step 3, calculation of vapor pressures.

Step 3—The total vapor diffusion resistance of this wall is as follows (see Table 1)

$$Z_{\text{wall}} = 39.73\ 10^9 \text{ m/s } (2.27 \text{ perm}^{-1})$$

Vapor pressure drops can again be calculated with Eq 2. The initial calculations are shown in Table 4.

Step 4—Figure 2 shows the saturation and calculated vapor pressures. This time comparison with saturation pressures reveals that the calculated vapor pressure on the interior surface of the sheathing [915 Pa (0.2702 in. Hg)] is well above the saturation pressure at that location [486 Pa (0.1434 in. Hg)]. This indicates condensation, probably on the surface of the sheathing, because condensation within the permeable insulation is unlikely. If the location of the condensation or the condensation rate are of interest, additional calculations (Steps 5 and 6) are necessary.

Step 5—Figure 2 shows that the calculated vapor pressure exceeds the saturation vapor pressure by the greatest amount at the interior surface of the plywood sheathing. This is therefore the most likely location for condensation to occur. With condensation at that surface, vapor pressure should equal saturation at that location (see Table 4).

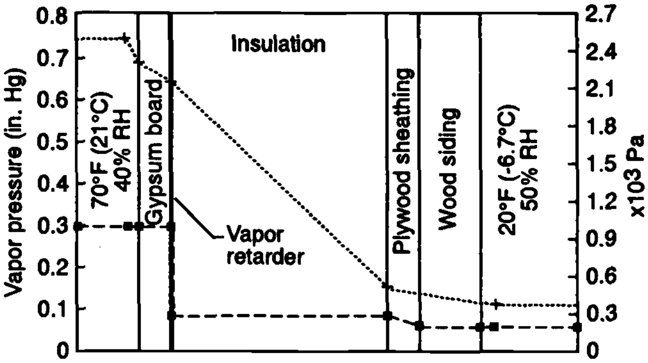

FIG. 1—Dew point method; example wall with vapor retarder. Dotted line is saturation vapor pressure; dashed line is calculated vapor pressure.

Step 6—The change of vapor pressure on the plywood sheathing alters all other vapor pressures as well as the vapor flow through the wall. The calculation of vapor pressures is similar to that in Step 3, but the wall is now divided into two parts: one part on the interior of the condensation plane (that is, gypsum board and insulation) and the other part on the exterior (plywood sheathing and wood siding). The vapor pressure drop over the first part of the wall is

$$\Delta p_1 = 1001 - 486 = 515 \text{ Pa } (0.152 \text{ in. Hg})$$

and that over the secod part is

$$\Delta p_2 = 486 - 371 = 115 \text{ Pa } (0.034 \text{ in. Hg})$$

The vapor diffusion resistances of both parts of the wall are

$$Z_1 = (0.11 + 3.5 + 0.6)10^9 = 4.21\ 10^9 \text{ m/s } (0.24 \text{ perm}^{-1})$$
$$Z_2 = (35 + 0.5 + 0.02)10^9 = 35.53\ 10^9 \text{ m/s } (2.03 \text{ perm}^{-1})$$

The vapor pressure drops can now be calculated from

$$\Delta p_{\text{material}}/\Delta p_i = Z_{\text{material}}/Z_i \qquad i = 1,2 \qquad (6)$$

Final calculations of vapor pressure are shown in Table 4. The vapor pressure no longer exceeds the saturation vapor pressure, which means that the condensation plane was chosen correctly. Figure 2 shows the vapor pressure profile (identified as vapor pressure, final calculation).

Vapor flow is no longer the same throughout the wall: vapor flow into the wall from the indoor air increased as a result of the lower vapor pressure at the plywood surface, while flow from the wall to the outside decreased. The difference between the two flows is the rate of moisture accumulation.

$$w_c = \Delta p_1/Z_1 - \Delta p_2/Z_2 = 515/(4.21\ 10^9) - 115/(35.53\ 10^9)$$
$$= 119\ 10^{-9} \text{ kg/s}\cdot\text{m}^2 \ (0.61 \text{ grain/h}\cdot\text{ft}^2)$$

TABLE 4—Initial and final calculation of vapor pressures in wall without vapor retarder.

Air Film or Material	Saturation Vapor Pressure, Pa (in. Hg)	Vapor Pressure, Pa (in. Hg)	
		Drop	Surface
	Initial Calculation		
Indoor air (40% RH)			
	2503 (0.7392)		1001 (0.2957)
Surface air film		2.2 (0.0007)	
	2305 (0.6807)		999 (0.2950)
Gypsum board		71.9 (0.0212)	
	2174 (0.6419)		927 (0.2738)
Insulation		12.0 (0.0036)	
	486 (0.1434)		915 (0.2702)
Plywood sheathing		718.9 (0.2123)	
	443 (0.1309)		196 (0.0579)
Wood siding		10.3 (0.0030)	
	381 (0.1124)		186 (0.0549)
Surface air film		0.4 (0.0001)	
	371 (0.1096)		186 (0.0548)
Outdoor air (50% RH)			
	Final Calculation		
Indoor air			
	2503 (0.7392)		1001 (0.2957)
Surface air film		13.4 (0.0040)	
	2305 (0.6807)		988 (0.2917)
Gypsum board		430.4 (0.1271)	
	2174 (0.6419)		557 (0.1646)
Insulation		71.7 (0.0212)	
	486 (0.1434)		486 (0.1434)
Plywood sheathing		295.8 (0.0874)	
	443 (0.1309)		190 (0.0560)
Wood siding		4.2 (0.0012)	
	381 (0.1124)		186 (0.0548)
Surface air film		0.1 (0.00004)	
	371 (0.1096)		186 (0.0548)
Outdoor air			

In our example, the plywood surface is below freezing, and this moisture would probably accumulate as frost. About a week of condensation at this rate would increase the average moisture content of the plywood by 1%.

The limitations of this method and recommendations for its use can be found at the end of the section on manual design tools.

The dew point method can be summarized as follows:

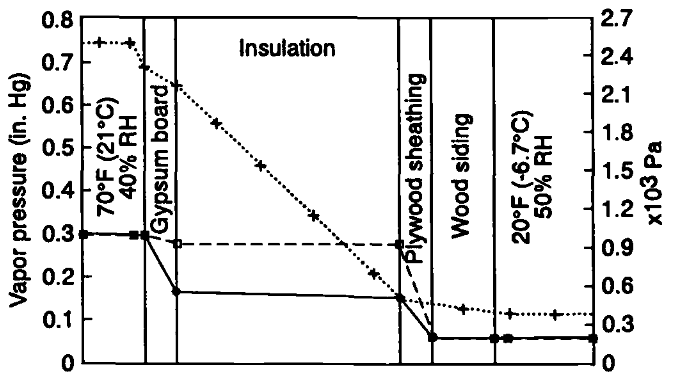

FIG. 2—Dew point method; example wall without vapor retarder. Dotted line is saturation vapor pressure; dashed line is initial calculation of vapor pressure; solid line is final calculation of vapor pressure.

1. Calculate temperature drops and surface temperatures.
2. Find corresponding saturation vapor pressures.
3. Calculate vapor pressure drops and vapor pressures.
4. Check if saturation pressure is above vapor pressure at all surfaces; if so, no condensation is indicated. Vapor flow through the wall may be determined if desired. (If condensation is indicated, continue with the following steps.)
5. Select condensation surface; vapor pressure at this surface equals the saturation vapor pressure.
6. Recalculate vapor pressures; if any vapor pressures are above saturation, Steps 5 and 6 should be repeated with a different condensation surface.
7. If needed, calculate rate of condensation.

Glaser Diagram

The Glaser diagram [2,3] is a variation on the dew point method. It is used primarily in Europe. The Glaser diagram is based on the following diffusion equation and definitions

$$w = -(\delta'/\mu')\ \Delta p/d \qquad (7)$$

where

δ' = diffusion coefficient of water vapor in air, s, and
μ' = diffusion resistance factor of the material.

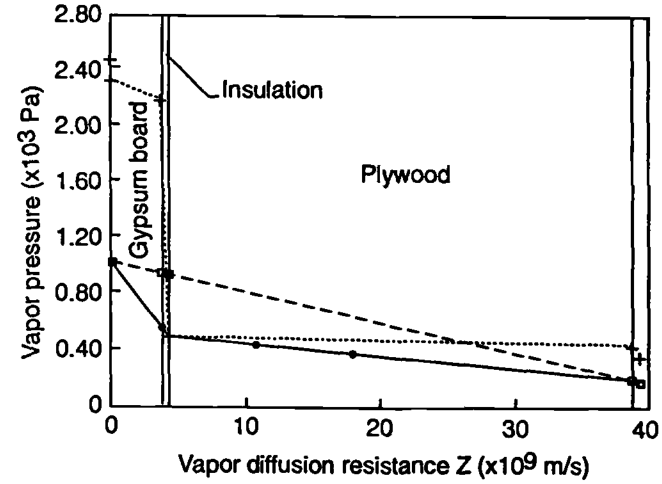

FIG. 3—Glaser diagram for example wall without vapor retarder. See caption to Fig. 2 for line designations. Dotted line is saturation vapor pressure; dashed line is initial calculation of vapor pressure; solid line is final calculation of vapor pressure.

The diffusion resistance factor is the ratio of the resistance to water vapor diffusion of the material and the resistance of a layer of air of equal thickness. The term *water vapor diffusion coefficient* is often used instead, defined by

$$\delta = \delta'/\mu' \qquad (8)$$

Substituting δ in Eq 6 shows that diffusion coefficient δ and permeability μ (Eq 1) are the same. However, permeability is usually expressed in English units (perm·in.), while the diffusion coefficient is usually expressed in metric units (s). Vapor diffusion resistance is again defined as

$$Z = d/\delta$$

The only difference between the Glaser diagram and the conventional dew point method lies in the horizontal axis of the diagram. Rather than using thickness of the materials, the Glaser diagram uses the vapor diffusion resistance as the horizontal axis (Fig. 3 shows a repeat of Example 2). Thus, the materials with the largest resistance are featured most prominently. The advantage of this display is that the vapor pressure profiles are converted into straight lines. Thus, individual vapor pressures need not be calculated. In the example of the wall without vapor retarder and condensation on the plywood, the vapor pressure profile consists of two straight line segments. The saturation vapor pressure still needs to be determined from temperatures, as in the dew point method.

Kieper Diagram

The Kieper diagram was first introduced by Kieper et al. [*4*] and described in greater detail by TenWolde [*5*]. As with the dew point method and the Glaser diagram, the Kieper diagram is based entirely on vapor diffusion theory. The advantages of this method are: (a) the same diagram can be used for different wall configurations, as long as indoor and outdoor conditions are not changed, and (b) the calculation does not need to be repeated if condensation is indicated.

Rather than graphing vapor pressures and saturation pressures, the Kieper diagram uses two parameters, x and y, representing thermal properties and vapor diffusion properties of the materials in the wall, respectively. The thermal property x parameter is defined as follows

$$\begin{aligned} x_1 &= R_1/R_{\text{wall}} \\ x_2 &= x_1 + R_2/R_{\text{wall}} \\ x_n &= x_1 + \ldots + x_{n-1} + R_n/R_{\text{wall}} \end{aligned} \qquad (9)$$

where R_1 and R_2 are the R values of the individual materials and air films. Values of x range from 0 to 1. Temperature in the wall can be easily expressed as a function of x

$$T(x) = T_i - x(T_i - T_o) \qquad (10)$$

where

T_i = indoor temperature °C (°F), and
T_o = outdoor temperature °C (°F).

The vapor diffusion y parameter is defined similarly as

$$y_n = y_1 + \ldots + y_{n-1} + Z_n/Z_{\text{wall}} \qquad (11)$$

and also ranges from 0 to 1.

If there is condensation or evaporation of liquid water at location (x,y), the net moisture flow to that point can be stated as

$$\begin{aligned} w_c &= \frac{p_i - p_s[T(x)]}{yZ_{\text{wall}}} - \frac{p_s[T(x)] - p_o}{(1-y)Z_{\text{wall}}} \\ &= \frac{1}{Z_{\text{wall}}}\,\frac{p_i - p_s[T(x)] - y(p_i - p_o)}{y(1-y)} \end{aligned} \qquad (12)$$

where

w_c = moisture accumulation rate, kg/m²·s (grain/ft²·h),
p_i = indoor vapor pressure, Pa (in. Hg),
p_o = outdoor vapor pressure, Pa (in. Hg),
$p_s[T(x)]$ = saturation vapor pressure, Pa (in. Hg).
Note: $T(x)$ is defined in Eq 10.

If w_c is positive, condensation (wetting) is indicated; if negative, evaporation (drying) takes place. The term w_c therefore indicates the wetting/drying potential at a given location in the wall or roof.

If we move the term Z_{wall} to the left side of Eq 12, the right side includes only x, y, and indoor and outdoor vapor pressures and contains no material property parameters

$$w_c Z_{\text{wall}} = \frac{p_i - p_s[T(x)] - y(p_i - p_o)}{y(1-y)} \qquad (13)$$

The left term of Eq 13 has the dimension of a pressure (in. Hg or Pa). Curves in the Kieper diagram connecting points where the product $w_c Z_{\text{wall}}$ is constant represent curves of "equal wetting potential." The curve where the wetting potential is zero is often called the condensation boundary curve. These curves only change with changes in indoor or outdoor conditions and do not depend on the wall or roof construction. Figure 4 shows the Kieper diagram with the curves for 21.2°C (70°F), 40% relative humidity indoor conditions and −6.7°C (20°F), 50% relative humidity outdoors. Various constructions can be analyzed in a single Kieper diagram if indoor and outdoor conditions are the same.

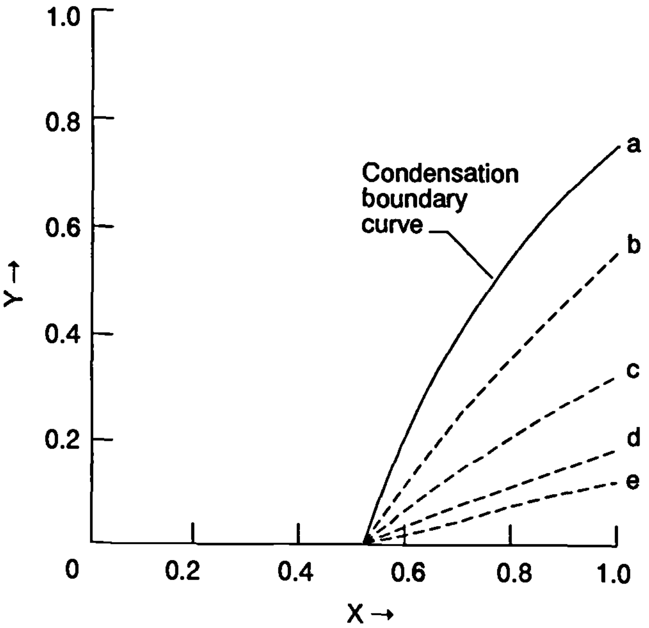

FIG. 4—Kieper diagram: moisture accumulation curves for indoor conditions of 70°F (21°C), 40% RH and outdoor conditions of 20°F (−6.7°C), 50% RH. W_cZ values for the curves are (a) 0, (b) 0.2 in. Hg (677 Pa), (c) 0.5 in. Hg (1693 Pa), (d) 1.0 in. Hg (3386 Pa), and (e) 1.5 in. Hg (5080 Pa).

Table 5 shows the x and y values associated with the examples used previously: a frame wall with and without a vapor retarder. When the wall profiles are entered in the Kieper diagram, as shown in Fig. 5, it is obvious that the wall with the vapor retarder is entirely outside the condensation region (the area below the condensation boundary curve). As expected, the curve for the wall without the vapor retarder penetrates the condensation region in the diagram. The diagram shows that the plywood surface has the greatest wetting potential. From the graph the wetting potential can be estimated at

$$w_cZ = 1.4 \text{ in. Hg (4740 Pa)}$$

With $Z = 2.27$ perm^{-1} (39.7 10^9 m/s), the estimated rate of condensation is

$$w_c = 1.4/2.27 = 0.62 \text{ grain/h}\cdot\text{ft}^2 \ (120\ 10^{-9} \text{ kg/m}^2\cdot\text{s})$$

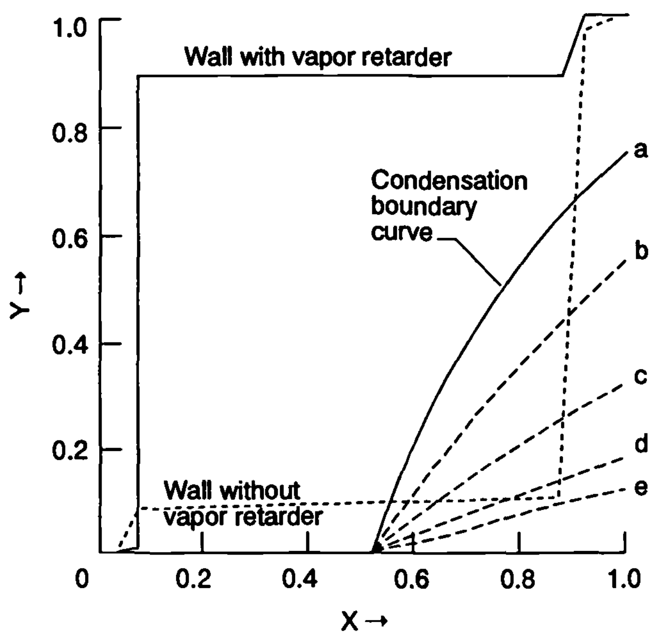

FIG. 5—Kieper diagram: example wall with and without vapor retarder, indoor conditions of 70°F (21°C), 40% RH and outdoor conditions of 20°F (−6.7°C), 50% RH. W_cZ values for the curves are (a) 0, (b) 0.2 in. Hg (677 Pa), (c) 0.5 in. Hg (1693 Pa), (d) 1.0 in. Hg (3386 Pa), and (e) 1.5 in. Hg (5080 Pa).

Limitations of Manual Design Tools

The methods discussed previously have the same severe limitations and should therefore be used with caution. The methods only "predict" condensation, not moisture damage. Many constructions can sustain limited periods of condensation without significant damage, especially if the temperatures are near or below freezing and the material is able to dry quickly. In addition, performance problems such as mold and mildew or paint failure are not necessarily related to surface condensation.

The methods ignore air leakage. If air leakage is present, it tends to dominate moisture transport. Even small amounts of indoor air leaking into the wall (exfiltration) can more than double the condensation rate during winter [6]. However, where exfiltration increases the potential for wetting, infiltration of dry cold air decreases that potential. If the amount and

TABLE 5—Kieper diagram: x and y values for example wall with and without a vapor retarder.

Air Film or Material	Thermal Resistance,[a] h·ft²·°F/Btu	Permeance,[b] perm	Diffusion Resistance, rep	x	Vapor Retarder, y	No Vapor Retarder, y
Air film (still)	0.68	160	0.006	0.049	0.0003	0.003
Gypsum board, painted	0.45	5	0.2	0.081	0.011	0.091
Vapor retarder	...	0.06	16.67	0.081	0.891	...
Insulation	11	30	0.033	0.871	0.893	0.105
Plywood sheathing	0.62	0.5	2	0.916	0.998	0.986
Wood siding	1	35	0.029	0.988	1.000	0.999
Air film (wind)	0.17	1000	0.001	1.000	1.000	1.000
Total						
With vapor retarder	13.92		18.94			
Without vapor retarder	13.92		2.27			

[a] See Table 1 for SI values.
[b] 1 perm = 1 grain/ft²·h·in. Hg.

direction of airflow are known, the effects may be estimated with more sophisticated methods, discussed later in this chapter. However, usually insufficient information is available on the airflow patterns in wall and roof cavities to estimate the effect on moisture conditions.

The methods do not recognize liquid capillary transport or any transport mechanisms other than diffusion. This tends to result in the underprediction of moisture transfer in materials such as wood at higher moisture contents. For instance, in plywood, moisture transfer may be as much as 16 times greater under wet conditions than under dry conditions and in waferboard, three to four times greater under wet conditions [7].

All three methods are steady-state and do not recognize the effects of moisture and heat storage. This may be a major drawback when trying to determine the potential for damage in a wall or roof with large storage capacity or in a climate with a low drying potential. In those cases, moisture stored during an earlier part of the season may cause damage at a later time.

When moisture condenses or evaporates, latent heat is released or absorbed, raising or lowering temperatures. The analysis does not take this into account. In most practical cases, this is not a major effect unless the condensation/evaporation takes place on an exposed surface (for example, window condensation).

All three methods are one-dimensional; that is, the effect of corners, holes, or cracks, studs, or other thermal "bridges" cannot be evaluated.

Recommendations for Use

Although manual design tools have many limitations and are based on simplifying assumptions, they have the advantage of being relatively simple. Such tools have not been thoroughly evaluated, nor have they been compared with more sophisticated analytical tools. The following recommendations therefore primarily reflect the opinion of the author of this chapter.

- The methods should only be used if the user is reasonably sure that the construction is relatively airtight.
- Monthly averages should be used for indoor and outdoor temperatures and relative humidities. Using design temperatures usually leads to very restrictive design specifications.
- If condensation is indicated, the user should evaluate the potential hazards to the structure and the inhabitants. This evaluation should include an estimate of the total moisture accumulation, the storage capacity of the material, and the temperature at the condensation plane. The potential for drying during the next period should also be taken into consideration.
- Erroneous conclusions about the rate and location of condensation when using the dew point method or Glaser diagram can be avoided. If the first calculation indicates condensation, a condensation plane should be selected and the procedure should be repeated until the vapor pressure does not exceed the saturation vapor pressure anywhere in the construction.
- Results should be used with great caution. They are primarily useful for comparing the condensation risks in alternative airtight constructions.

NUMERICAL TOOLS

This section briefly discusses several relatively simple numerical analytical methods that are not included in Chapter 2. All the models discussed in this section are limited to one-dimensional analysis.

MOISTWALL, developed at the Forest Products Laboratory, is a numerical version of the Kieper diagram [5]. The program calculates moisture accumulation potential at each material surface using Eq 10. If all values are negative, no condensation is indicated. If some results are positive, the maximum is selected. MOISTWALL was implemented on a programmable calculator and has not yet been adapted to personal computers. Therefore, this program is not readily available.

In the MOISTWALL-2 program, the effect of airflow was added to vapor diffusion [6]. The airflow is assumed to be a uniform one-dimensional exfiltrative or infiltrative flow. In all other respects, this method has the same limitations as the manual design methods. As with the original MOISTWALL program, MOISTWALL-2 has not been implemented on a personal computer and is therefore not readily available.

A different model, named MOISTWALL-3, has been developed at the Forest Products Laboratory for the personal computer but has not yet been reported in the literature. This model recognizes both vapor diffusion and airflow in and out of the cavity, is able to account for dry-cup and wet-cup permeance values, and is capable of calculating the moisture content of the various materials in the wall. It is limited to one dimension and is unable to account for capillary flow. The model also ignores heat storage and latent heat effects.

An analytical model of moisture in cavity walls or roofs was published by Cunningham [8,9]. This model is a simpler representation of moisture flow and storage: the cavity is treated as a single homogeneous region with the wood stud as a moisture storage medium. In a later version [10], separate moisture release into the cavity (such as leaks, soil moisture) are also included. This simpler approach is very useful for estimating approximate drying times for wet wall cavities, assuming different levels of air leakage. However, the method is less suited to estimating the response to large temperature gradients in the insulated cavity (very cold or hot climates) or to using hygroscopic insulation materials (e.g., cellulose).

A description of a one-dimensional finite-difference moisture transfer model was recently published by Spolek et al. [11]. The driving force within each material is assumed to be the moisture content gradient, whereas hygroscopic properties are considered at the surface of materials only. While this allows analysis of walls or roofs under isothermal conditions, the model does not account for increased moisture movement within hygroscopic materials (wood, masonry) under temperature gradients. Many other models, discussed in Chapter 2, more accurately account for this and usually are more suitable for analysis of exterior walls and roofs containing hygroscopic materials.

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12

Measurement Techniques and Instrumentation

by Peter L. Lagus[1]

THIS CHAPTER DESCRIBES MEASUREMENT TECHNIQUES and instrumentation for the measurement of moisture in the air (relative humidity), moisture in building materials, water vapor transmission, water leakage, and building airflow. The chapter does not discuss the extensive literature regarding temperature measurement (an important component in understanding the dynamics of vapor formation and transport in buildings). To do so would only duplicate information contained elsewhere and which is easily obtainable by the practicing engineer. For instance, Ref *1* contains an excellent overview of the various electronic temperature measurement systems and provides detailed references for further study.

The importance that the engineering community attaches to moisture and humidity is attested to by the fact that the ASTM *Index of Standards* contains in excess of 150 entries under the categories of "moisture determination" and "relative humidity." If one adds the three additional topics mentioned in the first paragraph, the number easily exceeds 200. In order to simplify the task of finding ASTM standards relevant to building investigations, Table 1 is provided. It lists, by designation and title, standards that either are, or potentially could be, useful to the practitioner in attempting to undertake moisture or moisture-related investigations within the building environment. This table is by no means exhaustive and is meant as a guide. Additional moisture-related standards have been promulgated by ASHRAE, ANSI, and other standards writing or professional organizations.

MEASUREMENT OF RELATIVE HUMIDITY

There are a large number of techniques available for measurement of relative humidity (RH), since relative humidity is an important consideration in such diverse fields as atmospheric science, soils science, materials processing, agriculture, instrumentation, health, and many others.

The most precise techniques for the measurement of RH are those relied upon by atmospheric scientists to supply accurate data over a wide range of temperatures, airflows, and pressures. For the most part, these techniques are slow and require relatively bulky equipment. For building investigations, they may be usable in some circumstances. Within the building context, an excellent review is contained in Refs *2* and *3*.

There are many techniques which utilize small sensors that can be used for building moisture measurements. Techniques which have been or could be used in RH measurement are summarized in Table 2. Brief descriptions of each are also provided. It should be noted that published data on such parameters as response time, accuracy, and precision vary widely between sources. The table represents an attempt to present ranges of values where available.

Often, availability or familiarity play the largest role in determining which particular technique is used for RH determination. Reference to Table 2 will provide an experimenter with an envelope within which he can confidently use a particular type of measurement. The table also points out potential pitfalls in any particular technique and provides a range of conditions over which a given measurement technique is likely to be valid.

Sling Psychrometers

The reduction in temperature of a wetted surface owing to evaporation cooling can be used to determine the amount of moisture in the atmosphere. The ambient air temperature and pressure must also be known. This principle is used in the operation of the wet-bulb psychrometer, which consists of two temperature sensors, one of which is wrapped in clean muslin. The muslin is wetted with distilled water, and the instrument is placed in an airstream of from 3 to 5 m/s. The indicated temperature difference of the two sensors is easily converted to relative humidity or dew point through the use of psychometric tables. ASTM E 337-84 (1990) provides a detailed description of the measurement technique.

Commonly used temperature sensors for wet-bulb hygrometry include mercury-in-glass thermometers, resistance thermometers, thermocouples, and thermistors. Various means exist to produce an airstream for the wet-bulb thermometer. The sling psychrometer consists of two thermometers mounted side by side on a metal plate or frame that can be whirled by hand. The two thermometers mounted in this way also can be placed in a housing located in front of a hand-powered fan [*4*].

Dew Point Hygrometers

When a shiny metal surface exposed to the ambient air is cooled to a temperature below the dew point, moisture from the layer of air immediately adjacent to it condenses to form dew. The appearance of the surface changes markedly on the appearance of the condensate, and such a change is readily observed. If the temperature of the surface is measured at the precise instant when dew formation occurs, then this mea-

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[1] Lagus Applied Technology, Inc., San Diego, CA.

TABLE 1—ASTM standards relevant to moisture or humidity measurement in building investigations.

ASTM Designation	Title
C 70-79 (1985)	STM for Surface Moisture in Fine Aggregate
C 324-82 (1988)	STM for Free Moisture in Ceramic Whiteware Clays
C 566-89	STM for Total Moisture Content of Aggregate by Drying
C755-85 (1990)	SP for Selection of Vapor Retarders for Thermal Insulation
C 1104-88	STM for Determining the Water Vapor Sorption of Unfaced Mineral Insulation
C 1136-92	SS for Flexible, Low Permeance Vapor Retarders for Thermal Insulation
D 644-89	STM for Moisture Content of Paper and Paperboard by Oven Drying
D 779-89	STM for Water Resistance of Paper, Paperboard, and Other Sheet Materials by the Dry Indicator Method
D 1860-87	STM for Moisture and Creosote-Type Preservative in Wood
D 1884-89	STM for Moisture in Mineral Aggregate Used on Built-up Roofs
D 2216-90	STM for Laboratory Determination of Water (Moisture) Content of Soil and Rock
D 2247-87	SP for Testing Water Resistance of Coatings in 100% Relative Humidity
D 2987-89	STM for Moisture Content of Asbestos Fiber
D 3017-88	STM for Water Content of Soil and Rock in Place by Nuclear Methods (Shallow Depth)
D 3201-86	STM for Hygroscopic Properties of Fire-Retardant Wood and Wood-Base Products
D 4178-82 (1987)	SP for Calibrating Moisture Analyzers
D 4230-83 (1989)	STM for Measuring Humidity with Cooled Surface Condensation (Dew-Point) Hygrometer
D 4263-83 (1988)	STM for Indicating Moisture in Concrete by the Plastic Sheet Method
D 4442-92	STM for Direct Moisture Content Measurement of Wood and Wood-Base Materials
D 4444-92	STM for Use and Calibration of Hand Held Moisture Meters
D 4643-87	STM for Determining Water (Moisture) Content of Soil by the Microwave Oven Method
D 4933-91	SG for Moisture Conditioning of Wood and Wood-Base Materials
D 4959-89	STM for Determining of Water (Moisture) Content of Soil by Direct Heating Method
E 96-92	STM for Water Vapor Transmission of Materials
E 154-88	STM for Water Vapor Retarders Used in Contact with Earth Under Concrete Slabs, on Walls, or as Ground Cover
E 241-90	SRP for Increasing Durability of Building Constructions Against Water Induced Damage
E 283-84	STM for Rate of Air Leakage Through Exterior Windows, Curtain Walls, and Doors
E 331-86	STM for Water Penetration of Exterior Windows, Curtain Walls, and Doors by Uniform Static Air Pressure Difference
E 337-84 (1990)	STM for Measuring Humidity with a Psychrometer (the Measurement of Wet and Dry Bulb Temperatures)
E 398-83 (1988)	STM for Water Vapor Transmission Rate of Sheet Materials Using A Rapid Technique for Dynamic Measurement
E 514-90	STM for Water Penetration and Leakage Through Masonry
E 547-86	STM for Water Penetration of Exterior Windows, Curtain Walls, and Doors by Cyclic Static Air Pressure Differential
E 741-83 (1990)	STM for Determining Air Leakage Rate by Tracer Dilution
E 779-87 (1992)	STM for Determining Air Leakage Rate by Fan Pressurization
E 783-84	STM for Field Measurement of Air Leakage Through Installed Exterior Windows and Doors
E 1105-90	STM for Field Determination of Water Penetration of Installed Exterior Windows, Curtain Walls, and Doors by Uniform or Cyclic Static Air Pressure Difference
E 1186-87 (1992)	SP for Air Leakage Site Determination
E 1258-88 (1993)	STM for Airflow Calibration of Fan Pressurization Devices
F 372-73 (1984)	STM for Water Vapor Transmission Rate of Flexible Barrier Materials Using an Infrared Detection Technique
F 1249-90	STM for Water Vapor Transmission Rate Through Plastic Film and Sheeting Using a Modulated Infrared Sensor

NOTE—In this table the following abbreviations are used: STM for Standard Test Method; SRP for Standard Recommended Practice; SP for Standard Practice; SG for Standard Guide or Guideline; SS for Standard Specification.

surement is a direct determination of the dew point. The difference between the ambient air temperature and the dew point can be used in conjunction with the saturation vapor-pressure curve for air to determine the moisture content of the ambient sample [*5,6*].

Condensation-temperature measurement by the chilled-mirror method is capable of providing a long-term humidity measurement that is acceptable in the absence of recalibration. Information on the use of dew point hygrometers can be found in ASTM D 4230-83 (1990).

Dew Cell

The dew cell measurement is also called the salt-phase technique. It utilizes a lithium-chloride (LiCl)-soaked wick wrapped around an insulated tube similar to that of a LiCl resistance sensor. This technique relies on a different principle from that of a resistance sensor and permits an absolute determination of humidity. LiCl absorbs humidity from the surrounding air and becomes electrically conductive. The current passing through the LiCl generates heat and tends to evaporate water from it. An equilibrium is soon reached when the layer neither gains nor loses water to the surrounding air. Equilibrium is reached at that temperature of the salt solution at which the partial pressure of water over a saturated solution equals the ambient water vapor pressure [*7*].

Since the vapor pressure of saturated LiCl solution at different temperatures is accurately known, the instrument needs no empirical calibration. The output can be calibrated in dew point temperature directly.

Fog-Type Dew Point Meter

The fog-type dew point meter is another type of dew point instrument that produces adiabatic cooling by compressing an air sample within a chamber followed by sudden expansion [*8*]. The initial pressure required to produce fog only in the expanding gas is found by trial and error; dew point tem-

TABLE 2—Relative humidity sensors.

Type	Method of Operation	Approximate Range	Approximate Uncertainty	Response Time	Primary Output Parameter
Psychrometer, sling	Measurement of water temperature due to evaporation	10 to 100% RH	3% RH	Medium	Temperature
Dew and frost point (chilled mirror)	Measure temperature at which dew or frost forms on chilled mirror	−100 to +200°F (dew or frost point temp)	4 to 0.4°F (dew or frost point temp)	Medium-fast	Temperature
Dewcell (LiCl sensor)	Measurement of equilibrium temperature of saturated salt solution	−20 to +160°F (dew or frost point temp) (depends on ambient temperature)	3°F (dew or frost point temp)	Medium	Temperature
Dunmore	Measurement of resistance of aqueous LiCl in binder	7 to 98% RH	1.5% RH	Fast	Resistance
Jason	Measurement of impedance of Al_2O_3	25 to 85% RH	5% RH (increasing slowly to 10% RH from 32°F to −40°F)	Fast	Resistance
Ion Exchange (Pope)	Measurement of impedance of ion exchange resin	10 to 100% RH	Same as Jason	Fast	Resistance
Carbon	Measurement of resistance of a dimensionally variable carbon impregnated film	10 to 100% RH	Same as Jason	Fast	Resistance
Brady array	Change in electrical conductance of chromium/gold oxide coating	0 to 100% RH	±2%	Fast	Resistance
Piezoelectric crystal	Measurement of frequency change of quartz crystal covered with moisture film	−108 to 77°F (dew or frost point temperature)	5% of range (for frost points from −67 to −4°F)	Medium	Frequency
Color change	Color change of salts amount of dissolved moisture	10 to 80% RH	10 to 20% RH	Slow-medium	Color
Mechanical	Dimensional changes of natural and synthetic fibers	10 to 90% RH	±5% at best	Slow-medium	Dial reading
Thin film polymer (capacitive)	Measurement of electrical circuit frequency change as polymer absorbs and releases water vapor (change in dielectric constant or C)	0 to 80% RH 80 to 100% RH	2% RH 3% RH	Medium-fast	Capacitance
Electrolytic	Electrolysis of moisture absorbed on dessicant	−100 to 30°F	±5%	Fast	Current
Fog type	Expansion of compressed air sample	−76 to 70°F (dew or frost point temperature)	2°F (dew or frost point temperature)	Slow-medium	Temperature
Lynn-Alpha hygrometer	Selective absorption of Lynn-alpha radiation by water vapor	−30 to 86°F (dew or frost point temperature)	2°F (dew or frost point temperature)	Fast	Temperature

perature is then determined by calculation or graphical means. A variant of the basic device uses a radioactive source to create adequate nucleation centers for low dew point temperatures.

Lyman-Alpha Hygrometer

The Lyman-alpha hygrometer is based on the very strong selective absorption of Lyman-alpha radiation by water vapor. The instrument provides a direct measure of absolute humidity as a result. The theory, design, and construction of such a hygrometer are discussed in Ref 9. Owing to the slow degradation of the detector window material used, a variable-path technique is employed to make the instrument self-calibrating.

Dunmore

Resistance-type hygrometer elements were first developed by Dunmore at NBS [*10*]. These elements consist of thin copper wire wound on a glass tube and coated with LiCl. LiCl is nonconductive below an RH of 12%. Above 12% RH, the conductivity LiCl is proportional to relative humidity. Versions of this sensor incorporate a polystyrene coating on the glass and addition of polyvinyl acetate (PVA) to the LiCl to reduce polarization effects. No one element can adequately span the complete range of RH from 10 to 100%. For this reason, an array of elements is utilized in each sensor, each element spanning a short RH range.

Sensitivity of the Dunmore sensor is poor at high RH. Long exposure to high humidity can damage the LiCl elements. Being a resistance device, the signal is affected by temperature and thus must be calibrated over the temperature range of interest.

Jason

In these sensors an aluminum strip is anodized to produce a porous thin oxide coating. A gold coating is then applied to one face of the sensor to form a parallel resistance-capacitance network. When water is adsorbed into the aluminum oxide, its impedance decreases. This decrease can then be used to calibrate the sensor versus RH. These sensors show little temperature effect over the range of 0 to 80°C and are insensitive to air velocity. Above 90% RH, however, problems with drift, slow response, and hysteresis may occur. The sensors are easily contaminated and must be shielded from dust and pollutants [*11*].

Ion Exchange (Pope)

In this sensor, the electrical impedance of a sulfonated polystyrene ion-exchange resin coating on a polystyrene substrate is used as a measure of RH. The sensor has a useful temperature range of −65 to +35°C [*12*].

Carbon

This type of sensor consists of a composite of carbon particles suspended in a hygroscopic matrix, typically a hydroxyethyl cellulose formulation [*13*]. As the matrix shrinks and expands in response to changes in RH, the carbon particles move closer together and farther apart. This changes the electrical resistivity of the composite, which can then be calibrated with respect to RH. These sensors are temperature dependent, with serious nonlinearity below 0°C. Sensitivity is poor below 30% RH.

Brady

The Brady Array [*14*] utilizes a gold electrode with a chromium/gold oxide coating. When an oscillatory voltage is applied, the lattice structure of the electrode vibrates at a frequency which is a submultiple of the natural vibrating frequency of the water molecule. As water enters and leaves the array, it interacts with the lattice, causing bond distortion and release of energy to free electrons in the metal. This changes electrical conductance, which can be calibrated as a measure of RH.

Piezoelectric Crystal

This method is basically a gravimetric approach to measurement of RH. A crystal quartz oscillator is operated at a specific frequency while coated with a hygroscopic material. As the crystal gains or loses water, its weight, and hence its frequency, will change. Frequency can then be calibrated versus RH.

Commercially available units use LiCl as the hygroscopic material. Other substances such as molecular sieves, polar liquids, polymers, and silica gel have been experimentally evaluated [*15*]. The method is extremely sensitive and can detect as little as 0.1 ppm water vapor but can be used up to 30 000 ppm (saturation). These sensors are used mainly under flowing air conditions, such as in process gas streams.

Mechanical

Many organic materials change in dimension with changes in humidity; this action is used in a number of simple and effective humidity indicators, recorders, and controllers. Motion caused by changes in dimension, through a suitable linkage, causes a pointer to move across an indicating dial, a pen to move across a recording chart, or actuates a pneumatic or electric control mechanism [*16*].

Commonly used organic materials are human hair, nylon, dacron, animal membrane, animal horn, wood, and paper. However, no organic material has been found to reproduce its action consistently over an extended period. Responses can be affected significantly by exposure to extremes of humidity. Such devices require initial calibration and frequent recalibration; however, they are useful, because they can be arranged to read directly in terms of relative humidity and are simpler and less expensive than most other types.

Thin Film Polymer (Capacitive)

A thin hygroscopic polymer is used as the dielectric material in a capacitor. Due to the high dielectric constant of water, small changes in the moisture absorbed by the dielectric result in measurable changes in capacitance. Usually the frequency in a tuned circuit is measured rather than capacitance. Temperature-dependent complications arise from the polymer used. The amount of moisture absorbed and desorbed by dielectric compounds changes with temperature. To correct for these problems, temperature compensation of some sort must be used, based on idealized models of the polymer's temperature behavior. Individual probes, of course, deviate from the model [*17*].

Water-soluble contamination affects the vapor pressure in capacitive systems and causes the sensed RH to vary as the contamination builds up. Impurities also alter the dielectric constant of the water and hence the capacitance of the probe, further changing readings.

Electrolytic

In the electrolytic hygrometer, air is passed through a tube, where moisture is absorbed by a highly effective desiccant, usually phosphorous pentoxide, and electrolyzed. The airflow is regulated. Consequently, the electrical current required for electrolysis can be related to the humidity. The instrument is usually designed for use with moisture-air ratios in the range of 1 to 1000 ppm, but can be used with higher humidity [*18*].

TECHNIQUES FOR MEASUREMENT OF MOISTURE CONTENT IN SOLID MATERIALS

A variety of techniques exist for measurement of moisture in solids. The following discussion is confined to those techniques that measure moisture content in a nondestructive manner. These are summarized in Table 3. Techniques which require oven drying, gravimetric determination, chemical analysis, extraction, or removal of a portion of the material to another location are excluded. Although such techniques may be highly accurate, they do not allow for rapid measurement of moisture content under field conditions. These tech-

TABLE 3—Measurement techniques for moisture in solid materials.

Method	Availability	Accuracy	Response Time	Effects of Temperature	Interferences
Electrical resistance	Commercially available. For use on wood, textiles, paper.	Best obtainable is ±0.5%.	Instantaneous	Strong temperature effect. Must be calibrated for temperature.	Dissolve salts, moisture gradients, electrode contact.
Capacitance	Commercially available for use on wood, paper.	Best obtainable is ±0.5%.	Instantaneous	Complex effects for power-loss and admittance types.	Salts have minor effect. Moisture gradients.
Nuclear thermalization	Commercially available for use in soils. Have been used on roofs.	Depends on count rate and material. Best obtainable is ±0.3 lb/ft^3.	>4 min for highest accuracy	Little effect.	Material containing H atoms, certain elements (B, Cd, Mn, Cl, Fe).
Thermal conductivity	Some commercial units available for soils.	Not reported.	3 to 15 min	Temperature must be constant during test.	Sensor contact. Variable temperature. Temperature gradients. Inhomogeneities in material.
Ultrasonic	Commercial units available for on-line and portable measurement.	±1%	Instantaneous	No effect.	Density, elastic properties of material, cracks in material.

niques can be used to calibrate or verify results obtained from field-usable methods.

Electrical Resistance Techniques

For most porous materials, an increase in moisture content will result in a decrease in electrical resistivity. Although pure distilled water exhibits very high resistivity (on the order of 10^7 ohm-cm), even small amounts of dissolved ions can dramatically reduce this value [19]. The water contained within most porous materials dissolves ions from the walls of internal pores. Thus, pure water resistivity can be reduced below that of distilled water. Since the resistivity of most inorganic and organic solid nonconductors is relatively high, the water contained within the pores of such a material carries the majority of electrical current when the material is subjected to an applied voltage. This electrical resistivity is temperature dependent and is also frequency dependent. Measurements using direct current and low-cycle alternating current are subject to error due to effects of ionic polarization.

Measurements of moisture content using electrical resistance techniques can be divided into two distinct categories. In the first, which may be termed "direct" measurement, probes are inserted into or placed on the surface of the material of interest, and its electrical resistance is read directly. Previous calibration for the particular material and geometry over the range of moisture content of interest allows these readings to be interpreted.

The second, or "indirect" approach, involves use of a secondary material for which the relationship between moisture content and electrical resistance has been established. If this material (containing embedded sensors) is then placed into the material of interest and allowed to come to equilibrium, a relationship between moisture content of the known and unknown materials can be established. A prime example of this technique is the use of gypsum block gages to measure moisture content of solids [20].

Electrical resistance moisture gages are widely utilized in the wood industry [21]. The resistance of wood increases by a factor of about 10^7 over a range from fiber saturation (near 30% moisture content) to the oven-dry condition. In this range, there is a linear relationship between the log of resistance and the log of moisture content. Above fiber saturation, sensitivity is greatly reduced, and correlation with gravimetric methods is poor.

Portable battery-operated instruments are generally available with direct reading scales calibrated for one or more wood species. Information on application to other species and on temperature corrections is typically supplied by the manufacturer. Probes generally are of the two or four-pin type, which are driven into the wood a fixed depth prior to obtaining the reading.

Resistance devices have been applied to materials other than wood, though on a more limited scale. Blocks of plaster, gypsum, or fiberglass have been embedded [22,23] in soils and other materials [24] and used to measure moisture content. Success with this approach depends on a close match between the sorption characteristics of the two materials. Plaster gages work best in materials which are able to maintain their moisture content close to saturation until the moisture content of the plaster gage in contact with the material has fallen to about 30%. As dissolved salts can interfere with readings, ionic barrier gages [25] improve reliability in materials where salts are a problem. Resistance gages have also been applied to concrete using conductive-rubber electrodes [26] and using a wet-cell four-pin surface technique [27].

Various interferences can reduce the accuracy and reliability of electrical resistance moisture meters. A 2 to 4% decrease in resistance per 1°C increase in temperature is common, this effect being more pronounced at higher moisture contents. This corresponds to an error of 1% (by weight) of moisture content for every 1°C change of temperature. Dissolved salts can also affect results, especially at concentrations greater than 2000 ppm [28]. As previously mentioned, gradients in moisture content across a specimen will complicate interpretation of meter readings. Electrode contact may also be a problem, especially when surface probes are used on very dry materials, and where corrosives can cause buildup of corrosion products when probes are inserted into moist materials for long periods of time. ASTM D 4444-92 provides guidance in the use of resistance-type meters for moisture measurements in wood and wood-based products.

Capacitance Techniques

A variety of instruments have been developed to measure moisture content of porous materials by means of electrical capacitance. Since the dielectric constant of water is known to be approximately 80 over a wide range of temperatures and frequencies, and since dielectric constants of most dry and solid materials range from 2 to 4 [*29*], capacitance measurements can be used to determine the moisture content of porous materials. For real systems, calibration must be carried out for each case. It should also be noted that capacitance is proportional to the *volume* fraction of water present in the sample under test. To express moisture content on a weight basis, the sample density must be known or determined by an independent technique.

As with resistance methods, instrumentation based on measurement of capacitance is widely used in the wood and paper industries for determination of moisture content. The method is generally used in the range of 0 to 35% moisture content. A number of different approaches to utilization of capacitance as a means of moisture measurement are available. Instrumentation based on direct measurement of dielectric constant has been developed, but is not generally available commercially due to technical problems and high cost. Power-loss–type meters, which measure dispersion of energy within the dielectric, are more common. Capacitive admittance–type meters, in which the electrodes serve as a capacitor in a parallel resistance capacitance circuit, are also commercially available. Other types utilizing resonance circuitry and beat frequency oscillation have also been developed. Most of these instruments are designed to operate in the radio frequency range (10^3 to 10^8 Hz). Operation near the higher end of this range reduces the influence of dissolved ions on the measurement [*30*].

Most capacitance meters are designed to operate using a fringing-field concept. That is, the sample under test is not placed between the plates of a capacitor, but is placed in contact with an electric field formed around electrodes protruding from the body of the meter. Depending on electrode design, penetration into the material for commercially available units varies from 1 to 50 mm.

The capacitance method, in principle, is subject to fewer interferences than the resistance technique. In pure capacitance-type systems, temperature has little effect. However, power-loss and admittance instruments include a conductance contribution which varies with temperature and must therefore be included in the calibration. Effects of dissolved salts can be minimized by operating at higher frequencies. Specimen contact is normally not a problem, as fringing-field techniques do not require electrode contact with the test surface.

Specimen dimensions are important, however, as the field produced by the electrodes must be wholly within the material of interest. Gradients of moisture within the specimen may, as previously noted, lead to erroneous results, as will films of water on the test surface [*31*]. ASTM D 4442-92 provides guidance in the use of capacitive meters for moisture measurements in wood and wood products.

Neutron Thermalization Methods

Measurement of moisture content by detection of particles given off by thermalization of neutrons has gained wide acceptance as a rapid field and production technique, especially in soils engineering [*32–34*]. Typical nuclear meters utilize an Americium-Beryllium (Am-Be) source which emits neutrons of average energy near 4.5 MeV. These neutrons interact with atomic nuclei in the sample under test, transfer kinetic energy, and are "thermalized" to an energy level of about 0.025 MeV. These thermal neutrons are back scattered and then detected by boron trifluoride (BF_3) detectors on the meter.

Hydrogen atoms have a moderately high absorption cross section; that is, the probability that a thermal neutron will be absorbed is fairly good. Since hydrogen is normally present (as moisture) in quantities far exceeding the amounts of other high cross-sectional elements commonly encountered in soils, this technique has proven quite useful in measurements of soil moisture. It should be noted that elements such as boron, cadmium, manganese, chlorine, iron, and some others, if present in sufficient quantity, will lead to appreciable measurement errors. Also, the technique is not specific to water, but detects all hydrogen atoms in the sample. This can include hydrogen contained in organic solid materials, bitumen, and oils, as well as crystalline water of hydration.

Commercial nuclear moisture meters are designed to operate over a rather large effective volume. This can range up to 10 to 20 cm deep, 25 to 45 cm long, and 10 to 40 cm wide. The exact volume depends on the particular meter, the material being measured, and the amount and distribution of moisture in the sample. It is obvious that this type of meter does not afford a "point" measurement and would not be applicable to building components which are limited in size in one or more dimensions.

Nuclear meters have also been used in laboratory studies on concrete moisture contents [*35*] and in field surveys on roofs [*36,37*]. In the latter case only qualitative information is generally available, as the presence of roofing felt, asphalt, and other organics contributed to the readings and resulted in an overestimation of moisture present in the roof. ASTM D 3017-88 provides guidance in using nuclear moisture meters in soils. This guidance is easily applicable to the use of these meters in roofing materials and other building-related materials.

Thermal Conductivity Techniques

Thermal conductivity techniques rely on the increase in thermal conductivity of porous materials with increasing moisture content. Generally, transient heat-flow techniques are used. In these, the temperature of the material is measured at some distance from the heat source, or alternatively, the temperature rise of the heat source itself is measured.

Originally developed for measuring thermal conductivity of liquids [*38*], the transient (or "hot-wire" technique) has been applied to firebrick [*39*], concrete [*40*], and insulating materials [*41*]. The heat source can either be cast into the material or can be inserted as a self-contained probe into less rigid materials such as insulation and soils. By use of twin probes inserted into small holes drilled into brick units [*42*], the technique has been used to monitor moisture content of walls over long time periods.

As the measurement is indirect, calibration is needed for each particular material to which the technique is applied. Bloodworth [*43*] has applied the technique to soils over a range of 4 to 35% moisture content, but a separate calibration was required for each soil type. In addition, the sensor must be in thermal equilibrium with the surrounding material prior to test, and the temperature should not change during the test.

Ultrasonic Techniques

The propagation of acoustic waves in the megahertz region through solid materials will be altered by the presence of water. Wave velocity decreases as moisture content increases. This principle has been used in the design of moisture content instrumentation using ultrasonic transducers. Applications have been made to soils [*44*] and wood products [*45*].

The technique is capable of measuring very high levels of moisture content and has been applied to green woods exhibiting values up to 140% moisture content by weight. While dissolved salts do have an effect, their contribution can be reduced by operating at high frequencies. Temperature has only a minor influence on results.

Drawbacks to this technique are the requirement for mechanical coupling to the specimen, and the requirement that the specimen be wholly contained between receiver and transmitter. Also, other variables such as density, elastic moduli of inclusions (such as aggregates or concrete), cracks, and inhomogeneities in the medium can influence the results. The method, while applicable to homogenous materials under fixed conditions, may be difficult to apply to the wide variety of building materials which must be considered in building envelope systems.

Miscellaneous Techniques

There are a number of techniques that have not been described which may be useful for moisture content measurements. Microwave, infrared (IR), and nuclear magnetic resonance (NMR) techniques can be used under some circumstances to provide a measurement of moisture content. Microwave and NMR techniques have not been extensively studied for this application, and IR techniques have a fundamental limitation to measurement of surface moisture only. Extensive use of NMR techniques for in-situ moisture (and hydrocarbon) determination has been made in the oil exploration industry. The equipment is, however, quite bulky and not well suited to building diagnostic applications.

WATER VAPOR TRANSMISSION TESTS

In the absence of convective transport (air-borne transport), water vapor is transported within the building environment by diffusion, either through still air or through building materials such as paper, plastic films, fiberboard, gypsum, plaster, wood products, and plastic. Water vapor transmission tests attempt to measure this diffusion under carefully controlled experimental conditions. References *46* and *47* provide added detail to the summary information provided in this section.

The mathematical description of diffusion has been exhaustively studied by classical physicists and engineers for several hundred years. The basic idea (which is common to diffusion in both gases and liquids) is that a higher concentration of gas or liquid contained within a dissimilar gas or liquid will always migrate to a region of lower concentration even in the absence of other driving forces such as gas or liquid flow or temperature gradient. This tendency of a higher concentration to move (or diffuse) toward a lower concentration is governed by Fick's law of diffusion.

By considering water vapor as a gaseous concentration that approximates an ideal gas, it is possible to mathematically describe the basic concepts embodied in water vapor transmission tests. The steady state diffusion of water vapor through uniform material from one side (denoted below as Side 1) to a second side (denoted below as Side 2) due to a difference in water vapor concentration is governed by Fick's law of steady state diffusion as follows

$$\frac{dm}{dt} = DA\frac{(C_1 - C_2)}{\Delta x} \tag{1}$$

where

D = diffusion coefficient, m^2/s,
A = area, m^2,
C = mass concentration of water vapor per unit volume, kg/m^3
m = mass flux of water vapor per unit time, kg/s, and
x = material thickness, m.

By approximating the behavior of water vapor using the ideal gas law and assuming small differences between Side 1 and Side 2, a simpler formulation of Fick's law is written

$$\frac{dm}{dt} \approx MA(e_1 - e_2) \tag{2}$$

where

$$M = \frac{D}{R_w T_1 \Delta x} \tag{3}$$

e = vapor pressure of water vapor, Pa,
R_w = gas constant for water vapor, $J/kg \cdot K$, and
T = absolute temperature, K.

Here, M = permeance coefficient $kg/s \cdot m^2 \cdot Pa$.

In words, the water vapor permeance defined by Eq 3 is the time rate of water vapor transmission through a unit area of flat material or construction induced by the unit vapor pressure difference between two specific surfaces under specified temperature and humidity conditions. It turns out that by measurement of water vapor transmission through a particular material, it is possible to calculate the permeance of a material of interest. Note that permeance is a measure of performance and is not an intrinsic property of a given material. Values of the permeance coefficient for many building materials are published in numerous handbooks and manufacturer data sheets such as Ref *48*.

For historical reasons the unit of water vapor permeance, the perm, was defined in terms of inch-pound units. A material allowing 1 grain of water vapor to pass through an exposed area of 1 ft^2 of material in 1 h driven by a vapor pressure difference between the two sides of 1 in. Hg is said to exhibit a water vapor permeance of 1 perm. There is not a similar unit for SI units, although some of the literature speaks of a "metric perm." If permeance data are to be presented in metric units, convention appears to be to provide them as $g/(Pa \cdot s \cdot m^2)$ rather than as metric perms to avoid confusion.

The most widely referenced method for measurement of water vapor transmission of materials is ASTM E 96-92. This test method gravimetrically determines the steady state water-vapor transmission properties of either building or packaging materials. In use, a specimen is sealed to the mouth of a water-vapor impermeable test cup containing either water or a desiccant. This specimen plus test cup is then placed in an atmosphere in which humidity and temperature are controlled. Figure 1 provides an illustration of a test sample cup with a specimen to be measured in place. The test defined by ASTM E 96-92 is an isothermal test; that is, no temperature gradient is allowed between the two sides of the test. The aim of the test is to compare materials with the highest possible precision. It is not reasonable to assume that the water-vapor transmission coefficient determined in the test relates to actual field conditions; neither can it be assumed that a water-vapor transmission coefficient measured by this test will be capable of calculating actual moisture flow rates for conditions different from those employed during the testing. However, the test itself has proven to be useful in a wide variety of other water-vapor transmission considerations. It has been used in research and development work to compare materials and to calibrate dynamic and comparative water-vapor transmission test equipment. It has been used to train laboratory personnel and also for studying changes in material performance such as the effect of aging on membranes [*49*].

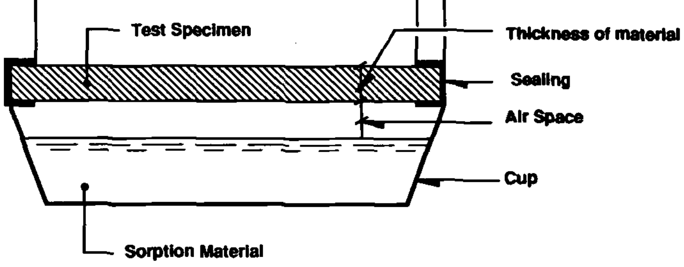

FIG. 1—Test apparatus for wet and dry cup tests.

ASTM E 96-92 is actually comprised of two basic methods known as the desiccant method (dry cup method) and the water method (wet cup method). In the dessicant method the specimen is sealed to the open mouth of the test dish containing a desiccant, and the assembly is then placed in a controlled atmosphere. Periodic weighing will determine the rate of water-vapor movement through the specimen into the desiccant. In the water method the dish contains distilled water. For this case, the weighing determines the rate of vapor movement through the specimen from the water to the controlled atmosphere.

It should be noted that the vapor pressure difference is nominally the same in both methods. The standard allows for testing both with humidity at 50 and 90% relative humidity and describes six "standard test conditions" that are outlined in Table 6 of the standard. Unfortunately, the standard requires a great deal of operator technique, and care must be paid to obtaining proper sealing of the specimen to the test dish, careful weighing of the sealed specimen during testing with a balance of appropriate sensitivity, and maintaining the proper atmosphere for the test. In addition, proper air velocities over the surface of the material must be maintained.

The water method is normally less reliable than the dessicant method, particularly for hygroscopic materials. The water method is sensitive to changes in relative humidity and surface resistance on the high relative humidity side [*50*]. Also, when used with hygroscopic materials, it often generates a water vapor transmission coefficient that includes a substantial contribution from flow in the absorbed or condensed liquid phase. The dessicant method suffers from uncertainties related to actual experimental conditions such as the sealing of the edges, humidity oscillation, airflow, insufficient surface areas, barometric pressure variations, stabilization of vapor flux, and the calculational technique [*51*].

In addition to ASTM E 96-92, three additional standards exist for testing water vapor transmission rates through sheet material. These standards are ASTM F 372-73 (1984), ASTM F 1249-90, and ASTM E 398-83 (1988). In F 372 a dry chamber is separated from a wet chamber of known temperature and humidity by the barrier material to be tested. The time for a given increase in water vapor concentration of the dry chamber is measured by monitoring the differential between two bands in the infrared spectral region, one in which water molecules absorb and the other where they do not. This information is then used to calculate the water vapor movement through a known area of barrier material.

ASTM F 1249-90 is similar to F 372 except that the sensing is performed by means of a modulated infrared sensor. In addition, the standard provides for comparing the electrical signal measured through a test film with that of a signal produced by measurement of a calibration film of known transmission rate. It is possible with knowledge of both of these signals to calculate the rate at which moisture is transmitted through the material being tested.

ASTM E 398 allows for dynamic evaluation of the rate of transfer of water vapor through a vapor retarder material. In this test, the specimen is mounted between two chambers, one of known relative humidity and the other of dry air. After a period of time has elapsed, the response of a humidity sensor in the dry chamber is recorded. Measurement of humidity is accomplished by any of several methods, such as electrical resistance elements, electrical cells, or the infrared technique of the previous standards. This particular test is used primarily to compare different materials at standard conditions, as opposed to predicting their actual performance under field conditions.

All of the above test methods are basically designed to provide water vapor transmission rates under isothermal conditions. However, in most applications in which water vapor transmission is of interest, temperature differences are present in addition to water vapor pressure differences. Presently, only the Swiss Standard SIA279 affords measurement of water vapor transmission under thermal gradient. Thus, for most practical applications, it is difficult to reliably apply vapor transmission rates or permeance values determined with laboratory standards to actual vapor transmission behavior under field conditions.

WATER LEAKAGE THROUGH WALL AND WALL COMPONENTS

Water leakage through wall, windows, and doors has been a major problem in building construction, and for a long time the performance of windows in particular has been a major concern of building owners and managers [*52*]. ASTM published the first test method for windows in 1967. The scope of the method was later expanded to apply to curtain walls and doors. A separate method, based on early work by the National Bureau of Standards (now the National Institute for Standards and Technology) [*53,54*], was promulgated for masonry walls in 1974.

The need for separate methods for curtain walls (primarily metal curtain walls) and for masonry was due to the fact that masonry has, to a certain degree, the ability to absorb and store water harmlessly. Metal curtain walls do not. Therefore, the performance of masonry walls is more dependent on the duration of the water spray than is the case with metal curtain walls.

Because window and wall performance is not only dependent on good design and fabrication practices but also to a large degree on proper installation, laboratory test results are not necessarily representative of the performance of the same unit installed in a building. Therefore, ASTM has established separate methods for conduct in the laboratory and in the field.

All standard test methods for water penetration of walls and wall components are based on the same principle: The specimen is subjected to a water spray, and simultaneously air pressure is applied across the specimen. The various methods differ primarily by the method of applying the air pressure and whether the test is performed at the laboratory or in the field on an installed unit. The air pressure may be static, static cycled, or applied dynamically by creating an airstream. As a general rule, the principle of field tests is the same as that for laboratory tests. Upon cessation of the test period, the location of any water leaks, and in some cases the quantity of water penetrating the innermost face of the specimen, is reported.

E 331-86 is a standard procedure for determining the resistance to water penetration of exterior windows, curtain walls, and doors under a uniform static air pressure difference. Water is sprayed against a specimen for 15 min and any resulting leakage noted and measured. The method has good reproducibility and is therefore used extensively for "proof testing" required in various labeling programs.

E 547-86 is analogous to E 331 with the exception that the specimen is subjected to cycled pressure differences while maintaining the water spray. Each cycle consists of approximately 1 min at zero pressure and 5 to 15 min at the specified test pressure. The method recognizes that in actual service the window, door, or curtain wall is not subjected to only a single cycle. Although the number of cycles is typically low (the method specifies a minimum of two), if the test is conducted over numerous cycles, the results should provide more reliable data than the uniform static test. On the other hand, E 547 is less reproducible than E 331.

E 1105-90 is a method of performing an E 331 or E 547 test under field conditions, i.e., on a specimen (window, curtain wall, or door) installed in a building. The test can also be used to investigate water penetration in joints between assemblies installed on exterior walls. The static air pressure difference is either uniform or cyclic. The method is useful for field quality control during the installation of walls and windows and for evaluation of existing structures.

E 514-90 is a laboratory test for determining the resistance to water penetration and leakage through unit masonry subjected to wind-driven rain. A test is run over a 4-h period during which time the back of the specimen is observed both for the arrival of dampness and the arrival of liquid water.

AAMA Standard 502.1-83 [*55*] describes a test method using one or several airplane engines to develop a wind blast directed against the window or wall with water injected into the airstream. The method is commonly referred to as the "dynamic method." The wind blast serves both to create a pressure differential across the specimen and to accelerate the water droplets. The test closely simulates actual exposure of windows and walls during rainstorms, but the test results are difficult to reproduce. The test is primarily used for curtain wall specimens and for developmental testing. It is generally performed in a laboratory installation, although field tests can also be performed.

In addition to the above methods codified into standards, the so-called"fire hose test" is useful in evaluations of existing buildings. The method simply consists of spraying water from a hose onto the building wall, usually with an air pressure differential from that naturally existing at the building at the time of the test. The test can be applied to large walls or wall segments, even on fairly tall buildings, if sufficient water pressure is used. The test is useful for detecting gross leakage in a building and to identify areas to be tested with ASTM E 1105-90. For houses and small buildings, the method can be used in conjunction with a fan, such as a blower door, to create a partial vacuum inside the entire structure and thus establish an induced specified pressure differential. The test then approaches that described in E 1105-90, except that the water spray is not closely controlled and the test, therefore, has poor reproducibility.

AAMA 501.2-83 [*56*] describes a more controlled test similar to the above for the water leakage performance of existing curtain walls. It prescribes the nozzle and pressure to be used, the specific steps to be followed, and the test periods. In

AAMA 501.3-83 [57], a pressure chamber is added; the basic procedure otherwise is the same as that used in AAMA 501.2.

All of the above test methods provide procedures for conducting the tests. However, they do not provide end-point criteria. These are given in E 1017-88 for residential window assemblies, which provide for ten "grade levels," depending on the design wind load as determined in ASCE 7-88 (formerly ANSI A58.1) [58].

BUILDING AIRFLOW

In moisture investigations, only relatively recently has it been generally recognized that vapor transport by airflow within a building is an important mechanism. In fact, at a recent ASTM Symposium on Water Vapor Transmission [59] the point was forcefully made:

> It was 30 years . . . before it was clearly established and widely accepted that the leakage of air from inside a building through constructions and not vapor diffusion alone was often the principal means by which water vapor moved to cold surfaces. The concept of vapor diffusion was not wrong, but it was not the only way. It is incredible, in retrospect, that it should have taken so long to reach this conclusion, but there were many reasons for this.

In the following sections the basic ideas and instrumentation necessary to understand and carry out measurements of airflow in buildings are presented. The literature of this field is contained in a disparate collection of journals, but is excerpted and summarized quarterly as an annotated bibliography called *Airbase* published by the International Energy Agency's Air Infiltration and Ventilation Centre (AIVC) located in Coventry, England. Any detailed investigation into building airflow measurement techniques or measured data is well served by first perusing several issues of *Airbase*.

Measurement of Building Airflows

Two distinct but complementary methods have been developed to study airflows within buildings. One class of methods uses one or more tracer gases in conjunction with the equations for conservation of mass to study the airflow within a building. A second class of methods relies on measuring the airflow required to induce a positive or negative pressure differential between the building (or room within a building) and the surroundings.

Tracer gases have been used to measure air infiltration and ventilation characteristics of buildings for about 30 years. There are three principal tracer gas techniques for quantifying airflow rates within a structure, namely, the tracer dilution method, the constant injection method, and the constant concentration method. The tracer dilution method is a direct way of measuring the airflow rate extant within a building under ambient flow conditions and forms the basis of ASTM E 741-83 (1990). The constant injection method is an indirect method, i.e., it measures the equilibrium tracer concentration within a ventilated area. This concentration can be related to the airflow rate if the tracer release rate is known. The constant concentration method is also an indirect method. It measures the amount of tracer as a function of time required to maintain a constant concentration within a ventilated zone or zones. The quantity of tracer injected can be related to the airflow rate. These tracer techniques can also be used to measure induced airflow rates in buildings such as those created by a mechanical air-handling system.

The previously described tracer techniques are generally used to investigate flow as it occurs under naturally existing pressure and temperature driving forces. The second technique uses one or more external fans to pressurize (or evacuate) a structure to a much higher pressure differential than that induced by naturally existing conditions and to measure the flow required to accomplish this simultaneously. A plot of induced flow versus differential pressure can then be used to infer various leakage properties of the structure in question. In large mechanically ventilated structures, the building air handling unit(s) have been used as the pressurization fan (or fans) [60]. ASTM E 779-87 describes the measurement procedure.

Tracer Gas Methods for Measuring Building Airflows

To interpret data resulting from tracer gas methods, one employs a mass balance of the tracer gas released within the building. Assuming that the tracer gas mixes thoroughly and instantaneously within the structure, the mass balance equation is

$$\frac{dC(t)}{dt} = F(t) - q(t)C(t) \tag{4}$$

where V is the building volume, $C(t)$ is the tracer gas concentration (dimensionless), $dC(t)/dt$ is the time derivative of concentration, $q(t)$ is the volumetric airflow rate out of the building, $F(t)$ is the volumetric tracer gas injection rate, and t is time. The outdoor tracer gas concentration is assumed to equal zero.

The air exchange or infiltration rate I is given by $I(t) = q(t)/V$ where I is in air changes per hour (h^{-1}).

Concentration Decay Method

The simplest tracer gas technique is the tracer gas decay method [61]. This technique is also the subject of a standardized measurement procedure, ASTM E 741. After an initial tracer injection into the structure, there is no source of tracer gas. Hence $F(t) = 0$, and, assuming I is constant, a solution to Eq 1 is

$$C = C_0 \exp(-It) \tag{5}$$

This method requires only the measurement of relative tracer gas concentrations, as opposed to absolute concentrations, and the analysis required to determine I is straightforward. In use, Eq 2 is often recast to the following form

$$I = 1/t \ln(C_0/C) \tag{6}$$

The essential elements of this test are illustrated in Fig. 2. The measuring equipment can be located within the structure, or building air samples containing tracer may be collected in suitable containers and analyzed off-site [62,63].

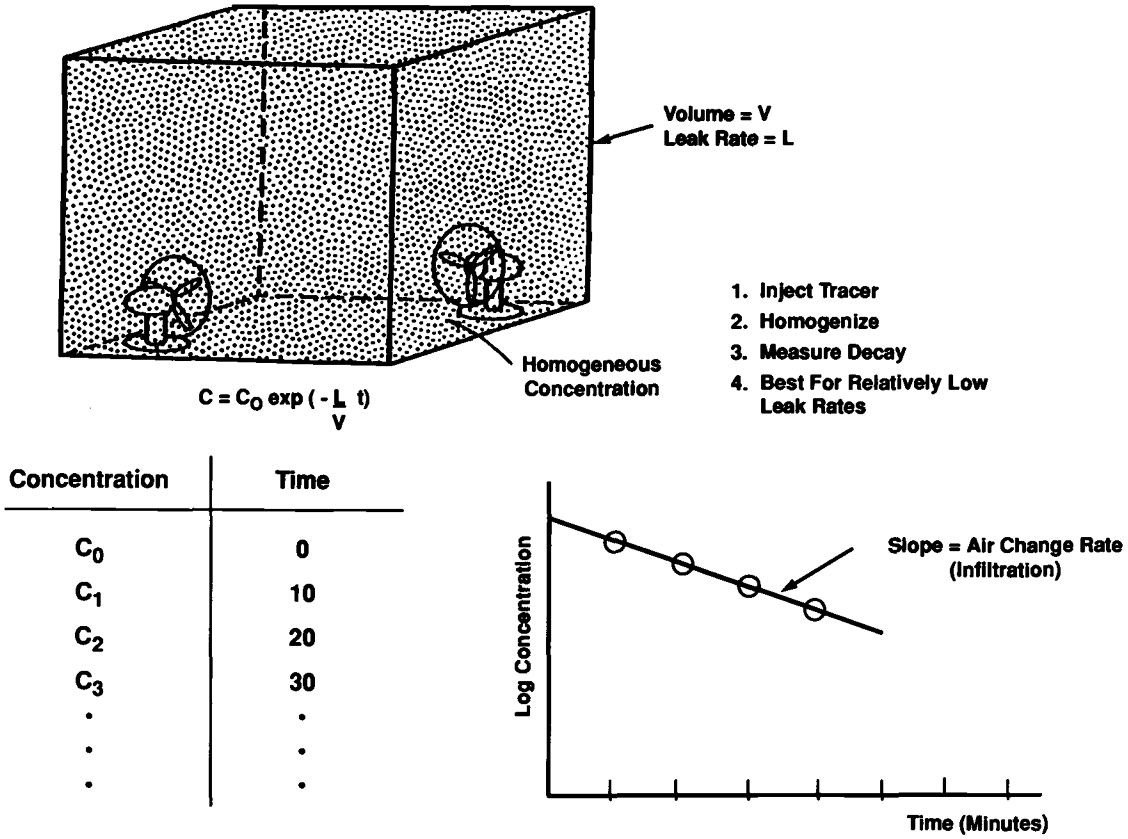

FIG. 2—Essential elements of tracer dilution test.

Constant Concentration Method

The constant concentration technique requires the use of automated instrumentation to simultaneously analyze tracer gas concentration and inject an appropriate quantity of tracer gas in order to maintain a constant concentration within a room or building. For constant concentration, i.e., $dC(t)/dt = 0$, Eq 4 reduces to

$$C(t) = F/q \tag{7}$$

However, since mixing of the tracer gas within a volume takes a finite amount of time, $dC(t)/dt$ is never really equal to zero unless C is constant. Hence, Eq 7 is not an exact mathematical solution, and measurements based on this equation will be subject to errors. An advantage of the constant concentration technique is that it can be used to measure simultaneously the infiltration rates into different zones of a building.

A constant concentration tracer gas system (CCTG) using a single tracer gas, sulfur hexafluoride (SF_6), has been developed by Princeton University [*64*]. The system feeds back estimated infiltration in order to maintain zone concentrations at a preselected target value. The actual CCTG measurement system consists of three modules: (1) an electron capture gas chromatograph which incorporates a back-flushed molecular sieve column to attain rapid throughput; (2) a tracer injection module which uses computer-controlled solenoid valves and calibrated orifices to provide tracer flow in up to ten zones; and, (3) a sampling module in which a microcomputer controls the number of zones sampled or the number of measurements in a zone. The microcomputer also handles the data acquisition requirements.

N_2O has been used as a tracer coupled with a continuous IR analyzer [*65*]. Release of N_2O was controlled by a microcomputer which also sensed the IR response and fed back the value to attempt to hold the N_2O concentration constant.

Constant Injection Method

The third tracer gas technique is referred to as the constant injection technique in which $F(t)$ = constant. If I is also assumed to be constant, a solution to Eq 1 is

$$C(t) = (F/q) + (C_0 - F/q)\exp(-It) \tag{8}$$

After the transient dies out, one obtains the simple constant injection equation, $C = F/q$.

This relation is valid only for cases in which the infiltration rate is constant for a sufficiently long time; thus, the results obtained with this technique are exact only when the system is in equilibrium. Otherwise, the results will be subject to errors, with the magnitude of these errors depending on the extent of the departure from equilibrium. The use of this technique is illustrated schematically in Fig. 3.

Tracer Gas Measurement Techniques

Instrumental techniques used to measure tracer gas concentration are listed in Table 4, along with some of the gases appropriate to each instrument. All of the gases listed have

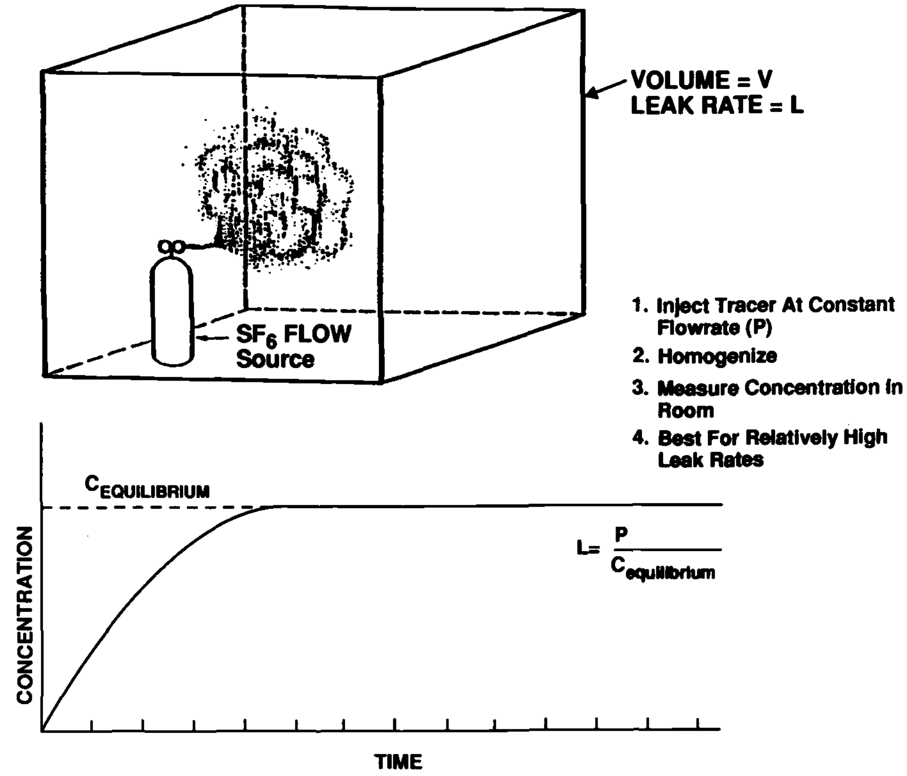

FIG. 3—Essential elements of constant flow injection test.

been used for airflow measurements within buildings or individual rooms. Note that most of the instrumental techniques are based on gas chromatography. In its simplest form a gas chromatograph comprises: (1) a chromatographic column which consists of a tube of material which separates the components of a gaseous mixture into a distinct spatial and temporal order by means of surface interaction forces; and (2) some means to detect the various gases as they exit the column.

Tracer gases measured with electron capture detector gas chromatography are commonly used for measurements in large buildings [*66*] primarily due to cost considerations. However, measurements have been performed in large buildings using infrared absorption [*67,68*] and flame ionization detector gas chromatography [*69*].

Measurement Fundamentals

Referring to Table 4, the thermal conductivity detector was among the first detector types used to perform airflow rate measurements in buildings [*70*]. The detector operates by sensing the change in temperature of a heated element as gases with different thermal conductivity pass over it. The change in temperature changes the resistance of the heated element, which can be sensed in a bridge circuit. Addition of a chromatographic column enhanced the specificity somewhat, although the lower limit of detection remained at 0.001 (volume/volume).

TABLE 4—Tracer gas measurement devices.

Technique	Gases
Thermal conductivity detector	H_2, He, CO_2
Electron capture gas chromatograph	SF_6, refrigerants, perfluorocarbons
Flame ionization gas chromatograph	C_2H_6
Infrared absorption continuous analyzer	CO, CO_2, SF_6, N_2O, C_2H_6, CH_4
Residual gas analyzer (mass spectrometer)	He, Ar, SF_6, Ne, refrigerants

The electron capture detector in conjunction with a chromatographic column exhibits extraordinary sensitivity to halogenated compounds [*71*]. The sensitivity approaches one part in 10^{12} for SF_6. It does not, however, respond to all gases which pass through it. Electron capture detection entails the use of a radioactive source (often tritium or nickel), which ionizes a stream of gas passing over it. Electrons so generated are sensed by appropriate circuitry. When a chemical specie which has a high affinity for electrons (e.g., halocarbons, perfluorocarbons, sulfur hexafluoride) enters the detector, the number of electrons collected within the detector decreases proportionately. This decrease is sensed by the detector's electronic circuitry and results in an appropriate signal.

A flame ionization detector utilizes a hydrogen flame as an ionization source. By itself, a hydrogen flame (in air) produces relatively few ions. If an organic compound is introduced into the flame, a relatively large increase in ion production occurs. This ion current can be sensed with appropriate electronics. The flame ionization detector (FID) exhibits a response to a wide variety of compounds and is often referred to as a universal detector. The detector exhibits a sensitivity approaching one part in 10^{10} for many compounds. The need for an open hydrogen flame, however, usually limits its utility to laboratory-type situations.

Infrared (IR) absorption detectors operate by sensing the IR absorption peaks as a gas passes through an optical cell. For those gases which exhibit appropriate IR absorption bands, the detector can be used as a continuous monitor down to concentrations approaching one part in 10^5. As a chromatographic detector, the lower limit of detection can approach one part in 10^8.

Multiple Tracer Techniques

In some cases, a single zone is not adequate to understand a building's airflow characteristics. In other cases, one is interested in the airflow between the various zones of a building. In these cases, multi-chamber building models and either a constant concentration multizone technique or a multiple tracer gas measurement technique is used. Multiple tracer measurements often involve the use of gas chromatographs designed to determine simultaneously the concentration of the different gases [*72*]; however, separate continuous infrared analyzers have also been successfully used for simultaneous analysis of SF_6, CO_2, and N_2O [*73*].

Multiple tracer gas measuring systems have been developed using both decay and constant injection techniques. In decay measurements, a tracer or several tracers are released at various locations as pulses, and their concentrations are monitored in the various zones over time. Several measurement systems employing the decay method have been developed [*74–76*]. Both systems employ gas chromatographs equipped with electron capture detectors to measure either refrigerants or perfluorocarbon tracers.

A multiple tracer measurement system (MTMS) which injects a unique tracer gas into each zone has been developed by Lawrence Berkeley Laboratory [*77*]. One continuous flow injection tube and one continuous sample tube are required for each zone. Air sampled from each zone is sequentially introduced into a residual gas analyzer (i.e., a quadruple mass spectrometer), which measures the intensity of selected peaks that uniquely identify and quantify the concentration of all the tracers in each zone. At present a number of tracer gases (He, SF_6, several halocarbons, Ne) have been used successfully. In order to keep concentrations within acceptable limits, MTMS attempts to keep the concentration of each gas at a constant value in the zone in which it is injected. Since (in contrast to the CCTG system) the analysis is not dependent on holding constant concentration, the control is optimized for stability rather than fast response.

Techniques encompassing the release and measurement of multiple perfluorocarbon tracers (PFTs) have been developed by Brookhaven National Laboratory [*78*]. The PFTs are emitted at a steady rate by miniature permeation sources, with a different PFT being emitted into each well-mixed zone of the building. Three methods are currently available for measuring the PFT concentrations in the building zones: (1) passive adsorbent tubes known as CATS (capillary adsorption tube sampler); (2) BATS (Brookhaven atmospheric tracer sampler), a programmable, pumped device which automates the collection of air onto adsorbent tubes; and (3) a real-time instrument which both collects and analyzes sampled air for PFTs with a resolution of about 5 min. Samples collected using either CATS or BATS are returned to the laboratory where they are analyzed using gas chromatographic separation and electron capture detection. This need for remote analysis represents a major drawback to the conduct of airflow pattern experiments when more immediate data are often desirable.

TABLE 5—Cost and experience level for various measurement techniques.

Technique	Cost, Dollars	Experience Level
IR absorption, continuous	6K	Low
Thermal conductivity GC Electron capture GC IR absorption GC Flame ionization detector GC	4 to 10K	Moderate
Constant concentration (Princeton)	20K	High
Multi-tracer Residual gas analyzer (LBL)	40K	High
Multi-tracer, multi-channel Electron capture chromatograph	25K	High
PFT tracer	200 to 600 Samplers	Low
	25 to 50K Analyzers	High[a]

[a] Analysis done off site in analytical laboratory.

Most of the measurement schemes depend in the final analysis on a chromatographic technique. The measurement systems can be expensive, and they require a fair amount of experimental expertise. Representative costs and degree of experimental difficulty are provided in Table 5.

Fan Pressurization Airflow Measurements

In general, two types of fan pressurization devices have been used, the RPM blower door and the orifice or nozzle blower door. Each consists of a variable speed fan affixed to a frame that can be mounted in the door of a structure to be tested (hence the name "blower door"). In the RPM type, flow is inferred from the RPM of the fan motor. Thus the blower exhibits a different calibration curve for each pressure attained within the structure. RPM blower doors do not yield a direct measure of induced flow. RPM blower doors were the first pressurization devices commonly used for induced pressurization measurements. For the most part, they have been replaced by the orifice or nozzle blower door. In this type of device, flow is inferred by measuring the pressure drop induced across a large nozzle or orifice by the fan. These devices are usually calibrated to read induced flow rate directly. Figure 4*a* depicts a generic experimental configuration for the performance of a fan pressurization test, while Fig. 4*b* provides a schematic drawing of a typical blower door apparatus.

In practice, one measures a series of flow (Q) versus differential pressure (dP) points for a structure of interest. The resulting data are fitted to an equation of the form

$$Q = C(dP)^n \tag{9}$$

where

Q = flow rate,
dP = differential pressure,
C = leakage coefficient, and
n = leakage exponent.

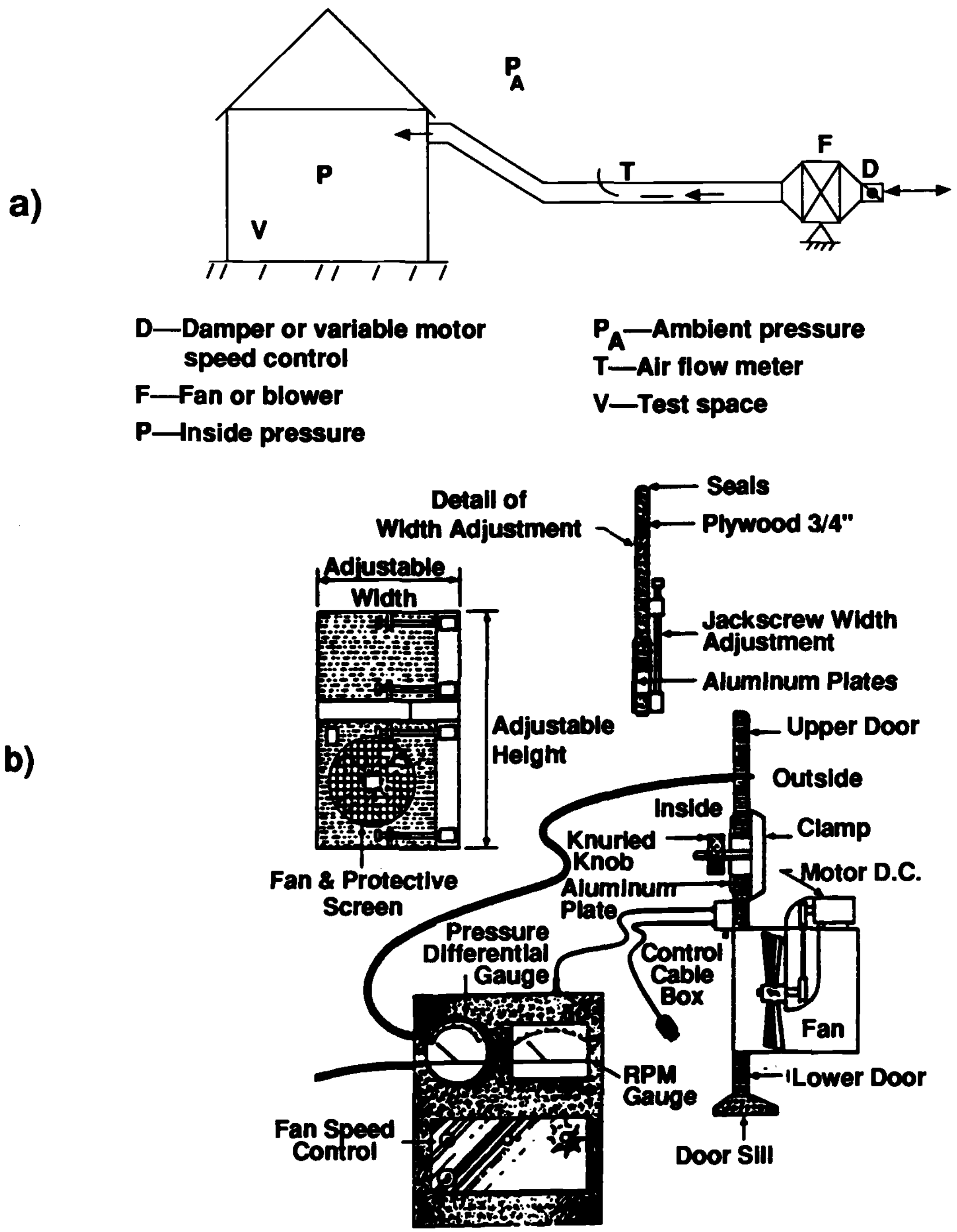

FIG. 4—(a) Generic pressurization test; (b) fan door pressurization device.

C and *n* are obtained from the least squares fitting of the flow versus pressure data. With a knowledge of *C* and *n*, one can calculate the effective leakage area, *L*, of the structure

$$L = C(dPr)^{(n-1/2)}\left(\frac{S}{2}\right)^{1/2} \tag{10}$$

where

S = indoor air density, and
dPr = differential pressure at reference pressure, often taken as 4 Pa.

Often two values of *L*, one for pressurization and one for evacuation, are averaged to obtain a representative value of *L*. For a limited class of structures (single story, detached dwellings) the resulting value of *L* can be combined with a calculational model to arrive at an estimate of the natural infiltration rate of the structure in question [79].

The fan pressurization technique can be used in larger buildings where it is not possible or practical to use an external pressurization fan if the building possesses a suitable air-handling system. If the system possesses sufficient capacity, all supply fans are operated while all return and vent fans are turned off. All return dampers are closed so that air may only escape through doors, windows, and other leakage sites in the building envelope [*80*].

A fan pressurization device can also be used to evaluate the leakage of individual building components. In its simplest form, this can be done by enclosing a volume over the interior face of the building component to be tested. ASTM E 783 provides guidance for performing such tests. Air is supplied to or exhausted from the volume at a specified static pressure, and the flow required to maintain this pressure is measured. Figure 5 illustrates the basic experimental setup. Data analysis is similar to that for leakage area of an entire structure. This test can be made more accurate if the pressure in the room containing the component is balanced to that in the measurement chamber. This balancing is often performed using an auxiliary fan located in the room.

Building-component air-leakage measurements can be performed under laboratory conditions. A test chamber is used into which various specimens are fitted. The airflow and pressure difference can be accurately determined under laboratory conditions. This type of test has the advantage that large numbers of samples can be examined under similar conditions, and the effects of climatic factors are eliminated. ASTM E 783 provides guidance for performing such tests. It should be pointed out that laboratory-based measurements may produce significantly different results from on-site evaluations due to differences in workmanship and installation technique.

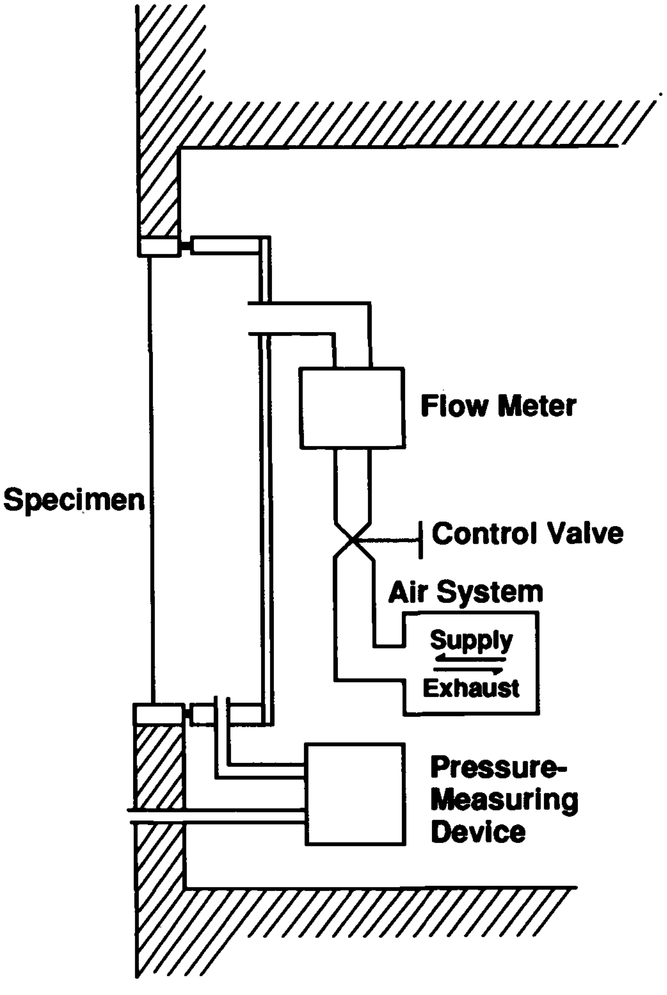

FIG. 5—Apparatus and setup for component leakage test.

The air leakage through the entire surface of exterior or interior walls can be evaluated by a multi-fan technique. This technique is particularly appropriate for large, multi-celled buildings such as multi-apartment dwellings [*81*]. A single apartment will have a number of exterior and interior walls. If a normal fan-pressurization test is performed, the measured leakage will include the leakage through several internal walls as well as any exterior walls.

If, however, the pressure in the adjoining zones is balanced with that in the main test zone so that there is a zero pressure difference across interior walls, then no air leakage will occur through internal flow paths, and only the leakage through exterior walls will be measured. In order to achieve this pressure balance, each surrounding zone must be pressurized along with the main one. Thus, more than one set of fan pressurization equipment is required. The technique works particularly well in row-type housing.

Qualitative Leak Location

Often only the location rather than the magnitude of a leak needs to be uncovered. There are a number of measurement techniques which provide qualitative information about air leakage paths in buildings. Many of these are described in detail in ASTM E 1186.

The most sophisticated of these methods is infrared thermography. In this technique thermal radiation (which depends on surface temperature) is converted by a thermographic camera to a visible image. In order to detect leakage paths, a building can be pressurized or depressurized (evacuated). Tests are usually performed when there is a decided temperature difference between inside and outside. When depressurizing, the ingress of cold exterior air cools the surface adjacent to cracks and leakage paths. These colder areas are detectable with the thermographic camera. Conversely, pressurizing causes a flow of warm interior air to flow through the leakage paths to the exterior where it again creates a temperature difference which can be seen with the thermographic camera.

Thermal imaging equipment is expensive and requires a high level of expertise to use effectively. The major difficulty lies in being able to discriminate between air leakage paths and other anomalies such as thermal bridges.

Smoke tests offer a cheaper and easier alternative for leak detection. Smoke can be produced in several ways, the most convenient being a hand-held puffer and smoke stick such as commonly used for mine ventilation surveys. The technique simply involves pressurizing a building and using a smoke source to trace the paths followed by leaking air. For those cases where the smoke cannot be easily seen, it is possible to use a tracer gas as a source and to sample the exterior for high concentration of gas. These high concentrations imply that gas is leaking from inside to outside via a path located nearby.

Sound waves pass readily through many of the same openings in the building envelope that allow airflows. Acoustic detection of leakage paths is therefore possible. A steady high-pitched sound source is placed within the building, and leaks are listened for on the exterior surface. A small microphone or stethoscope is used. Leakage paths correspond to an increase in the intensity of transmitted sound.

Airflow Pattern and Diffusion Measurements Using Tracer Techniques

As mentioned previously, in addition to diffusion, water vapor can be transported by airflows within a building in a manner analogous to the transport of gases such as CO_2, NO_x, and other contaminant gases. Transport of contaminant gases has been studied by means of tracer gas techniques. These measurements provide quantitative and qualitative information on the transport of contaminant gases within a building environment. For example, a multiple tracer release test within an industrial facility was performed using four distinct tracer gases simultaneously [*82*]. The resulting flow patterns from source locations are illustrated in Fig. 6. Source locations in this figure are denoted by circled S marks. The test consisted of a series of constant injection tracer releases at the source locations coupled with air sampling in the surrounding areas at locations designated by circled X marks. The migration of tracer from each source location was measured as a function of time. The solid arrows indicate the anticipated flow paths, while the dashed arrows indicate the actual flow paths. The resulting data provided qualitative flow data (in the form of migration pattern information) and quantitative data (in the form of transit times that allow estimates of convective diffusion coefficients to be made as well as dilution ratios between source and measurement locations) on contaminant transport. While this series of tests was performed to document contaminant spread, the test applies equally well to water vapor transport so long as adsorption and condensation phenomena are not considered likely or significant.

More recently studies involving the contemporaneous measurement of a single tracer as well as water vapor have been reported [*83*]. In addition to providing information about water vapor transport direction, the comparison of the

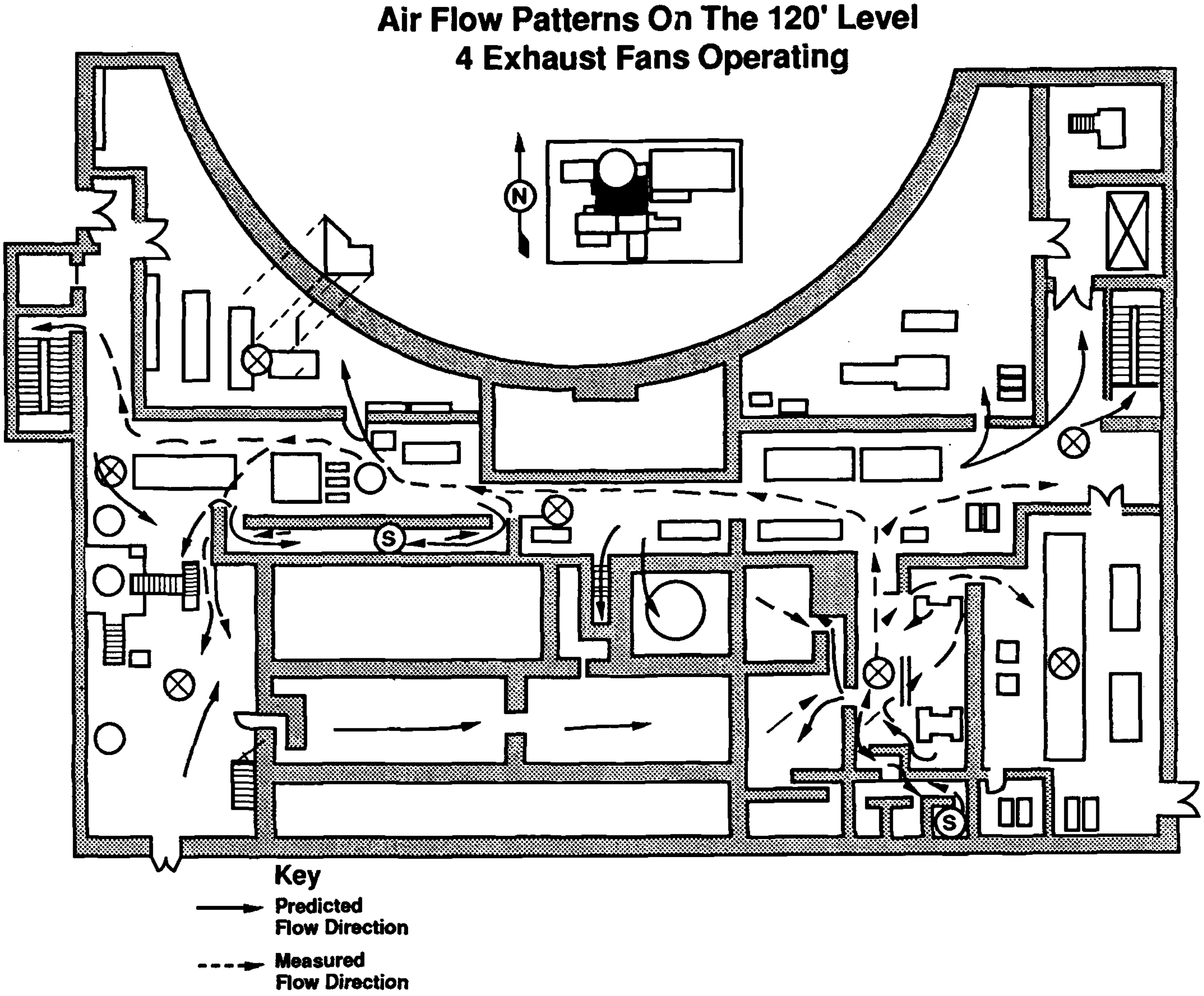

FIG. 6—Flow pattern test.

two measurements allowed inferences to be drawn regarding the amount of moisture adsorbed by surfaces and the effect of surface condensation.

In addition to determining moisture migration/airflow patterns, one can use tracer techniques to investigate moisture diffusion within wall cavities in a building. Any tracer can be used so long as absorption/condensation phenomenon are not considered likely or significant [*84*]. In the following example, the tracer gas sulfur hexafluoride (SF_6) will be used.

From kinetic theory it is known that the molecular diffusion coefficient D is inversely related to the square root of a molecular mass and that the characteristic diffusion time τ is inversely related to the diffusion coefficient. Thus for SF_6

$$\frac{D_{SF_6}}{D_{H_2O}} = \sqrt{\frac{M_{H_2O}}{M_{SF_6}}} \tag{11}$$

since

$$\frac{\tau_{SF_6}}{\tau_{H_2O}} = \frac{D_{H_2O}}{D_{SF_6}} \tag{12}$$

$$\tau_{H_2O} = 0.35\tau_{SF_6} \tag{13}$$

Thus kinetic theory allows direct calculation of diffusion times for water vapor from the measured diffusion time for SF_6. In theory, then, water vapor diffusion times within wall cavities can be easily inferred from the diffusion times measured for an easily measured tracer. Experimentally, injection of known quantities of tracer and measurement of resulting diffusion times is simpler than performing this same test using water vapor.

One *caveat* in the use of this technique is that the tracer must be introduced with no net velocity. This could most easily be accomplished by means of a diffusion source such as those that are commercially available for calibration of leak detection or chromatographic systems.

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13

Troubleshooting

by Heinz R. Trechsel[1]

In the minds of some, troubleshooting in buildings, particularly with regard to moisture problems, conjures visions of investigators poking with flashlights in dark corners or dangling from ropes on a building wall hundreds of feet above the street. While troubleshooting may include the above secretive or heroic modes of operation, more frequently and more typically troubleshooting involves the preparation of test protocols, performance of diagnostic tests, and the careful evaluation of test results. Troubleshooting building problems is much like the work of the detective who tries to solve a crime or the doctor who attempts to diagnose and cure a patient's illness. The term *building diagnostics* has come into frequent use and certainly can be applied to moisture investigations. The term *building diagnostics* here refers to the use of tests providing measurable results for determining the performance of buildings and their components. Although standard test methods are usually applied, it can include the development of tests for a specific case, as standard methods do not exist for all the tests an investigator may wish or need to undertake. In some instances, the evaluation of test results is straightforward, consisting of a comparison with some standard or code value; in others, it includes an element of the investigator's experience in similar cases. However, moisture investigations include more than the conduct of tests and measurements. They include the gathering of physical evidence, surveys of damage, and occupant surveys. Finally, the approach of the investigator and the determination of what tests to perform, at what time, and under what circumstances are still largely an art, and no two investigators are likely to follow the same protocol in the same case. As standardized test methods become more abundant, as they are applied with greater frequency, and as the community of investigators becomes more aware of each others' work, moisture investigations also will become more standardized as generally accepted protocols are adopted.

Chapter 12 discussed various techniques and methods for measuring moisture content and for moisture-related tests in buildings and for building components, products, and materials. It is the intent of this chapter to provide guidance on how and when to apply the testing and measurement methods to identify causes and mechanisms of moisture problems and to determine the most effective remedial actions.

Moisture problems are of many kinds; conditions and causes are various, and remedial actions depend on constructions, climate, occupancy, and other factors. At the present time, it is not possible to provide a detailed, specific standard method or guide on how to identify causes and determine effective remedial actions. It is, however, possible to give broad suggested concepts and approaches for such identifications and determinations.

IDENTIFICATION OF MOISTURE SOURCES

Before any attempt can be made to determine remedial actions, the source or sources of the moisture causing a problem must be identified. There are three basic forms of moisture sources: solid, liquid, and vapor. Solid water in the form of ice dams can be a cause of moisture problems during the winter and early spring in cold climates. However, this should be readily identifiable and is not discussed further here. Liquid water sources in buildings are mainly rainwater, groundwater, and sometimes leaking or burst pipes. Water vapor in cold climates is generated mostly by occupants or processes inside the building. In warm climates, water vapor can result from warm, humid air infiltrating into an air-conditioned building. A special case of condensation can occur if the drain pans from air conditioners overflow. This water may then leak into the wall construction, saturate cavities, and cause infiltrating air to reach dew points far above that of the exterior air. Vapor can also result from evaporation of groundwater, construction moisture, and rainwater leaked into wall cavities. A special case is "rising damp," in which moisture in liquid form moves up in walls through capillary action.

While the classification of water sources into liquid water and water vapor is useful, in actual buildings the two types are often interrelated. Liquid rainwater may leak into the building or building components and then evaporate, only to condense again at some later time and in a possibly quite remote location. Conversely, water vapor can condense, move as liquid water, and reappear in a different location, appearing to be rainwater. Construction moisture can fall into both categories. Although the origin of the moisture is generally liquid water, it sometimes manifests only as elevated humidity in the air and condenses on cold surfaces at or near air conditioning units or within exterior walls. Construction moisture includes moisture resulting from curing concrete or other construction activities. Construction materials are usually dry when delivered to a construction site, but if stored on site during rainstorms, they can become saturated with moisture.

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If such materials are subsequently installed in the building, they can add a considerable volume of moisture to "construction moisture" unless fully dried prior to installation. This applies particularly to wood and gypsum products. It would seem a prudent practice not to install any gypsum products that have been exposed to rainwater.

To determine if the moisture source is liquid water or water vapor, a visual inspection will sometimes suffice. For example, moisture in the form of liquid water may be seen to flow or drip in a conspicuous location during a rainstorm, and only during rain. But caution is indicated. The source of the leak can be removed far from the observed location of water.

More frequently, the issue is not simple or clear-cut. As indicated above, liquid moisture may be observed, but the source could be either a rain leak, condensation of humid air, a leaking water pipe, groundwater in crawl spaces or basements, or moisture from a combination of several of the above. Conversely, no liquid moisture may be observed, but mold and mildew may indicate the presence of either condensation or liquid water. The source of the moisture may also be a combination of liquid and vapor.

Except in the most simple cases, the identification of the source(s) of moisture requires the application of the investigator's knowledge of some or all areas in moisture control in buildings, from the fundamentals in moisture transport and condensation through related properties of building materials to effective measuring and testing techniques. The various chapters of this manual cover all of these areas.

One promising approach to determine whether the source of water in a wall or partition cavity results from a water leak (likely rainwater) is to monitor the temperature and relative humidity within the cavity and adjoining indoor and the outdoor air. A more detailed description of this approach is given below.

Note that these mechanisms (primary rainwater leaks which manifest themselves as condensation) apply not only to exterior walls, but can also involve interior partitions possibly quite removed from any possible leak if the exterior wall cavity is connected to an adjoining partition cavity. To identify the location of such leaks, it may be necessary to use tracer gas measurements, smoke candles, or sticks to determine airflow from the suspected water leakage site to the location of the observed moisture or mildew. (Care should be taken in the use of smoke candles, as they can set off fire alarms. In one instance, the author had the building engineer disconnect the smoke alarm system in the building to prevent the smoke from the candles from setting off the alarm, but the alarm mechanism to the local firehouse was not disconnected. Great was the surprise when, in the middle of the investigation, the entire city fire department with several trucks pulled up at the entrance to the building with sirens howling and lights flashing! Of course, small smoke "sticks" or "pencils" do not normally generate sufficient smoke to trigger smoke alarms, but caution is justified.)

Using techniques as indicated above leads to a combined analytical/experimental approach that, given sufficient time and resources, can determine all but the most unusual moisture sources in any given building. Unfortunately, neither time nor resources are ever unlimited. Thus, it is necessary to rely on the investigator's judgment as to which, how many, and when tests should be performed. Sometimes the most efficient and expedient approach is to conduct a minimum of tests and site investigations, develop and install the most promising remedial measures in a limited area, and observe and monitor their effect over a period of time. In other cases, an extensive diagnostic program must be conducted before any recommendations can be made. Such a program may need to cover a full seasonal cycle or only one or two seasons.

Rain Leaks

Except in dry climates, rain leaks should always be considered a likely water source in any building moisture problem. Common leak locations are in roofs and at roof penetrations; at flashings of all kinds and locations; window sash, doors, frames, and surrounds; balconies, railing anchors, and the joints between floors and adjoining walls; penetrations of ducts, pipes, and equipment through walls, such as through-the-wall HVAC equipment; and at joints of all kinds in the building envelope. Visually insignificant small cracks or openings can admit copious amounts of water during prolonged rainfalls. Hairline cracks in masonry walls or paint, staples or nails in building paper, and insufficient overlap of siding are possible leakage sites that can be difficult to detect, even at close proximity, and are therefore frequently overlooked.

In high-rise and commercial buildings, improper, degraded, or even complete absence of caulking in wall joints can be significant contributors to rain leaks. These defects are particularly critical in wall constructions without a cavity drainage system and a secondary seal. A careful survey of the exterior of the building envelope can generally identify probable leakage sites (in high-rise buildings, such surveys may require grappling skills and dangling from ropes high above the sidewalk![2]), but testing is required to verify leakage paths and severity. Visual observation on the inside of the building or building elements during heavy rains is helpful in pinpointing the rain leak and for establishing locations and areas for verification tests. (This is where the flashlight in dark corners comes in handy!)

The source of some rainwater leaks is obvious; others are difficult to trace. Some moisture problems from rainwater leaks appear in the immediate vicinity of the leak. Other rainwater leaks may not manifest themselves at or even near the location of the actual leak, but can appear significant distances, and several floors, from the leak's location. Even moisture problems on interior walls or ceilings far from the exterior may be caused by primary rainwater leaks.

Apparent condensation can originate from a rainwater leak saturating a wall cavity, causing the relative humidity of the cavity air to be higher than that of either the exterior or interior air. This moist air can then migrate to a colder area where the observed condensation occurs.

Water spray tests can be used effectively to detect rain leaks in suspected locations, but it is quite impractical to use water spray over the entire surface of the building. ASTM E 1105 method[3] for field tests for water leakage prescribes the use of

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[2] In practice, work from a scaffold or from a movable stage is more realistic. All equipment must, of course, meet OSHA standards for safety.

[3] Test Method for Field Determination of Water Penetration of Installed Exterior Windows, Curtain Walls, and Doors by Uniform of Cyclic Static Air Pressure Difference.

a pressure or evacuation chamber over the test location and the method for applying the water spray. A chamber is easy to install over individual window openings, but more difficult at wall areas without openings. In some cases, such as houses or small buildings, it may be easier to use the entire building interior as the chamber by using a blower door or similar device to create a partial vacuum inside the structure. Similarly, in larger buildings it may be possible to use an individual room, apartment, or floor as a depressurization chamber. A calibrated spray rack can then easily be moved to many locations on the outside of the building to provide a controlled water spray.

Significant rainwater leaks can be detected by the application of a water spray without a pressure difference. When uncontrolled water is sprayed against a wall without a pressure difference, the test is sometimes irreverently referred to as "fire hose test" (although normally conducted with a garden hose). While crude, such tests can be useful in cases of extremely leaking buildings or as a first step in an investigation. One advantage: It can cover a large area with little cost.

One promising approach to determine whether the source of water in a wall or partition cavity results from a water leak (likely rainwater) is to monitor the temperature and relative humidity within the cavity and adjoining indoor and the outdoor air. The measurement or monitoring can be accomplished by inserting sensors through small holes in the cavity. The holes, of course, need to be sealed after the tests. If the dew point of the air within the cavity is consistently during all or most seasons above the dry bulb temperature of both the indoor and outdoor air, the moisture in the cavity must result from a consistent liquid water supply, e.g., most likely a rainwater leak. The converse is not true, however. Liquid water could still be the only or contributing source, regardless of temperatures measured.

These mechanisms (primary rainwater leaks which manifest themselves as condensation) apply not only to exterior walls, but, as mentioned above, can also involve interior partitions possibly quite removed from any possible leak if there are air passages between the interior partition cavity and an adjoining exterior wall cavity near a significant rain leak. To identify the location of such leaks, it may be necessary to use tracer gas measurements or, more crudely, smoke candles or sticks to determine airflow from the suspected water leakage site to the location of the observed moisture or mildew. Air pressure measurements also can be used effectively to infer air movements. Because metal studs routinely include cutouts for electrical wiring, air passages between interior partition cavities and exterior wall cavities are more likely in metal wall constructions.

Rainwater can also be the cause for wet basements and crawl spaces when directed into basements and crawl spaces. Downspouts frequently drain directly at the crawl space wall, and splash blocks are sometimes missing or installed incorrectly. Also, improper grading in the vicinity of the building can contribute to rainwater leaks into basements and crawl spaces.

Condensation of Humid Air on Colder Surfaces

In cold climates, warm, humid indoor air can cause moisture problems in walls and roofs. This occurs when warm, humid indoor air infiltrates wall cavities and condenses on the colder exterior materials of the wall or roof. Moisture can also move by diffusion through building materials and condense in like manner on cold exterior surfaces. While it is generally agreed that mass transport of warm humid air is more likely to cause condensation in exterior walls or roofs [*1*,*2*], the potential contribution of diffusion should not be discounted. A combination of mass transfer and diffusion frequently takes place. For example, warm, humid indoor air infiltrating a wall cavity at interior openings such as electrical outlets or other utility penetrations can significantly increase the relative humidity within the wall cavity. Once inside the wall cavity, moisture can then move by diffusion through exterior building materials. If the exterior or some layer of the exterior wall construction is relatively vapor impermeable and at a temperature below the dew point of the cavity air, condensation will occur. Chapter 11 on Design Tools provides calculation methods by which the potential for condensation in exterior walls can be determined.

In warm and humid climates, such as along the coast of the Gulf of Mexico and in southern Florida, the moisture in ventilation or infiltration air can condense on cold surfaces, such as on interior walls, interstitial surfaces, ceilings, or room contents in air-conditioned buildings, or on cold basement and crawl space walls if surface or interstitial surface temperatures are below the dew point of the outdoor air. As a rule, in air-conditioned buildings, indoor wall surfaces are near and slightly warmer than the indoor room temperature, but localized surface temperatures may be lower than the room temperature when impinged directly by cold air from the air conditioning diffusers. Infrequent or only short-term temporary low surface temperature or high outdoor dew points, while causing condensation, are not likely to result in major damage, but if the conditions persist over prolonged periods, they will lead to mold growth. (See Chapter 6 on Moisture, Organisms, and Health Effects for a discussion on the conditions necessary to support mold growth.) Generally, conditions averaged over weeks or months should be used when investigating the potential for condensation due to infiltrating humid air. For outdoor air, monthly data from the weather service are thus more appropriate than a few individual measurements taken on site. See Chapter 7 on climate for available data.

The air in wall cavities can have a higher dew point than that of the outdoor air if rainwater infiltrates, accumulates, and evaporates in the cavities. Such air moving from the cavity to the building interior can have a dew point higher than that of the outdoor air and can condense when it comes in contact with cooled indoor surfaces even when the dew point of the outdoor air is below the temperature of any indoor or interstitial surfaces. The primary cause of the resulting condensation is the rainwater leak, and stopping the water leak is the proper corrective measure. A similar case is where drip pans of air conditioning equipment overflow or leak and saturate wall cavities.

In both warm and cold climates, the potential for condensation is directly related to the relative humidity of the air and the temperature of surfaces in contact with that air. Accordingly, the measurement of both will indicate whether condensation can or did occur. However, relative humidity and temperatures fluctuate with location and time. Thus, if on the day and at the time of a single measurement the conditions are such that condensation can occur, it does not necessarily follow that condensation did in fact occur to a degree sufficient to cause damage unless that condition was either frequently occurring or lasted more than a short period. Conversely, if the conditions measured indicate that condensation is not possible, it does not follow that under a different set of circumstances, such as weather, season, or different operating procedures, condensation could not occur. For this reason, the discussion below on location, frequency, and time of tests is most important in the context of condensation.

The effect of air conditioning systems on the potential for moisture damage is discussed in Chapter 10. Equipment with excessive capacity, having insufficient dehumidification capacity, and excessive intake of humid fresh air (or supply of unconditioned humid fresh air) both cause or contribute to excessive indoor air relative humidity, mildew, and resulting deterioration.

Moisture from Occupancy

Chapter 8 discusses the moisture generated by occupants and by the normal operation of the building. To avoid excessive buildup, all such moisture must either be stored harmlessly in building materials or furnishings, vented to the outdoors, or removed by mechanical dehumidification. For effective means of removing interior-generated moisture, refer to Chapter 10 on Heating and Cooling Equipment, and to the relevant chapters in Part 3 on Construction Principles and Recommendations. Moisture from breathing during sleep, slowly but steadily released over periods of several hours, can contribute significantly to indoor moisture and may be responsible for much mold and mildew in bedrooms [3].

Excessive interior-generated moisture manifests itself primarily through condensation on cold surfaces. In cold climates, condensation will form first on window panes and window frames, and condensation on window glass, readily observable by eye, is an indicator of high indoor humidity. As a general rule, condensation on double-glazed windows indicates excessive indoor moisture. Secondarily, excessive moisture manifests itself through the growth of mold and mildew in corners and other areas of outside walls with reduced air circulation, for example, behind furniture and drapes.

Occupants can cause moisture problems by excessive bathing, cooking, keeping of house plants and aquariums, and by lack of regular ventilation by opening windows and operating bathroom and kitchen fans. Careful management of indoor moisture can control or eliminate many moisture problems. However, the purpose of a building is precisely to provide shelter to perform such activities as bathing, cooking, breathing, etc. Therefore, a well-designed building allows great leeway to the uses of the occupant and should be designed and built to accommodate normal moisture sources without undue restrictions on the activities of occupants. Requiring careful moisture management by the occupant is no substitute or excuse for inadequate moisture-resistant design. In residential construction, this applies particularly to small and relatively inexpensive structures which are frequently occupied by large families. Such buildings should be designed to tolerate the possibility of large internal moisture loads.

Moisture from Wet Basements and Crawl Spaces

Moisture in basements and crawl spaces is already within the structure. If it remains within the ground contact spaces, it might not be of major concern. However, neither basements nor crawl spaces are generally effectively sealed from the spaces above, and the stack effect in most cases draws moist air from the lower levels up into the habitable spaces through cutouts in floors at utility penetrations, through access doors and stairs, and through cracks in the floor/wall joints.

Moisture from basements and crawl spaces manifests like occupant-generated moisture as condensation, frequently some distance from the crawl space or basement. It may be difficult to identify the cause of the condensation properly, but wet or humid basements and crawl spaces are likely sources for condensation of moisture on the first or second floors. Through wall or other cavities, humid basement and crawl space air can also gain access directly to the attic [4].

Frequently, condensation on cold water pipes in basements and crawl spaces are reliable signs of elevated moisture. Others are actual standing water. But even if none of these clear signs of moisture in basements are discernible, data on temperature (air and surface) and relative humidity in the crawl space or basement and comparison to the values obtained outdoors and in the living space above will usually indicate whether there is excessive moisture in the ground contact areas. If the dew point in the crawl space or basement is consistently above the dew point or, more drastically, above the dry-bulb temperature of the outdoor air or the air in the living spaces above, the ground is a likely moisture source. Remedial action can consist of reducing the moisture accumulation in the basements and crawl spaces by installing a moisture retarder over the floor and by ventilating the space through natural ventilation or with exhaust fans. Frequently, the slope of the ground outside the basement or crawl space can be sloped to more effectively drain surface moisture, or, more costly, foundation drainage, either outside or inside the foundation, may have to be installed.

To determine whether moist air flows from the earth contact areas into the living spaces above, tracer gas tests are useful. If moist air is found to migrate from wet basements or crawl spaces into living spaces above, all air paths—such as at utility penetrations and at pipe chases—should be sealed. The relative air pressure under normal conditions should be greater in the living space than in the earth contact space below to prevent the movement of humid crawl space and basement air into the living spaces above. Because earth contact spaces can remain relatively cool on warm days (flywheel effect) in climates with high outdoor humidity, condensation in such spaces is possible in warm climates with little rainfall. Such conditions are prevalent in some warm coastal areas.

Rising Damp

Rising damp is caused by the capillary rise of groundwater within masonry or other porous walls. Rising damp does not appear to be a significant problem in this country; it is, however, considered a major problem in Great Britain, where building regulations required the insertion of damp-proof courses as early as the 1870s [5]. U.S. building codes do not address this issue, but it is also of continuing concern in Australia, as indicated by a research study by Heiman on the effectiveness of methods for treating rising damp [*6*]. The reason for the difference in the prevalence of this phenomenon in the United States and Canada on the one hand and Britain and Australia on the other is not clear. Since climate does not appear to be a major factor, differing basement and foundation wall materials or workmanship may be two likely reasons. Also, it could be that dampproofing and waterproofing is more frequently applied on the outside of basement and foundation walls in both the United States and Canada than in Britain. In any case, rising damp does not appear to be a major problem on this side of the Atlantic and will not be further considered here. Those interested in the subject are referred to the excellent discussion in *Dampness in Buildings* [*7*].

Construction Moisture

According to ASHRAE, construction moisture can be a source of moisture in buildings for the first years of a building's use [*8*]. The amount of construction moisture differs depending on construction method used, weather conditions during construction, and construction sequence. The required period of drying out also differs depending on climate, weather conditions during and after construction, and building operating practices. The current trend to place buildings into service immediately upon completion (or even earlier) may be responsible for many of the more recent moisture problems. Review of construction logs, weather reports from nearby airports (to determine whether frequent rains during construction could have saturated unprotected building materials), material handling and protection practices of contractors and suppliers, and dates of completion and occupancy are useful in determining whether construction moisture may have been the cause of a problem or played a contributing role.

The potential for construction moisture-related problems is increased in constructions which incorporate vapor-retarding membranes. Whether these are installed as retarders or for other purposes, such as decorative, easy to clean interior finishes, such retarders not only retard the ingress of water vapor but also retard the drying-out process. If moisture problems appear within three years of completion in buildings with retarders in walls, ceilings, and floors, construction moisture can be a possible primary or contributing cause and should be investigated accordingly.

Construction moisture may manifest itself only as high interior humidity, or it may cause deterioration of building components and parts, such as corrosion of fasteners or rotting of wood. Green wood is a special case of construction moisture. With the enactment of recent codes requiring the moisture content of all lumber and plywood to be no more than 19% at time of incorporation in buildings, this should no longer be a serious problem in new constructions [*9,10*].

Combined Sources

In many cases of serious moisture damage in existing buildings, there is more than one single source of moisture. Sometimes, one source can be identified as the predominant source, and its elimination will suffice to prevent further damage or reduce the problem to manageable proportions. Often, several sources combine to cause a major moisture problem, although the individual problems created by each source alone would be minor. Accordingly, one not only needs to identify the various moisture sources, but also must assess their relative contribution to the moisture problem. In investigating moisture problems, it is therefore necessary to identify all probable moisture sources and to establish their contribution to the problem. If it is found that there is one predominant moisture source, the most cost effective remedial action can usually be determined with relative ease and confidence. If several moisture sources appear to be the cause of the problem or problems, the individual sources and their contribution must be established. It is frequently useful to determine remedial actions and their cost for each of the causes and to implement the actions stepwise based on cost and on the degree of their interference with the operation of the building and to monitor the effect of each action. Monitoring in this case means the continuous or periodic observation of the symptoms and the measurement of temperatures, relative humidity, or other appropriate values. Where the causes of the problems are seasonal, the process of monitoring and implementation of the various measures can take several years. In such cases it may be more beneficial to accept the higher initial cost of remedying all or most causes at once instead of disruptive drawn-out monitoring and construction activities. Where remedial actions in older structures promise to be substantial and costly, they can often be combined with a general rehabilitation of the structure at less additional cost.

Sometimes there is only one major moisture source, but it manifests itself as several. For example, rainwater that has leaked into a wall and accumulated in one location, and as discussed earlier, may evaporate, increasing the humidity within the wall cavity. If this air moves to other connected cavities, it can then condense and accumulate in several remote locations where the surface temperature is below the elevated dew point of the cavity air. Tracer gas or smoke tests may be useful in verifying air and moisture movements through wall cavities.

NUMBER, FREQUENCY, AND DURATION OF TESTS

In applying any tests or observations, it must be understood that a single data point sometimes is better than none, but that a single point can also be seriously misleading. If possible, the number of tests for determining each characteristic or condition—for example, the number of water vapor transmission tests for a particular material—should be sufficient to produce a statistically valid sample. The number of such a sample varies depending on the precision of the measurements, the desired confidence in the results, and the distributional properties of the measurements. Because tests in buildings can be very expensive, the necessary number of sample locations or sample materials may not be available, or timing is such that only a limited number of tests can be performed during a critical time period; the investigator is frequently tempted, or forced, to limit the number of tests to below that necessary for a statistically valid sample. Where this is the case, both the investigator and the client must be aware of the consequences in terms of increased error rate, reduced certainty, and reduced credibility of the test results. An outline of statistical issues involved in the selection of the number of tests is provided in Dr. Sheryl Bartlett's appendix to this chapter. The Appendix provides guidance for determining the necessary number of tests to satisfy statistical requirements. We discuss here other issues relating to frequency and duration of required tests.

Many moisture problems are seasonal, and it is not always clear which season is the critical one. For example, a major problem may occur in early summer and could be the result of the warm and humid summer condition or the delayed result of a cold weather condition. Thus, it is frequently necessary to conduct tests over one season or over a full annual cycle. Building owners, usually the investigator's clients, generally want an early indication of where the problem is and what can be done to "fix" it. In addition, diagnostic tests can interfere with the operation of the building, and the investigator is often under pressure to take shortcuts. Investigators need to resist such pressures because they lead to faulty analysis, incorrect identification of causes of problems, inappropriate remedial actions, a delay in solving the problem, additional cost to the building owner, and result in the embarrassment of the investigator. In litigations, shortcuts can also lead to lost lawsuits.

An action plan should be developed and discussed with the client for all major investigations. In preparing the plan, it is necessary not only to determine what tests to perform but also when and with what frequency the tests need to be performed. The plan should detail the testing protocols to be followed, the details of the tests, and the times and frequency when the tests need to be performed. The preparation and availability of a detailed testing plan is essential if the investigator wants to present his client with an early indication of the cost involved. An explicit, written plan is also useful in persuading a client that a major testing program needs to be undertaken. However, the plan should not be formulated until a preliminary investigation, including a site visit, provides the necessary background information.

Where major problems on a significant scale are to be investigated, automatic data collection systems should be installed. These can collect data during the normal operation of the building. Once installed, such systems allow the data collection to be performed on a continuous or periodic basis without further interference with the building operation.

LOCATION OF TESTS

As important as the number and frequency of tests are the locations selected for testing. It is normally not sufficient to take measurements only in one single location. The exact number of locations is dependent on the type of building, its design, and the nature and location of the problem. If the problem is clearly localized, it may be reasonable to assume that tests need only be conducted at the location of the problem. But, as a rule, several locations are necessary. Among the variables in location to consider are constructional differences, HVAC zones, orientation, and elevation (floors).

Careful consideration must also be given to select locations in which no problems have been found. Data from such locations, when compared to data from locations which do have a problem, can identify differences in conditions and can help in identifying the causes for the problem. In most cases it is necessary to collect data from a variety of locations, for example, on low, intermediate, and high floors of a high-rise building; on two or more orientations; on walls with and on walls without balconies; on walls with and without windows; and in locations with and without problems. The investigator needs to determine those locations which are necessary to accomplish his objective in each case. As a general rule, it is prudent to collect more rather than less data, as unnecessary data can always be discarded easily, while, for example, missing summer data can not be recovered in midwinter except by waiting for the next summer season!

The fewer locations chosen, the more care is required in selecting "typical" locations. The temptation can be great to select convenient rather than truly typical locations. "Convenient" in this case may mean more accessible to the investigator or less disturbing to the client in the continuing operation of the building. Both the investigator and the client need to recognize the cost of such "convenience" in terms of a possibly compromised, incomplete, or unsuccessful investigation.

EXAMPLES OF MOISTURE INVESTIGATIONS

The following presents four example studies. Two examples are buildings located in warm climates: a group of single-story, semi-detached military housing units located two miles from the Gulf of Mexico and a mid-rise building located on a Mid-Atlantic beach. In both examples, the investigations led to similar conclusions. However, the owner of the military housing, the U.S. Navy, invested in a multi-year study of a problem that affected potentially hundreds or even thousands of units and permitted extensive testing in one unit, additional tests in many more units, and also allowed the occupants of some 50 units to be interviewed. A thorough description of the former case was published by ASTM in *STP 992* [*11*]. In contrast, to minimize disruption of the building's seasonal operation, the owner of the mid-rise building initially seriously limited diagnostic work. The other two examples are located in cold and moderate climates: A group of moderate income homes in the northern Midwest which experienced serious moisture distress, and a multifamily complex in the Northwest. Although the budget for the investigation in the moderate income housing group was low, early correct tentative identification of the likely cause of the moisture distress and a concentration on relevant tests allowed for sufficient data collection to accurately establish the causes of the problem. The multifamily complex again allowed a major effort in both laboratory and field tests and in extensive field investigations.

The four examples presented are based on actual building studies and disputes in which the author participated. However, much of the work was performed by other investigators, including some on the other side of the dispute. Accordingly, data may exist, although not available to the author, that could alter the author's conclusions. In any case, the studies are presented here as illustrations of four different troubleshooting exercises rather than as an accurate record of actual cases.

Example 1: Warm and Humid Climate; Masonry Housing

Location and Topography

The houses are located approximately two miles from Pensacola Bay at an elevation just barely above flood level. The site area was used during World War II as an airfield and is essentially level. The site was generally open, interspersed with fir trees forming moderate screens between individual duplexes.

Climate

Heating degree days:	1654	
Cooling degree days:	2642	
Winter design temp:	99%	22°F (−6°C)
	97.5%	24°F (−4°C)
Summer design temp:	1%	92°F (33°C) DB, 78°F (26°C) WB
	2.5%	91°F (33°C) DB, 78°F (26°C) WB
	5%	89°F (32°C) DB, 78°F (26°C) WB
Summer dry-bulb:	93°F (34°C) and over:	18 h
	80°F (27°C) to 93°F (34°C):	1932 h
Summer wet bulb:	73°F (23°C) and over:	2487 h
	67 to 73°F	3600 h
Prevailing winds:	Summer: South Winter: North	

Based on this climate data, the buildings are located in a climate defined as humid [*12,13*].

Design, Construction, and Equipment

All buildings are one story, with 8-in. (200 mm) exterior painted concrete block walls, 1-in. (25 mm) plastic foam insulation, and interior painted gypsum board finish. The floor is slab on grade, the heating is natural gas warm air, and the air conditioning is electric.

Problem Manifestation

Significant mold growth on exterior walls and on furnishings, specifically on beds and dressers placed against exterior walls, and areas of water-logged gypsum board finish. Many areas of water-logged gypsum board were near or below windows. The problems seemed to be pervasive, and approximately one half of the units showed some distress. No significant seasonal variations in the occurrence of the moisture problems were reported. During an earlier attempt at correcting the problems, the original fiberglass thermal insulation was replaced with polystyrene board, and a liquid coating was applied to the interior face of the concrete block as a vapor retarder. Neither of these actions corrected the problems.

Diagnostic Work

For diagnostic purposes, the client made one unoccupied dwelling unit available for almost one year. Also, access for additional tests was provided to a sample of 30 units. The tests conducted in and around the test building consisted of:

- Water leakage tests at blank walls and at windows.
- Air infiltration tests, both tracer gas and blower door.
- Ground drainage tests.
- Water leakage tests at footings.
- Measurements of dry bulb temperatures and relative humidity inside, outside, and within the concrete block cavities. Temperatures and relative humidities were measured in five wall cavities of the test house during four one-week periods spread over essentially a full year. Readings were taken at 4 to 12-h intervals spread over almost a full year.

Measurement of temperatures and relative humidities within the wall concrete block cavities and tracer gas tests were performed selectively on an additional 30 units. In addition, an occupant survey was conducted on 86 units to determine the true extent of the moisture problems, possible moisture-related occupant behavior, and to identify problem locations within the units.

Results

The water infiltration tests indicated that gross leakage occurred at the window sill, and lesser but still significant amounts of water also leaked into the concrete block cavities on walls without windows. The tracer gas tests indicated overall air change rates (ACH) for houses with all interior doors open in the range of 0.16 to 0.53 ACH, with an average of 0.28 ACH. The air change rate within the bedrooms with the bedroom doors open was 0.1 ACH. With the bedroom doors closed, the air change rate within the bedrooms was below the capacity of the instrument to measure, that is, below approximately 0.05 ACH. The ground drainage tests indicated poor drainage, a finding consistent with observation of standing water during and for hours after brief but heavy rainfalls. The tests at the footings indicated that water could drain from the ground into the concrete block cavities at the top of the footings which were only between 4 and 6 in. (100 and 150 mm) below grade. The measurements of temperatures and relative humidity indicated that the dew point temperature of the air inside the concrete block cavities was, with the exception of one measurement period, consistently higher than the dew point temperature of the air either outside or inside the building. The occupant survey indicated that 66% of the houses had moisture problems, 93% of the problem areas were in bedrooms, 61% were under or near windows, and 39% were on blank walls. Problems were reported to be most severe after heavy rainfalls. There was no correlation between the number of houseplants and moisture problems.

Conclusions

Based on the results of the various tests, it was concluded that the primary source of the moisture problems was rainwater penetration into the concrete block cavities, and that summer condensation was at most a minor contributing factor. The low air change rate in the bedrooms was identified as a significant contributing factor in that any moisture infiltrated into the interior gypsum finish could not dry out as it apparently did in the living and kitchen areas, which had higher ventilation rates. A more water-resistant exterior painting system and increased ventilation in the bedrooms were developed as remedial actions.

Example 2: Fringe Climate; Mid-Rise Building

Location and Topography

The building is located directly on a Mid-Atlantic beach at an elevation just barely above flood level. The site faces southeast and is totally open to winds from the ocean.

Climate

Heating degree days:	2696	
Cooling degree days:	1823	
Winter design temp:	99%:	22°F (−6°C)
	97.5%	24°F (−4°C)
Summer design temp:	1%	91°F (33°C) DB, 79°F (26°C) WB
	2.5%	89°F (32°C) DB, 78°F (26°C) WB
	5%	87°F (31°C) DB, 78°F (26°C) WB
Summer dry-bulb:	93°F (34°C and over:	18 h
	80 to 93°F (27 to 34°C):	1160 h
Summer Wet-Bulb:	73°F (23°C) and over:	1582 h
	67 to 73°F (19 to 23°C)	2989 h
Prevailing Winds:	Summer: South Winter: North	

Based on this data, the site is in the ASHRAE-defined fringe climate, but close to the ASHRAE Condensation Zone III [*14,15*].

Design, Construction, and Equipment

The building is a 16-story hotel with an exterior insulated wall system. The HVAC system for the guest rooms consists of individual through-the-wall heat pumps and central units for the corridors, common rooms, and kitchens. Continuously operating fans ventilated the bathrooms. All guest rooms have sliding aluminum patio doors giving access to balconies. Guest rooms had interior vinyl wall covering.

Problem Manifestation

Significant mold growth on walls, including partition walls separating guest rooms, and on some furnishings. No mold or mildew was reported in the bathrooms.

Diagnostic Work

During an initial investigative phase, the exterior of the building was carefully inspected and tested for water leaks, and many instances of missing or poorly installed caulking were found. The wall was subsequently rebuilt, but no further tests were conducted.

When the moisture problems did not disappear, reasons

When the moisture problems did not disappear, reasons other than rain leaks were thought to be responsible for the mold and mildew. Accordingly, additional tests were conducted to determine air pressure differentials between the guest room interior and the outdoors and between the guest rooms and the corridors. In addition, temperatures and relative humidities were measured in two adjoining rooms, in the partition cavity between the two rooms, and in the cavity of the adjoining exterior wall. These measurements were conducted during one summer only over two periods of a few days. The rooms in which the measurements were taken were not in service; in fact, some care was taken to seal off the rooms from the rest of the building. The measurements within the partition and within the exterior wall were performed in one location each. After the results of the temperature and relative humidity tests were analyzed, a water leakage test was performed in the adjoining exterior wall area.

Results

The pressure measurement tests indicated that the guest rooms were operating under slight negative pressures. The temperature and relative humidity measurements within the partition between the two test rooms and in the adjoining exterior wall indicated that the dew point in both cavities was higher than that of the air in the two rooms and the outdoors. The water leakage test confirmed the existence of a significant water leak near the location where the temperature and relative humidities were measured within the wall cavities.

Conclusions

While a negative pressure can, in a warm and humid climate, cause the influx of humid air with a dew point above that of the conditioned indoor air or interior surfaces, in the particular location the average monthly dew point is less than the indoor design temperature even during the warmest summer months, preventing condensation on the walls except for possibly brief periods. Furthermore, the incidence of mold did not correlate with the measured negative pressure, which was purported to cause the movement of the warm, humid air into the rooms, as the incidence of mold growth was higher in the lower floors, which showed a lower negative pressure, than in the higher floors, which showed a higher negative pressure. On the other hand, the data from the temperature and relative humidity measurements suggested that a rain leak was likely somewhere near the measurement locations. Indeed, the water leakage test confirmed the existence of just such a leak.

There were other data available which were ignored or not adequately considered, contributing to a faulty conclusion. The first is the fact that the mold and mildew was not on the room side surface of the vinyl wall covering but on the back of the vinyl. Since vinyl wall covering is essentially water vapor proof, this suggests that the moisture causing the mold was originating within the partition, wall, or ceiling, and not from the room side. The second is the weather data, which showed that a storm with hurricane winds inundated the structure during construction, and gypsum board stored on open floors during the storm was reused, despite its being wet. That moisture, combined with moisture trapped in the floors, likely contributed to the problems. The upper floors were not yet constructed at the time of the storm, and moist gypsum board was therefore not installed on these floors. This could at least partially explain the lower incidence of mildew on the upper floors. Third, available data on wall cavity moisture was not properly interpreted. Finally, the correlation between the location of rainwater leaks and mildew in the guest rooms was ignored.

Example 3: Cold Climate; Moderate Income Homes in Northern Midwest

Location and Topography

The houses are located on individual sites in northern Wisconsin and Minnesota and on the upper Michigan peninsula. The terrain is generally flat to slightly rolling, and the houses were on both open and wooded lots.

Climate

Heating degree days:	8700	
Cooling degree days:	300	
Winter design temp:	99%	−17°F (−27°C)
	97.5%	−12°F (−24°C)
Summer design temp:	1%	87°F (31°C) DB, 72°F (22°C) WB
	2.5%	84°F (29°C) DB, 70°F (21°C) WB
	5%	81°F (27°C) DB, 68°F (20°C) WB
Summer dry-bulb:	93°F (34°C) and over:	6 h
	80°F (27°C) to 93°F:	226 h
Summer wet-bulb:	73°F (23°C) and over:	75 h
	67 to 73°F (19 to 23°C):	438 h
Prevailing winds:	Summer: South Winter: North	

Based on this climate data, the building are located in ASHRAE Condensation Zone I [*16*]. The above are averages for an area spanning approximately from 45 to 47° North Latitude and from 87 to 94° West Longitude. Within that area, the values for individual sites vary from the lowest to the highest by approximately 600 heating degree days, 10°F (6°C winter design temperatures, and 7°F (4°C) summer design temperatures. Prevailing winds for individual locations within the area vary in summer from south to southwest and in winter from east through north to northwest.

Building Design, Construction, and Equipment

The buildings are all one story and of prefabricated, panelized wood construction. The walls consist of 2 by 4-in. (100 by 100 mm) studs, 16 in. (400 mm) on center, various types of sidings, a building paper, plywood sheathing, mineral fiber insulation with various kinds of facings, and an interior of gypsum board. Similar panels were also used for the roof construction, creating a cathedral ceiling effect. Heating is provided by various means, but most houses also have either a fireplace or a wood-burning stove.

Problem Manifestation

Several years after construction, some houses were found to have deteriorated plywood sheathing. The deteriorations appeared to be most severe, but not limited to two areas: one directly under the bathroom window, the other high in the wall directly under the gables in the bedrooms. Other problems were mold growth on interior walls and widow trim and frames.

Diagnostic Work

Because of financial constraints, the diagnostic work was severely limited in scope. When several walls were opened up during an initial inspection in March of 1987, it was found that in a 4-ft (1.2-m) section the building paper had been omitted. The plywood sheathing in that place was completely dry and unstained, showing no evidence of prior moisture, whereas the plywood was dripping wet and heavily discolored only a foot away where the building paper was in place. This observation led to the tentative conclusion that the building paper acted as a vapor retarder, preventing the wall from drying out. Accordingly, a first series of water vapor transmission tests were conducted on samples of both the building paper and various facings of the thermal insulation blankets. Later, these tests were expanded to a large sample to determine whether the results of the few tests were indicative of all the membranes used in the buildings. Several home owners also complained about high moisture levels in their homes based on readings of homeowner's humidistats. This was consistent with the findings of a government commission which claimed that the primary cause of the moisture distress was the high relative humidity in the houses due to high occupancy loads and relatively tight construction. But no readings of relative humidity were taken over extended periods and in a statistically valid samples of homes. However, the degree of airtightness of a number of homes was established by both blower door tests according to ASTM E 779[4] and by passive tracer (perfluorocarbon) gas tests.

Results

The initial water vapor transmission tests showed that the exterior building paper had a water vapor permeance in the range of 0.1 to 0.5 perms (6 to 29 $ng/Pa \cdot s \cdot m^2$). According to ASTM C 755,[5] this classifies the building paper as a vapor retarder. The results further indicated that all insulation facing membranes had permeances greater than that of the exterior building paper. The additional permeance tests on the larger sample verified these results. The results of the permeance tests on the building paper were consistent with the manufacturer's product claims.

The air infiltration tests, both by blower door and by tracer gas, showed air leakage rates in the range of 0.2 to 0.6 ACH.

Conclusions

The results of the water vapor permeance tests indicated that the construction violated the long-established rule that the materials on the exterior of a wall should have a water vapor permeance of at least five times that of the materials on the indoor face of the wall [*17*], and that the primary cause of the moisture distress was moisture condensation on the incorrectly installed vapor retarding membrane on the win-

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[4] Test Method for Determining Air Leakage Rate by Fan Pressurization.

[5] Practice for Selection of Vapor Retarders for Thermal Insulation.

ter cold side of the wall, which also prevented the drying out of the plywood sheathing in the spring, thus causing the deterioration of the plywood sheathing. The results of the air infiltration tests indicated that the houses were relatively tight, but not extremely so. Thus, the lack of ventilation and infiltration could only have been a minor contributor at best.

The moisture distress below the bathroom window was most likely attributable to water leakage from direct shower water impingement on the window, condensation on the window panes, and the migration of some of this water into the wall below the window. The building paper at that location again prevented the ready drying of that moisture in the wall.

Example 4: Multi-Family Housing in the Northwest

Location and Topography

The building complex is situated on a gently west sloping site near but not directly on a narrow arm of a large bay off the Pacific Ocean. The site is known for occasional strong winds from both northerly and southerly directions.

Climate

Heating Degree Days:	4835	
Cooling Degree Days:	138	
Winter Design Temp:	99%	19°F (−7°C)
	97.5%	24°F (−4°C)
Summer Design Temp:	1%	86°F (30°C) DB, 66°F (19°C) WB
	2.5%	82°F (28°C) DB, 65°F (18°C) WB
	5%	79°F (26°C) DB, 63°F (17°C) WB
Summer Dry-Bulb:	93°F (34°C) and over:	4 h
	80 to 93°F (27 to 34°):	131 h
Summer Wet-Bulb:	73°F (23°C) and over:	0 h
	67 to 73°F (19 to 23°C):	49 h
Prevailing Winds:	Summer: North Northeast Winter: South	

Based on this climate data, the buildings are located in ASHRAE Condensation Zone III [*18*]. The climate is further defined by frequent rainfall. Precipitation is 39 in. (990 mm), distributed over 155 days with rainfall of 0.1 in. (2.5 mm) or more.

Design, Construction, and Equipment

The complex consists of several wings two to three stories in height, containing about 140 apartments, and common areas, including a kitchen and a dining room. The individual apartments have two and three bedrooms, one or two bathrooms, a small kitchen, and a living/dining room combination. Construction is 6-in. (150 mm) wood studs with painted gypsum board interior finish, a separate polyethelene vapor retarder, mineral fiber blanket insulation in the cavity, plywood sheathing, gypsum board sheathing for fire protection, a spunbonded olefin weather barrier, and painted cedar siding. About one half of the walls has an approximately 3-ft (0.9 m) roof overhang; the other half has a parapet with no roof overhang. The apartment bathrooms are mechanically vented, but not the kitchens. Apartments are individually heated by electric resistance baseboard, but have no air conditioning, and the corridors and common areas are centrally heated and air conditioned.

Problem Manifestation

Initially, moisture damage was observed as mold and mildew inside apartments, primarily near window heads. When the walls were opened in several locations, discoloration and disintegration of the gypsum board and plywood sheathings and mildew and rot on supporting wall framing were found to be pervasive.

Diagnostic Work

Four sets of investigations were conducted. In the first, tests were conducted to determine the performance of the windows as installed in the building. In the second, selected wall and parapet areas were opened to inspect the condition of the various layers of the wall to determine construction practices at window heads, eaves, and roof flashings and to measure the moisture content of the gypsum and plywood sheathings. The third set consisted of a complete mapping of moisture defects over the entire walls by removing all cedar siding, all damaged gypsum board sheathing, all damaged plywood, and any damaged 2 by 6-in. (50 by 150-mm) studs. The mapping also included the measurement of moisture content of wall materials. The fourth investigation was intended to determine the contribution to the moisture distress, if any, of condensation within the wall. This consisted of a review of relevant climate data and construction features and their correlation with the type and location of observed moisture distress and the conduct of E 96[6] wet cup water vapor transmission tests on the siding, weather barrier, gypsum sheathing, and plywood sheathing.

After tentatively deciding on remedial work, sections of the original and the rebuilt walls were subjected to extended (nine-day) water spray tests to determine the effectiveness of the planned rebuilding of the wall. The extended nine-day period was selected to approximate the cumulative effect of the frequent rain that is common during the rainy season at the location. During these tests the moisture content of the gypsum board and plywood sheathing was monitored through four electrical resistance probes each in the plywood and the gypsum sheathing. The only difference between the original and the rebuilt wall was a No. 15 asphalt-impregnated felt (formerly called 15 lb felt) in lieu of the spunbond olefin sheet weather barrier and a cedar siding with a 1-in. (25-mm) overlap in lieu of a ¼-in. (6-mm) overlap.

Results

Window tests: The on site window tests indicated defects at window joints and blocking of weep holes.

Selected wall openings: Many instances were uncovered where portions of the gypsum board sheathing were water logged, plywood sheathing was deteriorated, and some framing members showed signs of rot. These conditions were not only near windows but also at roof flashing, at locations where balcony beams framed into the walls, at downspouts,

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[6] Test Methods for Water Vapor Transmission of Methods.

and above the head of windows. It was also found that the wall siding, instead of the specified 1-in. overlap, averaged less than ¼-in. (6 mm). (This saved the contractor two to three siding boards per floor, or a total of roughly 10 000 line feet of 8-in. (200 mm) cedar siding!) In a few locations, the overlap was completely missing. Also, the flashing at both the roofing and at the window heads and the weatherbarrier was incorrectly installed and overlapped.

Mapping: The mapping of moisture distress indicated the following:

- Moisture content of the plywood sheathing ranged from a maximum of 47 to a minimum of 7% on walls without overhangs and from 27 to 2% for walls underneath overhangs.
- The average moisture content was greater on north and south facing elevations (18 and 19%, respectively) than on all other orientations (14%). Consistent with these measurements, the deterioration of walls was greatest on north and south elevations.
- Almost all gypsum sheathing needed replacement on walls without roof overhang, while on walls with overhang only a few areas on lower floors needed replacement.
- Framing members needed replacement only near downspouts and balcony framing, and only on walls without roof overhang.
- Gypsym board and plywood sheathing needed replacement on walls of both occupied and unoccupied areas, that is, on both conditioned and unconditioned areas.

The results of the water vapor transmission tests, averaged over nine samples, were as follows:

Siding:	10 perms (575 ng/(Pa·s·m^2)
Weather Barrier:	130 perms (7470 ng/(Pa·s·m^2)
Gypsum Sheathing:	45 perms (2585 ng/(Pa·s·m^2)
Plywood Sheathing:	10 perms (575 ng/(Pa·s·m^2)

The 6-mil polyethelene vapor retarder and the interior gypsum board were not tested as available data of 0.06 perms [3 ng/(Pa·s·m^2)] and 50 perms [2875 ng/(Pa·s·m^2)], respectively, were considered sufficiently well documented in the literature [*19*].

There were no differences between the perm rating of materials from wall areas that showed significant moisture distress and from areas with little or no moisture distress, that is, there was no correlation between moisture distress and the permeance of wall materials.

The extended water spray tests indicated that the reconstructed wall was more resistant to moisture penetration then the original wall. The moisture content readings[7] of the two walls were as shown in Table 1 at start of test, after six days, and after nine days.

TABLE 1—Results of water spray tests. The numbers represent gage readings. For plywood, these approximate actual moisture content. For gypsum board, the numbers indicate a relative degree of moisture content.

	At Start	Six Days	Nine Days
	ORIGINAL CONSTRUCTION		
Plywood	10%	13%	18%
Gypsum Board	Not Measured	49%	62%
	REVISED CONSTRUCTION		
Plywood	8%	9%	12%
Gypsum Board	Not Measured	14%	18%

Conclusions

All of the investigations led to the conclusion that the primary cause of the water damage was rainwater leakage. This is indicated by the correlation of greatest damage on the north and south walls with prevailing wind directions and on walls without overhangs.

It appears that the insufficient overlap of siding boards of the original construction was a primary cause of the water penetration through the siding. However, leakage through the siding should not have caused water penetration through the weather barrier. Incorrect flashing and installation of the weather barrier appeared to be strong contributing factors. In the waterspray tests, flashings and weather barriers in both specimens were correctly installed, and yet there was a very pronounced difference in performance. Since both the original and replacement barrier materials are claimed by the manufacturers to be watertight, the only remaining possibility would be that the water leakage through the original barrier occurred at fastener penetrations. It appears that the original material may have been incapable of sealing itself at nails and staples, while the replacement—relatively thick and plastic asphalt impregnated felt—may be capable, to some degree, of self-sealing penetrations.

No contribution of condensation to the moisture distress could be found. In fact, all signs pointed to a lack of such contribution: Specifically, the lack of correlation of wall areas of conditioned and unconditioned spaces with the incidence of moisture distress areas and the concentration of problem areas on north *and* south facing walls argue strongly that such contribution was minor at best. Also, the wall had an effective vapor retarder installed at the interior face of the thermal insulation and a vapor permeable weather barrier on the exterior, both in conformance with local building practices.

Comparison of the Four Examples

The four examples demonstrate that there are many approaches that can lead to correct assessments of the causes and successful remedial actions. They also show that the liberal use of diagnostic tools is likely to yield more useful and correct results than can be obtained with only minimal use of such tools.

The first example was carefully built on a significant database established over a full year's time. The client in that case was fully supportive and willing to assume the cost and delay resulting from a major diagnostic effort. The second example was driven by expediency. A more extensive data collection in the early phases of the investigation would have provided an earlier understanding of the true causes of the moisture distress. The third example falls somewhere in between:

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[7] Readings of the Delmhorst gages are given here. Although actual moisture content in percent will vary significantly from the given values, we are here only concerned with the relative values between the moisture content of the components of the original and rebuilt walls.

Financial constraints did not allow the extensive diagnostic approach that might have been desirable, but careful initial analysis and subsequent well-targeted and essential tests allowed the preparation of a good case as to the causes of the moisture problems. The fourth example, finally, demonstrates how a conclusion can be constructed from many different, and in themselves minor, observations, test results, and established existing data. The four examples indicate the value of using diagnostic tools in failure analysis, air infiltration and movement tests, temperature, relative humidity, moisture content measurements, and water vapor permeance tests, and how occupant surveys and weather data need to be integrated into the overall investigation.

Who Should Conduct the Tests?

All four examples indicate the importance of having tests conducted only by well-qualified experts. This particularly applies to water vapor permeance tests which should only be entrusted to laboratories with extensive experience with such tests. One major difficulty in using the test results is that the current test methods are based on differences in relative humidity as the only driving force. However, in buildings, the moisture movement is of many interrelated components, and the test methods, although providing useful data, provide only one set of data in this complex system [*20*]. But even the individual tests are difficult to perform with any degree of accuracy and reproducibility. Thus, Toas, in his report on an interlaboratory "round robin" conducted by ASTM Committee C16 in 1985 concluded "that the ASTM E96 test appears to be very operator dependent and requires a great deal of skill, but the round robin also shows that skilled operators in different laboratories can produce consistent and reliable results" [*21*].

During the work on the first example, the author had a painful and costly personal experience when permeance tests were entrusted to a laboratory that was well recommended but turned out to be totally inexperienced. The results of the tests were inconsistent and several orders of magnitude outside any rational range. Similarly, tracer gas tests are best performed and the test results analyzed by experts in that field. The typical investigator should guard against the natural inclination to also try to be testing technician unless he or she has the considerable training and expertise in the particular tests to be performed. There is, of course, no question that routine measurements such as temperature or moisture content measurements can and should be conducted confidently by any qualified investigator. However, the conduction of more elaborate tests or those that involve the use of expensive and complex equipment is another matter altogether. There are three issues involved. The first is a technical one: Can the investigator adequately maintain both equipment and proficiency for tests used only rarely? The second deals with ethics: Will the investigator conduct excessive tests simply because he or she has the equipment available and because the conduction of the tests increases billable hours? And third, will the client maintain the necessary confidence and support for an extensive and possibly expensive diagnostic program which can be interpreted as designed to greatly increase the investigator's fee? For all of the above questions, this investigator, after over ten years of practice, had decided to no longer conduct major tests but to rely on well-qualified and preferably local laboratories. The author recommends the same policy to all investigators. However, the investigator will want to be present during much of the testing as frequently much can be learned during the test.

STANDARD PRACTICES AND PROTOCOLS

Just as important as the availability of diagnostic tools is the availability of standard practices and test protocols. They are needed as a guide for the newcomer to testing. They are even more essential to allow the comparison of tests performed by different persons, in different locations, and at different times. Both ASTM Committees C16 on Thermal Insulation and E06 on Performance of Buildings have been in the forefront of standardizing test methods used in the building field.

Standard protocols, or guidelines, for investigating problems will greatly enhance our ability to investigate moisture problems, and it is not surprising that ASTM Committee E06 is in the process of developing a protocol for investigating wall failures. Such protocols will be a significant step toward establishing failure investigations, forensic engineering, and "troubleshooting" as a separate engineering discipline. Protocols for various typical investigations should and will be developed. Such protocols will encourage or force the use of building diagnostic tests, provide results that can be compared, and form the basis for establishing a database on moisture problems in buildings. Such a data bank covering moisture-related building failures would in the future permit investigators to compare results of investigations on similar and even dissimilar constructions. Only the availability of a significant and reliable data bank will eventually permit the establishment of realistic, achievable, and effective moisture-related performance criteria for new buildings, repairs, and building retrofit and renovation. The existence of the database in itself will encourage the further development of field tests methods, instrumentation, and standardized protocols.

A Suggested Outline Protocol for Conducting Moisture Investigations

The following are some of the major components of any moisture investigation. In most cases, not all the components are available, and seldom are they all needed. They should, however, be considered.

Review of Drawings and Specifications

For newer buildings, these are generally available, for older buildings seldom, or if available, may not be reliable. In any case, both drawings and specifications, if available, should be reviewed to determine whether actual construction and materials used conform to those intended. Recent "as builts" (construction drawings marked up to reflect actual construction as opposed to planned design) are generally reliable, but are seldom available. Owners of newer large buildings have usually some construction drawings available, but specifications are often not to be found, although they may be both more useful and take precedence over drawings. In small buildings and residential construction, drawings are frequently not available and specifications only rarely. Small scale ⅛ in. to the foot (1:100) floor plans and building sections are useful, but what is most desirable are large-scale wall sections and details, including details of unusual conditions.

First Site Investigation

Never attempt to solve a moisture problem solely based on second-hand data. A first-hand site investigation should always confirm information or data obtained from the owner, agent, or third party. The first site visit may be a relatively quick walk-through or it may include diagnostic tests, but the first visit should concentrate on verifying the conditions as related by the owner or agent or as described in drawings or third party reports.

Weather Data

Collect weather data. In older buildings, this applies primarily to data during and prior to the time a problem was observed. In buildings less than three years old, weather data during construction may be crucial. Major weather data and additional sources are discussed in Chapter 7.

Prepare Experimental Plan

As indicated above, all but the most simple problems require the development of an experimental plan. The level of detail of such a plan should be consistent with the severity and nature of the problem. The collection of data should be restricted to data that are truly necessary, but all necessary data should be collected. The plan should be developed as early as possible, but initially need not be elaborate and may be more in the form of a framework to be fleshed out, revised, and expanded. As new data are discovered, it may be necessary to change the plan.

Follow-up Visits and Diagnostics

Depending on the severity or complexity of the problem, there may be only a single follow-up visit required. More typically, several visits are necessary to gather additional information and to conduct diagnostic tests.

Building Diagnostic Tests

The following tests should be considered in most significant moisture investigations, although only a few may be selected in any one investigation:

- Moisture content of relevant building materials.
- Relative humidity and temperature indoors and outdoors. Determine daily and, in many cases, seasonal variations.
- Relative humidity and temperature in relevant wall cavities. These need to be measured over several days, in many cases over one or all four seasons.
- Surface temperature of walls, floors, ceilings, and interstitial temperatures inside building constructions.
- Air infiltration tests by tracer gas or pressurization, or both, of the whole building, individual rooms, or within wall and other building cavities.
- Air movement tests by tracer gas or smoke candles to characterize airflow patterns through and within buildings and wall and other cavities.

Occupant Surveys

Occupant surveys should always be conducted when neither the extent or nature of the problem are well understood or documented. In the first case study above, the precise locations of problems were known in one house, but only a survey of many houses could establish that these locations were typical. Also, the additional information that water leakage occurred in some houses at the floor was crucial in revising the experimental plan and in determining the causes of the moisture problems in the houses.

CONCLUSIONS

At this time, investigations of moisture problems are part art and part science. The development of new test and evaluation methods moves the activity more and more in the direction of science. However, constraints to successful investigations are not only lacking technology, but also lacking understanding and trust between owner and investigators.

Building owners and managers must cooperate fully with the investigator. They must recognize that moisture distress can have multiple causes, that the causes in many instances can be determined only through extended investigations over periods sometimes spanning a full annual cycle of seasons. They also must understand that moisture investigations may intrude on the normal operation of the building.

Investigators, on the other hand, must be sensitive to the owners' concern about intrusion into and disturbance of building operations, and investigators must develop an adequate investigative plan which minimizes such intrusions and disturbances, and they must honestly inform the owner of what is required, what time is involved, and what the consequences are of conducting a less than thorough investigation. It is, of course, frequently impossible to estimate accurately the extent, time, and expenses of required investigations, but it should be possible to determine with satisfactory accuracy the worst and best case for a given situation. Investigators, of course, must at all times keep abreast of new technology and use the appropriate tools available to perform the investigation, including diagnostic instruments and computer models. Investigators should also actively participate in the development of new technology, be it innovative test methods, computer simulations, or analytical evaluation methods. Only through such cooperative work can the science in building investigations grow and the need for art and intuition on the part of the investigator be reduced.

In conducting a moisture study, the investigator should be aware of the possible causes and must guard against preconceived notions. Although a majority of moisture problems appear to result from rainwater leaks, in cold climates condensation can be a major problem, and in warm and humid climates condensation is a possible cause of problems in air-conditioned structures and in all structures with high thermal mass. Air conditioning equipment with insufficient dehumidification capacity also is a frequent cause or contributor to moisture distress. Problems from burst pipes are infrequent and are generally obvious; remedial measures are the business of the well-established community of plumbers and building maintenance engineers. Groundwater is mostly a problem in residential construction and does not seem to be a major issue in basements of commercial buildings. However, conventionally constructed buildings have, by and large, sufficient redundancies to guard against single moisture causes, and, therefore, major moisture problems frequently have several causes, although one cause may be a dominant one. Therefore, all causes should be identified, although repairs may sometimes only need to address a dominant cause.

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APPENDIX

Statistical Considerations in Data Collection

by Sheryl Bartlett, Ph.D[8]

INTRODUCTION

In collecting data for troubleshooting, there are many issues to consider. The primary issue is that the data will have variation associated with it. Measurements taken in the morning are unlikely to be the same as those taken in the afternoon (within-day variation), nor are measurements taken on different days likely to be the same (between-day variation). Measurements taken in one location are unlikely to be the same as those taken in another location (between-location variation). Even measurements taken at the same time and in the same location may differ because the readings from the measuring device may vary. This variability leads to uncertainty in the conclusions that can be made about building inspection data. It is useful to be able to quantify this uncertainty in order to be able to make informed decisions.

Say there are two sets of measurements to be compared. If the data points appear to overlap, then making conclusions about the data is not a clear task. To put some credence to the comparison, a statistical test can be performed that will help in deciding if the two sets of data are the same or different. Since there is variability, a decision can never be made with 100% certainty. However, statements about the likelihood of being correct or incorrect can be made.

In this appendix, a brief introduction to the application of statistical concepts to building inspection data will be made. An example will be used to illustrate these concepts. The reader will be directed to standard statistical textbooks for details on the methodology.

AN EXAMPLE OF TYPICAL BUILDING INSPECTION DATA

To facilitate the discussion, an example using data for determining sources of moisture problems in buildings is presented. Dry-bulb and dew point temperatures were measured indoors, outdoors, and in various locations in a concrete block cavity. Since day-to-day variability and within-day variability was expected, measurements were taken on three different days and two or four times each day.

Although measurements were taken at several locations in the wall cavity, for the sake of simplicity, only one location will be presented in this example. The data for dew point and dry-bulb temperatures are presented in Tables A1 and A2, respectively.

The questions that are asked are whether or not the indoor dry-bulb and dew point temperatures in the wall cavity are different from those indoors or outdoors. Looking at the data in Table A1, the dew point temperature in the wall cavity is larger in all cases than that indoors. The dew point temperature in the wall cavity is also larger than the outdoor temperatures, but some overlap exists. Such clear differences are not apparent for the dry-bulb temperatures. The indoor temperatures are for the most part smaller than those in the wall cavity, but the outdoor and wall cavity temperatures look similar.

TABLE A1—Dew-point temperature (°F) indoors and outdoors and in a concrete block cavity.

Day	Time	Indoor	Wall Cavity	Outdoor
Day 1	4:30	65.0	79.0	74.0
	12:30	62.0	92.5	77.5
	16:45	58.5	86.0	77.0
	22:30	56.5	83.0	76.5
Day 2	6:00	59.5	77.0	71.5
	9:30	56.5	81.0	76.5
	18:30	57.0	88.0	77.0
	22:30	63.5	80.0	77.0
Day 3	9:30	70.5	81.0	76.5
	13:30	65.0	81.0	80.5

NOTE: $t_{°C} = (t_{°F} - 32)/1.8$.

STATISTICAL TESTS

Concept of Statistical Testing

To assess whether or not the two groups are different, a statistical test can be performed. A statistical test is set up by formally testing a hypothesis. The hypothesis is usually a *null* hypothesis, that is, that the means of the two groups are *not* different. The *null* hypothesis is tested against an *alternative* hypothesis. In this case, the *alternative* hypothesis is that the means of the two groups are different. A test statistic used to test the *null* hypothesis is computed. If the test statistic is larger than a previously specified value, then the *null* hypothesis is rejected and it is concluded that there is evidence to suggest that the two groups are different. Selection of the previously specified value is explained below.

There are two types of errors that can be made when testing a null hypothesis. First, the *null* hypothesis is rejected when it is true, and second, the *null* hypothesis is accepted when really it is false. These are called Type I and Type II errors, respectively. Ideally, both errors should be as small as possible.

Usually, in selecting an appropriate statistical test, certain assumptions about the data are made. Two common assumptions that enable standard statistical techniques to be used are that the observations are drawn independently and that they come from a common distribution. The normal distribution is a widely applicable distribution which is symmetric and bell shaped. Usually this assumption can be made about continuous measurements such as temperature.

TABLE A2—Dry-bulb temperature (°F) indoors and outdoors and in a concrete block cavity.

Day	Time	Indoor	Wall Cavity	Outdoor
Day 1	4:30	79.0	79.0	76.0
	12:30	81.0	96.0	91.0
	16:45	77.0	86.0	89.0
	22:30	79.0	83.0	78.0
Day 2	6:00	78.0	77.0	75.0
	9:30	76.0	81.0	80.0
	18:30	79.0	88.0	80.0
	22:30	77.0	80.0	79.0
Day 3	9:30	78.0	81.0	79.0
	13:30	79.0	91.0	84.0

NOTE: $t_{°C} = (t_{°F} - 32)/1.8$.

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The Example

Using data from the example, the difference between the two groups under consideration for each time and day is computed. The difference between the wall cavity and indoor and outdoor dew point and dry-bulb temperatures are given in Table A3. The question is, are the observed differences large enough to say that there is a statistical difference between the two groups or is there a chance that they appear different due to the randomness in the measurements?

In the example, it will be assumed that the dew point and dry-bulb temperatures are normally distributed. Thus, the appropriate statistical test to use is the t-test, which is constructed as follows. First, the differences, wall cavity minus indoor (or outdoor) temperatures, are computed for both the dry bulb and dew point (see Table A3). Second, the mean difference is computed by taking the average of the differences in each column in Table A3. Let x_{d1}, x_{d2}, up to x_{dn} be the differences between the first, second on up to the nth pair, respectively, where n is the number of pairs of differences (ten in the example). The mean difference $\bar{x}$ is computed as

$$\overline{x_d} = \frac{1}{n}(x_{d1} + x_{d2} + \cdots + x_{dn}) = \frac{1}{n}\sum_{i=1}^{n} x_{di}$$

Third, the sample standard deviation s_d is computed by first computing the sample variance

$$s_d^2 = \frac{1}{n-1}\sum_{i=1}^{n}(x_{di} - \overline{x_d})^2$$

then computing the square root of the sample variance, that is,

$$s_d = \sqrt{s_d^2}$$

Last, a t-statistic is computed as

$$t_{n-1} = \frac{\overline{x_d}}{s_d/\sqrt{n}}$$

where the subscript $n-1$ for the t symbol is a quantity known as the number of degrees of freedom. This quantity is the divisor for the sample variance s_d^2 shown above.

TABLE A3—Differences between wall cavity temperatures (°F) and indoor and outdoor temperatures (°F).

		Dew Point Temperature		Dry-Bulb Temperature	
Day	Time	Wall, Indoor	Wall, Outdoor	Wall, Indoor	Wall, Outdoor
Day 1	4:30	14.0	5.0	0.0	3.0
	12:30	30.5	15.0	15.0	5.0
	16:45	27.5	9.0	9.0	−3.0
	22:30	26.5	6.5	4.0	5.0
Day 2	6:00	16.5	5.5	−1.0	2.0
	9:30	24.5	4.5	5.0	1.0
	18:30	31.0	11.0	9.0	8.0
	22:30	16.5	3.0	3.0	1.0
Day 3	9:30	10.5	4.5	3.0	2.0
	13:00	16.0	0.5	12.0	7.0
Mean difference, $\overline{x_\alpha}$		21.5	6.5	5.9	3.1
Std s_d		7.4	4.2	5.2	3.2
t-statistic		9.19	4.86	3.59	3.02

NOTE: $t_{°C} = (t_{°F} - 32)/1.8$.

If the null hypothesis is true, then the t-statistic has a t-distribution with $n-1$ degrees of freedom. The t-distribution has a shape which is symmetric but wider than the normal distribution. As the degrees of freedom increase, the t-distribution looks more and more like the normal distribution. To make the decision as to whether or not the t-statistic is consistent with the t-distribution, the t-statistic is compared to tabulated values.

The tabulated value is selected by considering the risk that one wants to take in incurring a Type I error (rejecting the null hypothesis when it is really true). The probability of a Type I error is denoted by α and is referred to as the significance level. Table A4 contains probability points of the t-distribution such that the probability of a value being larger than the probability point is α. These probability points are denoted by $t_{\alpha,df}$ where df is the number of degrees of freedom. A significance level α of 0.05 is often selected. For the data in the example, there is no reason to expect the difference to be either positive or negative prior to collecting the data, so that the tabulated value must correspond to the value of alpha divided by 2. If the significance level is to be 0.05, then alpha over two is 0.025. If the absolute value of t_{n-1}, is larger than $t_{\alpha,n-1}$, then the *null* hypothesis is rejected.

For the example, the values for $\overline{x_a}$, s_d, and t_{n-1} for each of the four computed differences are given in Table A3. There are ten differences and ten minus one degrees of freedom. The corresponding tabulated value of the t-distribution is 2.262. All the calculated t-statistics in Table A3 are larger than this value. It is said that the two groups are significantly different from each other at the 5% level of significance. A more stringent level of significance, 0.01, corresponds to a tabulated value of 3.250. Under this criterion, the difference between the wall cavity and outdoor dry-bulb temperatures is no longer significant.

This is called a paired t-test since the differences in pairs of measurements are computed and the statistical test is based on these pairs.

Other Commonly Used Tests

Comparison to a Standard

The statistical test presented above is only one of a variety of tests that may be useful in building inspections. Sometimes the objective of the inspection is to compare measurements to a standard or code value (c). As in the paired t-test, the mean $\bar{x}$ and standard deviation s of the measurements are computed and the statistic

$$t_{n-1} = \frac{\bar{x} - c}{s/\sqrt{n}}$$

where n is the number of observations. This again is compared to percentage points of the t-distribution.

Two-Sample Comparisons

The paired t-test is a common test that is used when two groups of measurements are taken at the same time. It is said that the measurements are blocked on time. Sometimes the time factor is not part of the experimental setup. For example, a set of measurements in the spring of one year may be compared to those in the spring of the following year to determine if a change in moisture levels occurred over the year. Here it can be assumed that the groups are independent and a two-sample t-test performed. The t-statistic is constructed as

$$t_{n-2} = \frac{\overline{x_1} - \overline{x_2}}{s_p\sqrt{1/n_1 + 1/n_2}}$$

TABLE A4—Probability points of the *t* distribution.

	α							
df	0.30	0.20	0.10	0.05	0.025	0.01	0.005	0.001
1	0.727	1.376	3.078	6.314	12.706	31.821	63.657	318.309
2	0.617	1.061	1.886	2.920	4.303	6.965	9.925	22.327
3	0.584	0.978	1.638	2.353	3.182	4.541	5.841	10.215
4	0.569	0.941	1.533	2.132	2.776	3.747	4.604	7.173
5	0.559	0.920	1.476	2.015	2.571	3.365	4.032	5.893
6	0.553	0.906	1.440	1.943	2.447	3.143	3.707	5.208
7	0.549	0.896	1.415	1.895	2.365	2.998	3.499	4.785
8	0.546	0.889	1.397	1.860	2.306	2.896	3.355	4.501
9	0.543	0.883	1.383	1.833	2.262	2.821	3.250	4.297
10	0.542	0.879	1.372	1.812	2.228	2.764	3.169	4.144
11	0.540	0.876	1.363	1.796	2.201	2.718	3.106	4.025
12	0.539	0.873	1.356	1.782	2.179	2.681	3.055	3.930
13	0.538	0.870	1.350	1.771	2.160	2.650	3.012	3.852
14	0.537	0.868	1.345	1.761	2.145	2.624	2.977	3.787
15	0.536	0.866	1.341	1.753	2.131	2.602	2.947	3.733
16	0.535	0.865	1.337	1.746	2.120	2.583	2.921	3.686
17	0.534	0.863	1.333	1.740	2.110	2.567	2.898	3.646
18	0.534	0.862	1.330	1.734	2.101	2.552	2.878	3.610
19	0.533	0.861	1.328	1.729	2.093	2.539	2.861	3.579
20	0.533	0.860	1.325	1.725	2.086	2.528	2.845	3.552
21	0.532	0.859	1.323	1.721	2.080	2.518	2.831	3.527
22	0.532	0.858	1.321	1.717	2.074	2.508	2.819	3.505
23	0.532	0.858	1.319	1.714	2.069	2.500	2.807	3.485
24	0.531	0.857	1.318	1.711	2.064	2.492	2.797	3.467
25	0.531	0.856	1.316	1.708	2.060	2.485	2.787	3.450
26	0.531	0.856	1.315	1.706	2.056	2.479	2.779	3.435
27	0.531	0.855	1.314	1.703	2.052	2.473	2.771	3.421
28	0.530	0.855	1.313	1.701	2.048	2.467	2.763	3.408
29	0.530	0.854	1.311	1.699	2.045	2.462	2.756	3.396
30	0.530	0.854	1.310	1.697	2.042	2.457	2.750	3.385
40	0.529	0.851	1.303	1.684	2.021	2.423	2.704	3.307
50	0.528	0.849	1.299	1.676	2.009	2.403	2.678	3.261
60	0.527	0.848	1.296	1.671	2.000	2.390	2.660	3.232
70	0.527	0.847	1.294	1.667	1.994	2.381	2.648	3.211
80	0.526	0.846	1.292	1.664	1.990	2.374	2.639	3.195
90	0.526	0.846	1.291	1.662	1.987	2.368	2.632	3.185
100	0.526	0.845	1.290	1.660	1.984	2.364	2.626	3.174
∞	0.524	0.842	1.282	1.645	1.960	2.326	2.576	3.090

Source: SAS (1988).

where n_1 and n_2 are the sample sizes of the two groups, $\bar{x}_1$ and $\bar{x}_2$, the same means, and the sample variance

$$s_p^2 = \frac{(n_1 - 1)s_1^2 + (n_1 - 1)s_2^2}{n_1 + n_2 - 2}$$

is an estimate of the variance. This pooled sample variance is computed by taking a weighted averager of the two estimated variances of the separate groups, s_1^2 and s_2^2. Here, the number of degrees of freedom are $n_1 + n_2 - 2$, which is the divisor for the pooled sample variance, s_p^2.

The null hypothesis is "Are the two groups the same?" The statistic is computed and compared to the *t*-distribution.

More than Two Groups

Sometimes more than two groups are to be compared to do an overall test of significance. The null hypothesis is that there are no differences in the group means. If the groups are independent of each other, then a one-way analysis of variance is done. If the observations are blocked on time as in the example, then a one-way analysis of variance is done with a blocking factor. Details are given in any of a number of introductory statistics books such as *Probability and Statistics for Engineering and the Sciences* by Hines and Montgomery (see Appendix Bibliography).

Confidence Intervals

The preceding discussion revolved around testing hypotheses. An important question may focus on an estimate of the mean value of measurements. To estimate the mean of the measurements, $\bar{x}$ is computed. To determine the reliability of that estimate, a confidence interval can be constructed. The confidence interval is such that the probability that the interval contains the true mean is $1 - \alpha$, where α is the probability of making a Type I error. The interval is

$$\bar{x} \pm t_{\alpha/2,n-1}s/\sqrt{n}$$

Note that the larger the number of samples, the shorter the interval.

SAMPLE SIZE

When establishing an inspection routine, it is useful to know how many measurements need to be done. There are two ways of selecting a sample size. The easiest method is to base the sample size calculation on the confidence interval. A more involved method is based on the test of hypothesis.

Using the confidence interval as specified previously, the width of the confidence interval is

$$2 \times t_{\alpha/2,n-1}s/\sqrt{n}$$

If the confidence interval is to be no wider than δ with 5% confidence, then the sample size is

$$n = (2 \times t_{\alpha,n-1} s/\delta)^2$$

Note that $t_{\alpha,n-1}$ depends on the sample size, indicating that the sample size is computed iteratively. However, this can be easily solved using any computer spreadsheet package.

Returning to the example, say that an additional inspection was being planned. The number of samples is required to detect a difference in dew point temperature between a location in the wall cavity and the indoor temperature δ equal to 5°F. It is known from the previous inspection that the standard deviation of the differences is 7.4°F. The desired probability of a Type I error (α) is 0.05. The required sample size is computed as

$$\begin{aligned} n &= (2 \times t_{0.025,n-1} 7.4/5)^2 \\ &= 8.76 \times t^2_{0.025,n-1} \end{aligned}$$

Looking in Table A4, the values of the t-distribution which could be input into the above equation are in the column under $\alpha = 0.025$. If the degrees of freedom ($df = n - 1$) are 30, then $t_{0.025,30} = 2.042$ and the calculated n is 36.5. Thus, 31 as a sample size is too small. If the degrees of freedom are 40, then $t_{0.025,40} = 2.021$ and the calculated n is 35.8. Thus, 41 is too large. In fact, the number of pairs is between 36.5 and 35.8, so 36 would be an appropriate number of pairs of samples.

This may seem like a large number of samples, but that is due to the fact that the desired difference was quite small relative to the standard deviation. If, instead, a difference of 10°F was sought, then the required number of pairs would be 12.

In doing a statistical test, the probability of rejecting the null hypothesis when it was really true (Type I error) was preset. However, it is also crucial to make sure that the probability of accepting the hypothesis when it is false (Type II error) is not too large. This probability (β) may be quite large if the number of data points is small. The probability decreases as the sample size increases. That is why it is important to ensure that there are enough data points so that relevant differences are picked up by the significance tests.

The exact method for computing the sample size when an estimate of the sample variance is available and α and β are predetermined is complicated, and the reader is referred to the statistics textbooks in the Appendix Bibliography.

Fortunately, there is a simple method available for approximating the sample size which is remarkably accurate for the standard pre-set levels $\alpha = 0.05$ and $\beta = 0.20$. In the procedure, the ratio of the standard deviation to the difference in the means that needs to be detected, σ/δ, is first specified. For comparison of two independent groups, the sample size for each group is 17 times σ/δ to the 1.9 power. For the paired t-test, the number of pairs is 10 times σ/δ to the 1.8 power (see Dallal in the Appendix Bibliography). If one does not want to use fractional powers, raising σ/δ to the power of 2 will give slightly higher, though reasonable estimates of n.

Table A5 contains sample sizes for different ratios of σ/δ for independent and paired samples. If the standard deviation is equal to the desired difference, then ten pairs of samples are required. By doubling the number of pairs, a smaller difference in means (roughly two thirds the size) can be detected.

Sometimes, a measure of variation is not available when planning an experiment. A few initial measurements would help in determining the sample standard deviation. Measurements taken on the first day could be used for this purpose. One measurement is not enough to obtain a measure of variation since the calculated variance would be zero. More than two measurements are recommended, and five would give a fairly good idea of the variation.

TABLE A5—Estimated sample sizes for two sample t-tests.

σ/δ	Independent Groups	Paired Groups
0.25	2	1
0.5	5	3
0.75	10	6
1.00	17	10
1.5	37	21
2.00	63	34
3.00	137	72

THINGS TO LOOK OUT FOR

In using standard statistical procedures, assumptions are usually made about the data. In the ones discussed in this appendix, it was assumed that the data came from a normal distribution, that the data were selected randomly, and that the variance is the same for all points.

Variability

In collecting samples, the inspector must be aware of the amount of variability in the measurements. For instance, a measurement taken repeatedly under all the same conditions is unlikely to produce the same result each time. It is more likely that the measuring device or external factors that can not be controlled yield varying results. Knowledge of this variability will help in planning the number of measurements to be made.

Randomization

When collecting data, an inspector may be concerned about the representativeness of the measurements to the overall situation. To ensure representativeness, randomization of the sampling is important. For example, if three samples are to be taken from one location and compared to three samples of another location, the samples must be collected in such a way as to ensure that any differences in locations cannot be attributed to a time effect.

Randomization also insures the independence of measurements so that standard statistical procedures can be used in the analysis of the results.

Other Sample Design Issues

If several measuring instruments are available for collecting samples, then the arrangement of where and when to use the devices should be carefully considered. The numbers of observations done at each location could vary. However, optimal strategies usually require that equal numbers of measurements be taken at each location.

Distribution of the Measurements

The first assumption is that the observations from a group or scenario all represent the same population. It is usually said that the observations are identically distributed with the same mean and variance. If the sample sizes are very large, then the mean tends to have a normal distribution. If the sample size is small, then the assumption of normality may not be adequate, and in fact use of the assumption could lead to misleading statistical inferences. It is therefore important to be aware of the distribution of the measurement to be done.

A good idea of the distribution of the data can be obtained from prior data collections using the measuring device. It is beneficial to keep on record any prior data sets and analyze them for distributional properties. Histograms can be made of large data sets and the shape determined. If the distribution is symmetrical, that is, the left and right sides are mirror images, then a normal assumption could be adequate. A statistical test for normality can be done to see if the assumption is reasonable. If, however, the distribution appears to be unsymmetrical with a large amount of data toward zero but a few points that are large, then the distribution may be lognormal. In this case, the log of the measurements should be calculated. A statistical test could be done to see if the transformed measurements are normally distributed.

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Case Studies of Moisture Problems in Residences

by George Tsongas[1]

Purpose of the Chapter

The purpose of this chapter is to provide a survey and overview of the results and findings of case studies of moisture problems in buildings. By case studies is meant any field study or pertinent and realistic laboratory study dealing with some aspect of actual moisture problems in buildings. Moisture modeling studies are not included. The chapter describes both research and studies published in the open literature as well as studies conducted by the author. An effort has been made to avoid hearsay, "conventional wisdom," and other noncredible evidence with no factual basis. Most of the emphasis is on relevant U.S. and Canadian studies or experience.

Types of Case Studies Reviewed

The focus is on case studies of shell-dominated residential-type buildings because relatively little published information is available on moisture problems in other types of buildings. The findings for residences may be appropriate for light commercial buildings that act like residences but probably not for heavy commercial or industrial buildings. A distinction is made between older existing buildings and newly constructed buildings. Another distinction is made between studies of buildings in northern climates where the major emphasis is on winter heating and buildings in southern climates where the emphasis is on summer cooling. There are fewer published studies related to summer cooling moisture problems. There are also fewer unpublished case studies cited, in part because the author is more familiar with northern climates. While both laboratory and field studies have been surveyed, the emphasis is on field results of actual buildings. Relevant field tests of unoccupied test huts also have been included. Finally, studies are presented that identify excess moisture problems as well as those that deal with moisture control strategies.

Classification of Moisture Problem Case Studies

For organizational purposes, moisture problem case studies have been broken down into three separate categories: (1) indoor excess moisture problems, (2) exterior excess moisture problems, and (3) excess moisture problems inside exterior walls. Moisture is always present in buildings, but the levels may be low enough so that there are no associated problems. The term *excess moisture* refers to situations where moisture levels are high enough for problems to occur.

When and if they exist, moisture problems within walls usually have the most serious effect on the structure, although they tend to occur relatively infrequently. On the other hand, excess moisture problems and associated biological contaminants inside homes can dramatically affect the health of the occupants, and such problems are rather commonplace. However, until the recent concern over indoor air quality, indoor moisture problems had not received much serious research attention.

Indoor Moisture Problems

Moisture problems that occur within the heated indoor space include: mustiness, dampness, and odors; condensation on windows and sweaty pipes and toilets; window sill staining and damage from excess window condensation; mold, mildew, and stains on surfaces; and basement dampness and leakage. Water vapor in indoor air will condense on surfaces whose temperature is below the dew point temperature of the indoor air. For indoor air at 70°F (21°C) and 50% relative humidity, the dew point temperature is about 50°F (10°C). During the winter, surfaces such as windows are often cooler than the dew point temperature of the indoor air such that condensation will occur. Surface condensation such as window condensation is most prevalent during the coldest outdoor weather.

There is a definite influence of weatherization on the incidence of surface condensation. Adding insulation or storm windows helps reduce condensation because surface temperatures are warmed, whereas house tightening hurts because it increases the indoor moisture levels. In fact, weatherizers have become so good at house airtightening that the incidence of moisture problems is dramatically increasing in weatherized homes.

In order for mold and mildew growth to occur, the mean monthly relative humidity of the air next to the surface must be about 80% or greater [*1*]. This means the local indoor air must be fairly humid, with a relative humidity value generally greater than about 60 to 70%. The latter value is somewhat lower because indoor air is usually warmer than the surface temperature. Mold and mildew occur on cold surfaces where the relative humidity is highest, such as those caused by missing insulation or thermal bridges (local areas that are poorly insulated). It is typically noted on inside surfaces of window frames and exterior walls and ceilings.

The incidence of mold and mildew and other problems

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related to excessively high indoor relative humidities is extremely important because it has recently been connected to biological contaminants that are just now being recognized as causing significant health problems [*2,3*]. Moisture-related contaminants, including allergens that cause allergic reactions and pathogens that cause respiratory infections, are apparently on the rise, in part because of increased emphasis on house tightening and in part because of better recent recognition of the health problems along with improved diagnosis. There is a range of indoor relative humidities that promote optimum health of the occupants. One study [*3*] suggests 40 to 60%, but many building science and health professionals believe the range perhaps should be slightly lower (say 30 to 50%) to avoid the growth of biologicals (such as dust mites) and associated health problems (such as asthma).

Basements are included in the "indoor" category because they often are intentionally heated and many times are unintentionally heated. Furthermore, they often are well connected to the main living space from an air movement (and hence moisture) point of view. Basement dampness and leakage is usually caused by improper ground grading near the foundation, inadequate foundation drainage, leaky foundation walls, or poor flashing details. Often moisture in the ground around a basement is absorbed into the concrete and wicked by capillary action to the inside surfaces of the basement walls where it evaporates into the interior air space (the concrete surfaces often appear dry because of the evaporation). This situation is exacerbated by collection of rainwater next to foundations where downspouts do not drain into a sewer or other suitable outfall.

Exterior Moisture Problems

Exterior parts of the house include all areas outside of the heated living space, except for walls which are classified as a special category because of the considerable interest in them. Exterior problems that can be moisture-related include: roofing and/or attic condensation and frost; roof wood decay; blistering and peeling paint; wood siding shrinkage, cupping, and cracking; hardboard siding buckling; plywood siding delamination; condensation and decay in crawl spaces; and basement leakage due to improper grading or inadequate drainage.

Roofing and attic moisture problems are typically caused either by leaks or because moist indoor air is leaking into the attic. The major cause of some of these problems is often not related to excess moisture. For example, peeling paint is often caused by improper surface preparation or painting when it is too cold, and hardboard siding buckling is often caused by improper nailing.

Moisture Problems Inside Exterior Walls

Excess moisture problems inside exterior walls include high wood moisture contents (which by itself may not be a problem) and wood decay (sometimes called dry rot) and subsequent structural damage. Wood decay is caused by a fungal growth. The conditions required for the fungal growth are warm temperatures (24 to 33°C [75 to 90°F] is optimum, and there is no growth below 10°C (50°F)], high wood moisture content (greater than 30%, with no growth below 20%), and exposure to air [*4*]. Wood normally will not decay in winter because the conditions are not met. In the summer, wood normally dries out except when leaks exist such as roof or siding leaks that wet the wood.

FIELD STUDIES OF INDOOR EXCESS MOISTURE PROBLEMS

Older Existing Homes in Northern Climates

The Iowa Moisture Problem Survey

A survey of 334 Iowa households was conducted during 1988 to obtain baseline data on housing characteristics and energy efficiency to assess the incidence of moisture problems and to identify any relationships between the occurrence of moisture problems and house or energy characteristics [*5*]. Residents typically did not recognize problems caused by excess moisture in their homes (only 17% did). After definition (once prompted about specific types of problems), 98% of the residents reported at least one type of moisture problem. That is a higher incidence of moisture problems than ever seen elsewhere.

The most common types of moisture problems were: moisture condensation on windows (62%), exterior paint peeling (41%), staining of interior window frames and sills (31%), and mildew on walls/ceilings or in basements/closets (23%). Other problems identified were: decay/rotting of interior window frames/sills (20%), moisture/mildew problems in summer (18%), frost/condensation on walls/ceilings (13%), and interior paint peeling (10%). Moisture problems occurred particularly in energy-efficient houses. It was concluded that residents of single-family homes should continue to receive information on how to identify and correct any problems related to excess moisture.

The key finding is the very high percentage of reported moisture problems when the right questions are asked. Of course, the severity of the problems varies substantially. The more serious moisture problems require action, whereas some—such as minor window condensation—do not. Nonetheless, many of the older studies or surveys of moisture problems in homes dramatically underestimate the percentage of homes that supposedly have problems because the proper questions were not asked and those doing the asking did not understand the importance of asking the right question.

Furthermore, responses by occupants may be biased by the available literature that emphasizes that most houses are almost always good enough to resist moisture problems and that the occupants are the cause of most of the problems. This may strongly influence the response rate of people to any survey directed at the incidence of moisture problems. Thus, the Iowa survey findings are probably typical of most housing stock. Moreover, there are no published surveys of the incidence of moisture problems in multi-family housing; the situation there should be even worse for reasons that will be explained later in this chapter.

Finally, most agencies have focused on the durability issues associated with housing moisture problems. Only recently has it become clear that the very high incidence of moisture problems in homes is adversely affecting the health, welfare, and safety of the occupants. Thus, the need for action to resolve the moisture problems is probably more critical than has heretofore been believed. It is a problem that should receive considerably more attention.

The Portland Study

During the 1979–80 winter, the interiors of 103 older homes in Portland, Oregon [4792 degree days (DD)] were inspected and found to have an average indoor daytime relative humidity and temperature of 56% and 20.3°C (68.5°F) [*6*]. The average indoor relative humidity should be considerably higher in the milder fall and spring weather. Mold and mildew were noted in one third of the homes. While 73% of the homes had storm windows, window condensation was common. Only 46% of the homes used a bathroom exhaust fan and 91% lowered the thermostat at night, which can lead to increased nighttime relative humidities. While the homes were not particularly tight (blower test results averaged 16.2 ACH at 50 Pa, which corresponds to a natural infiltration rate of about three quarters), nonetheless there was a clear lack of satisfactory indoor moisture control that leads to high indoor humidities and resultant moisture problems in these older homes. Had these homes been airtightened, say as part of a weatherization program, the indoor humidities and problems would have been even worse.

The Spokane Study

The interior spaces of 96 older homes in arid Spokane, Washington (6835 DD) were similarly inspected during the 1982–83 winter and found to have an average indoor daytime relative humidity and temperature of 47% and 20°C (67°F) [*7*]. Mold and mildew were noted in 38% of the homes. While 96% of the homes had storm windows, 59% had condensation on windows and 36% had mold/mildew on window sills. In this sample of older homes, only 44% used a bathroom exhaust fan, while 61% lowered the thermostat at night, 27% had the clothes dryer vented indoors, 79% had no gutters or downspouts, and 43% (10 of 23) of the homes with partial crawl spaces did not have a ground cover. Even in this colder, drier climate, indoor moisture problems were very prevalent, indicating lack of indoor moisture control.

The Lane County Housing Authority Study

In November 1984, six small existing rental residences operated by the Lane County Housing Authority in Eugene, Oregon were inspected [*8*]. There were numerous complaints of moisture problems in the roughly 400 units in the complex; the six units visited were supposedly typical homes. The average relative humidity (RH) for all six units was 67%. Mold/mildew was observed in three of the six units. There was a minor amount of staining on window sills due to liquid accumulation from condensation; there was considerable window condensation in most of the units.

The bathroom and kitchen exhaust fans in many units were not working properly, some did not have fans, some fans were so noisy they were not used, and some occupants simply did not bother to use them. Clearly the occupants could not be relied upon to operate their fans to keep humidity levels at acceptable levels, especially since they did not understand the need to use exhaust fans to reduce the incidence of indoor moisture problems. Finally, the units had crawl spaces, but they had no ground covers.

The Housing Authority decided to install 36 pint-per-day portable dehumidifiers with automatic defrost control in each of the 400 units to provide automatic moisture removal and control. As a result, the incidence of problems and complaints dropped dramatically. Since their installation, the units have reliably controlled indoor moisture.

Canada Mortgage and Housing Corporation (CMHC) Study

In 1982, CMHC engaged a firm to determine the types of residential moisture problems encountered in different parts of Canada. The resulting survey [*9*] included only moisture problems already reported by CMHC (NHA) inspectors, municipal inspectors, and local housing authorities. Indoor problems included mold and mildew, window condensation and sill damage, and basement damage due to leakage and dampness. It was reported that there were at least 10 000 housing units in Canada which have both indoor and outdoor problems serious enough to cause financial loss. The number of homes then subject to moisture damage represented slightly more than 1% of the NHA housing stock. However, the incidence of such problems was expected to grow. Furthermore, the survey only accounted for those homes where damage was serious and reported because of the need for repair.

Thus, it is reasonable to assume that an even greater proportion of homes have unreported indoor moisture problems like mold and mildew and condensation damage that are primarily aesthetic rather than structural. If even 1% of the roughly one hundred million U.S. dwelling units have indoor moisture damage, then *one million U.S. homes* have indoor moisture damage. If the studies noted earlier are any indication, the existence of indoor moisture problems is much more widespread than just 1% of the housing stock. Clearly, there is a lack of adequate indoor moisture control in a large number of the existing U.S. and Canadian housing stock.

Tri State Homes

One of the most unique and severe cases of moisture damage in residential walls occurred in the large group of manufactured homes known as the Tri State Homes [*10*]. Between 1970 and 1982, more than 5000 such homes were manufactured, 3400 of which were built and installed in Wisconsin. After 1986, extensive wall wood decay was reported. The manufacturing company declared bankruptcy and was liquidated just before reports of moisture damage surfaced. As a result of the extensive wall wood decay and the associated publicity, considerable attention was focused on the attendant indoor moisture problems.

Site visits and home inspections, including a survey of homeowners and airtightness measurements, revealed that the homes were very airtight and poorly ventilated (no exhaust fans), leading to high indoor relative humidities. Mold and mildew inside the homes were common, but no more so than the older less airtight homes inspected in the Portland and Spokane studies [*6,7*]. Medical evaluation showed that the residents of these homes suffered more often from respiratory problems than residents of similar site-built homes included in the study. This appears to be related more to the high level of several pollutants in the homes than to the presence of fungal spores. However, no single individual contaminant could be identified as responsible for the irritant effect. Once again, this was another example of the widespread existence of indoor moisture problems in existing homes. More importantly, it is a major case where indoor moisture problems were conclusively shown to cause an unhealthy environment for the occupants [*11*].

Nova Scotia Interior Moisture Projects

Between January and March 1988, 94 homes across Nova Scotia, Canada, of different sizes, ages, and styles with reported moisture problems were inspected [*12*]. Moisture problems were caused by a combination of poor ventilation and high moisture generation, although other factors were involved. Condensation and moisture damage were most common on window sills, trim, and frames (85 of 94 homes), at outside wall corners (44 homes), on ceilings (33 homes), in closets (25 homes), in bedrooms (24 homes), and in attics (23 homes). While the number of indoor problems was high, the weather is rather severe from a moisture point of view (cold, humid, and windy), especially since there is little or no drying period during the year.

In 67 of the 94 homes, the inspection identified one or more sources of moisture as a potential contributor to the moisture problem in the home. Sources of moisture generation in order of frequency were: stove top boiling, wood stored indoors, showers, leaky or wet basements or crawl spaces, unvented clothes dryers, kerosene heaters, and furnace humidifiers. It is well known that the last two can be important sources of health problems.

While many homes had ventilation systems such as bathroom fans (59 fans) or vented range hoods (30) or a central ventilation system (19), many were undersized (too low a rated capacity) or poorly installed and were not moving sufficient quantities of air. Ventilation improvements were the most often recommended method of resolving moisture problems.

Unexpected findings of the project included: (1) the number of homes with serious deterioration in attic areas (sheathing damage often due to a combination of high interior humidity combined with a flawed ceiling air barrier allowing moist indoor air to enter the attic because of the stack effect), (2) the lack of mechanical ventilation in homes less than two years old, and (3) the number of 20 to 30-year-old homes with high rates of air leakage suffering from mold and condensation problems.

The study concluded that interior moisture problems are relatively widespread, and that they occur most often in homes with electric heat and in newer homes. It also was noted that understanding of moisture problems appeared to be poor among homeowners and contractors, inappropriate remedies often were used, and it was difficult for homeowners to find information and advice about their moisture problems.

In Phase II of this project [*13*], homeowners were surveyed to determine actions taken to resolve moisture problems and the effectiveness of the actions. In addition, five houses had ventilation equipment installed to determine its effectiveness.

A number of conclusions were reached. First, homeowners who acted in a substantial manner upon staff recommendations succeeded in either solving or reducing the moisture problem in their home. More than 75% of the moisture problems encountered during the home inspections were resolved or reduced at a total cost of less than $750 per home with a combination of measures in the following areas: (1) improved mechanical ventilation, (2) reduced moisture generation, (3) draftproofing, and (4) better air circulation. Almost 50% of the homeowners were able to carry out the recommendations without assistance from a contractor. Homeowners did, however, find it difficult to locate proper ventilation equipment, such as 110 ft^3/min fans, wind-up timers, vent hoods, and other fittings in retail stores. In addition, they reported difficulty arranging contractors willing to install low-cost ventilation systems in accordance with good practice. Finally, it was determined that there was no significant increase in heating or electrical costs as a result of operation of the exhaust-only ventilation equipment in the five demonstration houses.

Small Homes Council—Building Research Council (SHC/BRC)

Home inspections were conducted on 670 single-family residences in Champaign County, Illinois, and the SHC/BRC compiled the results in order to determine how widespread and severe moisture damage was within the county [*14*]. All visible surfaces were inspected.

Moisture problems were distinguished from water problems such as roof leaks. The results showed that 5.4% of the homes suffered major moisture damage—that is, damage which necessitated the repair or replacement of structural members (usually floor framing or attic sheathing). Another 35% suffered some sort of moisture damage to the visible surfaces, such as mildew, peeling paint, or deterioration of window finish, although that damage often was quite minor (for example, water spotting on ceilings or sign of condensation on windows). While the damage may be considered minor, the associated health effects may be serious. There was a clear correlation between the presence of evaporative sources of moisture, such as exposed soil in a crawl space, and damage to the structure. The evaporative sources are the concern of construction practice rather than lifestyle.

Miscellaneous Legal Cases

The cases described above have clearly demonstrated that indoor moisture problems are rather common in the United States and Canada. They are classic cases typically caused by an expected combination of weather effects, excess moisture sources, and lack of systems to control excess moisture. Most of the cases that will be described in this and the following sections are rather different in that there was some unexpected but nonetheless commonplace cause, such as leaks.

Severe mold and mildew was found to exist on walls and carpets in a large number of the 72 units in a four-year-old condominium apartment complex in Seattle, Washington. The problem was initially blamed on lack of a wall vapor barrier. The actual cause was traced to a variety of external wall leaks that allowed rainwater to enter the walls from the outside, soak the cellulose wall insulation, and wet the walls and nearby floors. The water leaks occurred where the inexpensive caulk sealing external wood siding and stucco joints deteriorated with age and where exterior sealing was unsatisfactory.

In another Oakland, California case, a strong musty/moldy smell in a kitchen and its cabinets as well as warped hardboard siding were traced to an automatic lawn watering sprinkler that was misaimed and wetted the siding every day. While it is often difficult to recognize and diagnose, sometimes indoor moisture problems are caused by leaks and other external water sources. Incidently, in the Portland Study [*6*] about 12% of the 103 homes had wall leaks that affected the moisture content of the wall cavity wood members or the cavity insulation.

A common example of external water sources often observed in the field by the author is where gutter downspouts are missing or not connected to a sewer or other suitable outfall. The water drains into the ground right next to the foundation, wicks through and under the concrete foundation, enters the crawl space ground, evaporates from the ground (typically when no ground cover exists), and enters the house as a result of normal air infiltration.

Based on unpublished test results from the Building Research Association of New Zealand, the author has estimated the rate of evaporation of moisture from 1000 ft^2 of normal soil to be about 100 lb per day, whereas the rate increases to about 400 lb per day if there is standing water covering the crawl space ground. These results are in agreement with other estimates [*15*]. Obviously the estimated values are highly dependent on soil conditions, but the main point is that large amounts of moisture can evaporate from crawl space soil. Likely a substantial portion of that moisture gets into the house above since infiltration pulls air from the crawl space into the house because of the stack effect. Thus moisture from a crawl space often results in mold and mildew in closets or other interior spaces with poor air circulation and can result in increased indoor relative humidities which then lead to problems. If left uncorrected, it also can result in decay of floor wood members. The evaporation moisture source can be substantially reduced by the addition of a ground cover.

Another legal case involved a very small 1915 Portland home that had an acrid musty smell throughout the house, very bad mold and mildew on the inside of the exterior walls, moldy clothes in bedroom closets, and mold in kitchen closets on exterior walls. The walls were not insulated. There was a gas heater in the living room but no heaters in the other rooms. The house was supported by wooden posts directly in contact with the ground and had no foundation walls. The shingle siding was directly in contact with the ground. Water from the downspouts at the corners of the house soaked the crawl space and wetted the support posts. They, as well as the siding, were rotted out. Rather than fix the source of the problem, the owner drilled holes in the wall shingles to ventilate the walls and even left the 1-in. holes open! That ventilation, of course, cooled the wall cavity and the plaster walls and increased rather than decreased the mold and mildew. This example points out that many people do not understand the effects of moisture in buildings.

In a recent case in San Francisco, a five-year-old home that was one of seven similar units had unusually high moisture contents in the wood members of one of its wall cavities. All the other units had much lower moisture levels in their walls. Inspection revealed that the master bedroom had considerable window condensation during very mild spring weather. Furthermore, there was severe mold on the sheetrock in the master bedroom closet. The relative humidity in the bedroom was found to be about 65%. Inspection in a remote corner of the crawl space revealed a substantial tub leak that had wetted the wall near it, tore up the fiberglass batt insulation in the area as a result of the water in the insulation, and left water pooling on the crawl space ground that was uncovered because a geologist told the owners that the ground needed to breath to release its moisture! Careful inspection of the tub showed relatively small cracks in the tub grouting that were leaking substantially during daily showers. These leaks were the cause of the mold in the bedroom and the elevated wall moisture levels. Various building personnel and the owner had tried without success to determine the cause of the closet mold over a five-year time span.

Another legal moisture problem case involved a municipal pool building in western Oregon. The building houses two large pools, a small whirlpool, locker rooms, exercise rooms, and mechanical equipment rooms. Shortly after the building was built about five years earlier, the sloped metal roof began what was believed to be leaking regularly into most of the interior spaces. It was thought to be caused by a roof leak because the leaking got worse every time it rained. In addition, there was water leaking into light fixtures and collecting in noticeable amounts both inside and outside of the building, and some of the metal hardware inside the building was corroding badly.

The metal roof was repaired to prevent leakage by caulking all seams and installing taller metal seam caps, but the leakage persisted. The mechanical HVAC equipment also was checked to see if any part was malfunctioning and somehow causing the problem, but no problems were noted. The problem later was diagnosed as a simple dew point phenomenon combined with an improper design of the mechanical system that was to provide comfort control of the indoor air.

Given the indoor air conditions for the pool building of about 60 to 65% relative humidity and 27 to 29°C (80 to 85°F), the dew point temperature of the indoor air was just a little less than about 21°C (70°F). Furthermore, the HVAC system did dehumidify the indoor air, but it supplied 10% outdoor air for ventilation, and there was no dedicated part of the system to exhaust indoor air. By virtue of this design flaw, the building was pressurized, and the humid, corrosive indoor air that needed to be exhausted simply leaked out through the building shell wherever it could, including through the cathedral-type enclosed roof cavity with its wooden structural members and its metal roof.

Thus, any time the outdoor air temperature and the adjacent metal roof surface was below the 21°C (70°F) dew point temperature of the indoor air, moisture in the air in the roof cavity condensed on the underside of the metal roof. In western Oregon, the outdoor temperature gets below 21°C (70°F) almost every day of the year, and so condensation occurred most every day. When it rained, the metal roof surface was further cooled, and so the opportunities for condensation increased even further.

The condensed water then flowed down the inside of the roof cavity, collected at wooden battens that supported the metal roof, and eventually leaked out of numerous small openings in the interior and even exterior of the plywood ceiling deck, especially where lighting fixture connectors and conduit penetrated the deck.

After the problem was correctly diagnosed, the roof was opened from the outside in a few locations, inspected, and the moisture content of wooden members measured. Generally speaking, the wood was very wet in many locations, measuring above 50% moisture content in more than one spot. Furthermore, the wooden battens and the plywood decking were decayed in a number of places. The whole roof needed to be replaced.

What is unfortunate is that installation of a few hundred dollar simple exhaust fan to slightly depressurize the building so humid indoor air could not get into the roof cavity probably would have prevented this moisture problem that ultimately cost close to a million dollars. As a first line of attack in designing to prevent moisture problems in pool rooms, the indoor air space almost always should be depressurized.

It also is frustrating to realize that mechanical engineering and architecture design professionals could make such basic design errors in a building where understanding moisture was of such crucial importance. It is further frustrating to realize that numerous building professionals—including maintenance personnel, contractors, and mechanical engineers—were unable to properly and quickly diagnose what is a relatively straightforward moisture problem. It is clear to this author that the fundamentals of moisture in buildings is poorly understood by most building professionals. It is also clear that the concept of the building as a system where each subsystem can and usually does have an effect on all others is even more poorly understood. The lesson to be learned here is that training is badly needed at all levels that focuses on developing a basic understanding of the role of moisture in buildings, especially in the context of the building as a complete system.

Weatherization Cases

Recently in Portland, Oregon, an older apartment complex experienced complaints of increased mold and mildew and window condensation after the complex had ceiling insulation blown in. The mold occurred primarily on the ceilings near the exterior walls. The units had concrete block walls, were very airtight, had no kitchen or bathroom exhaust fans, and were small in size. The units probably had high indoor relative humidities prior to the weatherization.

Sealing leaks and blowing the ceiling insulation tightened the house, resulting in even higher indoor relative humidities. However, the ceiling mold resulted because the ceiling insulation was blown in without eve baffles (that are supposed to keep insulation out of the soffit vents) and did not extend to the outer edge of the ceilings. Thus, the outer ceiling surfaces near the soffitt vents were cold, which coupled with the higher indoor relative humidities, led to mold in that area. Once baffles were added and the ceiling was properly fully insulated, the mold problems were no longer present.

The point of the above case is that poorly executed weatherization can cause indoor moisture problems. Moreover, untold numbers of cases of indoor moisture problems have been created by weatherization of homes by weatherization contractors, utilities, and low-income housing weatherization crews. The low-income homes are much more prone to such problems because the agencies weatherizing them focus on airtightening measures (often using blower doors to find leaks) and because those homes typically have conditions and construction characteristics that make them more susceptible to moisture problems. Furthermore, it is not uncommon for low-income housing weatherization crews to reduce the airtightness of those homes by 25 to 50%, especially with the introduction of high-density blowing of cellulose of wall insulation and the sealing of attic bypasses and duct leaks. Furthermore, the low-income homes are typically small in size, kept cooler than most, more likely to have poor or unused spot ventilation systems or none at all, and have higher than average occupant loads—all of which lead to higher indoor relative humidity levels [*16*].

Typically, about 10% of the homes visited already are too tight and below tightness guidelines [*17*] established by the agencies to avoid indoor air pollution problems, including moisture problems. Building tightness limits for existing homes have been developed, usually based on the ventilation requirements of 15 ft^3/min per person or 0.35 ACH, whichever is greater, set out in ASHRAE Standard 62-1989. These guidelines assume that mechanical ventilation is too expensive and so limit the tightness of buildings as a means of trying to assure adequate fresh air for the occupants.

The situation with weatherization of existing homes may become critical in the near future. While low-income housing weatherization agencies are just now recognizing that airtightening to save energy definitely can lead to moisture problems and consequent health effects, most utilities that are just now expanding their weatherization programs are not aware of the huge potential for such problems. We have seen just the tip of the iceberg. Moisture-related problems in existing homes are already widely present, and the more such homes are tightened the more moisture and health problems we will see.

Moreover, almost all our experience is with single-family detached housing. Yet it would appear that the situation with multi-family housing may be much worse. It simply has not been studied. The units are smaller, there is less exterior wall area through which infiltration occurs that flushes away moisture generated indoors, and the ventilation systems appear to be poorer. The situation may be just as bad in manufactured homes because of their small sizes, high occupant loads, and relatively poor ventilation systems.

Simply stated, indoor moisture control in all types of *existing* homes is a myth. If it happens, it usually occurs by happenstance rather than by proper design. Thus, indoor moisture control in existing housing is a major problem that needs considerable further study.

One other significant cause of indoor moisture problems was noted by Bruce Davis, at the time housing director of the Economic Opportunity Agency in Fayetteville, Arkansas. In that part of the country as well as elsewhere, unvented gas, propane, and kerosene space heaters are commonly in use in low-income housing. It is also common for low-income households to use their ovens to heat the dwelling. One study found that between about 40 and 50% of all urban low-income dwellings are heated with their stoves [*18*].

With such heaters, all the products of combustion, including water vapor, are exhausted directly into the indoor living space. Continuous operation of a typical 30 000 Btu/h unvented heater produces about 8 gal of water per day, which is more than twice that generated by a typical family of three or four (about 3 to 4 gal per day). Some ovens and unvented space heaters can produce up to about 50% more water than that example. Thus, homes with unvented space heaters often have very major indoor moisture problems. Bruce Davis can attest to numerous such cases. Such homes should never be tightened as part of a weatherization program, as the indoor moisture situation can only get worse.

Finally, in working with a Cape Cod, Massachusetts utility doing weatherization of existing homes, it was noted that a majority of homes there had dehumidifiers operating in basements during the summertime to control humidity. This moisture problem appears to be caused at least in part by evaporation of moisture from concrete basement walls and floors; it may also be related to infiltration of humid, warm outdoor air that condenses on the cold concrete surfaces that are below the dew point of the air that enters the basement. This summertime moisture problem is under study by the utility. It appears to be rather common in many parts of the United States and Canada. If nothing else, it results in considerable energy use to operate the dehumidifiers.

Incidently, the author has developed a detailed residential moisture problem assessment form/checklist for the utility to help its weatherization personnel assess and resolve moisture problems; it is presented in the Appendix.

Older Existing Homes in Southern Climates

Gulf Coast Masonry Wall Homes Field Study

Moisture problems in hot and humid southern climates are fairly common, but there is little field study documentation in the open literature (in part perhaps because such "problems" are assumed to be fairly normal). Trechsel et al. [*19*] conducted a survey of 86 houses with masonry walls in Pensacola Naval Station, Florida. Of those houses, 30% had current, past, or potential moisture problems and 48% had mildew problems. A total of 66% had mildew or moisture problems, or both, and only 34% had neither moisture nor mildew problems. Moisture was commonly observed in the gypsum board, the source of which was rainwater penetration through cracks in the masonry walls and at windows.

Of 28 rooms with identified moisture problems, 26 (93%) were bedrooms. Problems also were found in bathrooms and mechanical rooms, but were not counted. No problems were found in living rooms. Of the 28 moisture problems, 61% were under or next to windows, and 39% were either on walls without windows or at some distance from the window. Inadequate wintertime ventilation along with insufficient winter heat, particularly in bedrooms, contributed to the moisture problems.

Florida Air Conditioning System Studies

Over the past few years, the ductwork of hundreds of air conditioned homes in Florida have been examined and sealed. It has been found that the ducts are leaky, which affects energy use and moisture problems within the homes. Leaky supply ducts in attics simply waste energy, but leaky returns in attics often suck in hot, humid air from the attic that causes poor air conditioning performance and sometimes makes the houses more humid than without the air conditioning. This leads to moisture problems like the growth of mold and mildew. Sealing the ductwork has been found to solve the problems.

Operation of forced air distribution systems also has been found to create substantial pressure imbalances within the homes, often sucking hot and humid outdoor air into wall and other cavities where the moist air then condenses on relatively cool surfaces exposed to air-conditioned air. That, too, has led to indoor moisture problems and could very well be the source of health problems.

Newly Constructed Homes in Northern Climates

The Northwest Wall Moisture Study

In 1986–1987, the interior living spaces and the ventilation systems of 86 newly constructed houses in the Pacific Northwest were inspected in detail to determine if building them to energy-efficient standards with more insulation [at least R-3.3 $m^2 \cdot K/W$ (R-19°F$\cdot$ft$^2\cdot$h/Btu) in walls] and relatively airtight with an air-vapor retarder causes indoor moisture problems or damage [*20,21*]. The test houses were located in three climate regions: 50 in the metropolitan Seattle-Olympia area, 16 on the rainy Washington coast, and 20 in the cold Montana region. The 86 test homes selected were chosen from 257 randomly selected candidate single-family homes, almost half of which had moisture problems.

The homes ranged in age between a few months old and about three years old. Of the 86 test homes, 73 had an air-to-air heat exchanger (AAHX); the others had a dehumidifier. At the time of the study, whole house exhaust-only ventilation was not in use in the region. The mean air change rate of the homes, as determined from blower door tests of some but not all of the homes using the Lawrence Berkeley Laboratory methodology [*22*], was 0.28 ACH.

Numerous moisture-related problems were observed within the homes, primarily because of inadequate moisture control and consequent high indoor relative humidities. One third of these new homes had mold and mildew on indoor surfaces such as walls, one third had mold and mildew on window frames and/or sills, almost three quarters had condensation on window glass and frames, and one quarter had window sill damage as a result of window condensation.

A majority of the ventilation systems, including spot exhaust fans and air-to-air heat exchangers, were not working as well as expected or were not being used by the occupants. Overall, for a variety of reasons there was no AAHX ventilation in about one third of the homes, no kitchen ventilation in almost two thirds of the homes, and no bathroom ventilation in about half of the homes. Of the bathroom exhaust fans that did work, the actual exhaust flow of the systems, including ducts, that were measured was only about half of the rated capacity of the fans. All of these ventilation system problems resulted in inadequate removal of excess moisture.

The findings of the study dramatically point out the need for better indoor moisture control in these and other new homes. For future tightly built homes, moisture control must have a much higher priority in their design, construction, inspection, and ongoing operation. Specific recommendations to improve indoor moisture control through better ventilation, dehumidification, and automatic control of such systems were made to researchers, builders, and contractors; building code officials; and energy-efficient home occupants.

The Effect of Ventilation on Indoor Moisture Levels

Most indoor moisture problems are related to too much moisture (i.e., too high relative humidity) within the heated living space. A typical family generates about 20 to 24 pints of water vapor per day (about 3 gal), the majority of which is due to respiration and perspiration (see Chapter 8). That moisture, which is continuously added to the interior space, must be removed in order to maintain satisfactory indoor conditions. Typically, the water vapor generated indoors is removed or flushed out by the infiltration of cold, dry outdoor air, often with the help of mechanical ventilation and/or dehumidification. In very cold climates where the outdoor air is very dry (cold air holds little water vapor), natural infiltration and ventilation usually works well during the winter. However, in mild and humid climates, or during fall and spring even in areas with cold winters, the outdoor air may be almost as moist as the indoor air, making infiltration and ventilation less effective in removing the indoor moisture. In such cases, possibly continuous ventilation or more likely dehumidification may be necessary to maintain satisfactorily low indoor moisture levels.

Indoor Moisture Control Using Ventilation

The traditional approach to indoor moisture control is to utilize ventilation. In older homes, spot ventilation in the form of bathroom and kitchen exhaust fans has been the only mechanical ventilation. Because such systems often are subpar or not used, ventilation has not proven to be particularly effective in older homes. Often older homes have been relatively leaky, which has resulted in sufficient natural ventilation (infiltration) to control indoor moisture levels, albeit somewhat poorly in many climates and situations.

In newly constructed homes, spot ventilation is now being augmented with additional central ventilation using air-to-air heat exchangers (AAHX) and whole house exhaust-only ventilation systems. Yet as noted above [*20,21*], these systems have not provided satisfactory indoor moisture control. Part of the reason is that they have not been used as much as needed, if at all, and another part is that the systems often have not been designed or installed properly so that they work as they should.

However, another important reason that is usually not recognized is that all ventilation systems do not provide anywhere near the actual ventilation flow that one expects based on the nominal or rated capacity or flow rate. For example, in the Northwest Wall Moisture Study and other studies measurements of flow through bathroom exhaust fan systems, including the ductwork and terminations, have found the measured ft^3/min flow rate typically to be about half of the rated value [*20,21*]. Thus, a 50 ft^3/min fan system has a measured flow rate of about 25 ft^3/min.

There is one other factor which is not well understood that leads to a further reduction in the actual ventilation when an exhaust fan is turned on. This phenomenon can be explained as follows. Since in cold climates during the heating season, air is naturally leaving the building near its top (exfiltration) and entering near its base (infiltration), there is a region in between where there is no flow. That region is known as the"neutral pressure level or plane." Above that plane the pressure of the indoor air is greater than that of the outdoor air, whereas below the plane the pressure of the indoor air is less than that of the outdoor air. If there is no wind and the locations of any openings in the building shell are evenly distributed, then the neutral pressure plane will be at the mid-height of the building.

If a ventilation fan exhausts air at the ceiling level during cold weather when there is no wind, then the total airflow out of the building is the sum of the mechanical ventilation exhaust airflow plus the natural exfiltration. This must be equal to the amount of air entering the house due to infiltration. In order for the infiltration to increase when the fan is turned on, the surface pressures must be redistributed such that the neutral pressure plane moves upward.

When the plane rises, the exfiltration that occurred before the fan was turned on decreases. In a sense, some of the air that was exfiltrating when the fan was off is mechanically exhausted when the fan is on. Thus, the real additional ventilation of the house when an exhaust fan is turned on is less than the measured airflow through the fan system. The net actual ventilation is only about half of the measured flow rate through the exhaust fan system. For example, if a 25 ft^3/min airflow is measured through a nominal 50ft^3/min bathroom exhaust fan, the real additional ventilation of the house is only about 12 ft^3/min. Thus, the actual increase in ventilation when an exhaust fan is turned on is only about one quarter of the nominal or rated flow rate! This effect has been measured by Palmiter [*23*].

What this means is that exhaust ventilation systems do not do what they have been supposed to do for all these years. The conventional sizing rules simply provide inadequate amounts of ventilation.

This problem is further compounded by the fact that occupants seldom run their spot ventilation systems such as bathroom fans for more than 5 or 10 min (if at all). Given the above results about actual ventilation versus rated capacity, the fans should be operated four times longer to provide sufficient ventilation. It is no wonder that ventilation has been ineffective in controlling indoor moisture problems.

In order for it to work, fan capacities have to be markedly increased or operating times have to be increased. Operating times can easily be increased by using automatic controls such as automatic dehumidistats or timers. These controls turn the fans on when indoor humidity levels rise above preset values, and the fans run long enough to reduce the relative humidity to the set value and then automatically turn off. No occupant action is required. In the author's own home, the bathroom exhaust fan is controlled with a dehumidistat. After a shower, the fan typically runs about 1 h before automatically turning off (the measured flow rate is 40 ft^3/min).

Indoor Moisture Control Using Dehumidifiers

Another approach to controlling indoor moisture control that has proven successful in a wide range of conditions is to install a portable dehumidifier. Dehumidification is probably the most effective strategy for houses with indoor moisture problems, especially in mild and humid conditions since during such times ventilation may not be particularly effective.

One U.S. field study by the author [*24*] in which the performance of a dehumidifier was monitored in an actual home found that an indoor relative humidity of 50% or somewhat less could easily be maintained in a home that would otherwise have indoor relative humidities in the mid-60s. Two Great Britain field studies also found that dehumidifiers work well, even at fairly low indoor temperatures [*25,26*]. The author is presently field testing a new high-capacity dehumidifier, and preliminary results indicate that it can maintain an indoor relative humidity of about 40 to 45% while costing less to operate than a conventional residential dehumidifier.

Field experience that is seldom published has resulted in a useful set of selection-and-use recommendations. A model with automatic defrost control needs to be selected so the unit will operate most effectively at typical winter indoor temperatures. Otherwise the coils will frost or freeze up, and little or no water will be removed, even though the unit appears to be running. Since even units with automatic defrost control still frost up a little bit at low indoor temperatures, it helps to locate the unit in a small room such as a closet so that the heat from the unit warms the air, reduces frosting, and thus results in the unit operating more efficiently.

It also is important to select a model with large enough capacity (say greater than 36 to 40 pints per day water removal capacity) so that sufficient water vapor can be condensed out of the indoor air to maintain satisfactory indoor relative humidity levels during non-summer conditions when the indoor conditions are cooler. See the July 1990 *Consumer Reports* magazine for assistance in selecting an appropriate model (about $300). If possible, locate the unit on a shelf in a laundry closet so the washer drain can be used for disposal of the collected condensate. Any closet will do if the door is louvered or undercut, but then a drain line needs to be plumbed. Avoid installing dehumidifiers in bedrooms because their noise can be bothersome. If that is the only available location, then install a timer so the unit will not operate during sleeping hours. Note that dehumidifiers generally are not added to forced air heating systems because of the relatively very high cost to do so.

In most cases, annual operating costs should be less than $50. The operating cost is for electricity, but it should be noted that the units act as space heaters that displace the need for the main home heating system. Moreover, the units condense water out of the air and that releases "free" heat, so they are rather efficient. In the U.S. field study noted above [*24*], the free heat amounted to 60% of the purchased energy. For electrically heated homes with elevated moisture levels that need to be controlled, installing a dehumidifier may be economically justifiable as an energy conservation measure; thus, a moisture problem may turn into a energy resource.

FIELD STUDIES OF CRAWL SPACE MOISTURE PROBLEMS

Most state building codes require the use of crawl space ventilation and many require installation of a ground cover. Ventilation is intended to help dry out any moisture that might get into the crawl space, while the purpose of a ground cover is to reduce the input of moisture from the ground caused by evaporation from the surface of the soil. Conventional wisdom, especially within building codes agencies, has it that crawl space ventilation is absolutely necessary in all climates and that the addition of a ground cover reduces the amount of ventilation area needed, typically from about 1 ft^2 per 150 ft^2 of floor area without a ground cover to about 1 ft^2 per 1500 ft^2 of floor area with a ground cover, depending on the vent screen type [*27*]. However, it is generally believed that some ventilation is still necessary even if a ground cover is in place.

While the importance of a ground cover is irrefutable, the effect of the degree of coverage has been of some concern. More importantly, there is now growing research evidence that crawl space ventilation may not be necessary. In fact, many building scientists now recognize that in some warm, humid climates where homes are air conditioned, venting in the summer may actually increase the incidence of condensation and subsequent wood decay and structural damage. The humid, outdoor air acts as a source of moisture, and the floor temperatures in air conditioned homes are often below the dew point temperature of the ventilated crawl space air. Sealing the vents in the summer in such situations typically will reduce the incidence of condensation. The field studies described below deal with these and other questions.

University of California Ventilation and Ground Cover Study

Recent efforts to save energy have resulted in the use of insulated crawl space foundation walls in combination with a ground cover and reduced area crawl space vents that close automatically when outdoor temperatures are low [typically below about 4°C (40°F)]. That approach raised concern over the possible effect on wood moisture levels, especially in slow-draining soils. A field study to answer such concerns was undertaken by Quarles [*28*] to examine the effects of the presence of a ground cover and of ventilation on the moisture content of wood framing members in a crawl space in slow-draining soil.

The test home was located in Richmond, California (in the San Francisco Bay area). Wood moisture contents were monitored over a 16-month period with resistance-type moisture probes while amounts of ventilation and ground coverage were varied. Venting strategies tested included: standard venting (1 ft^2 per 150 ft^2 of floor area), reduced venting (1 ft^2 per 1500 ft^2 of floor area), and no venting. Ground cover levels included 0, 75, 90, and 100% coverage. Testing was not conducted with no ground cover and no venting because with no cover and reduced ventilation mold began to grow on the joists in one corner of the crawl space. Soil moisture and crawl space relative humidity and temperature also were monitored.

Results showed that, with venting reduced to 1 ft^2 per 1500 ft^2 of floor area, adequate protection against high moisture contents could be obtained with as little as 90% ground cover. The results of this study indicated that adequate protection against excessively high wood moisture contents in crawl spaces can be obtained with any of the following treatment combinations: (1) standard venting, no ground cover, (2) reduced venting, 90% ground cover, (3) reduced venting, 100% ground cover, and (4) no venting, 100% ground cover (and probably 90% ground cover). The critical factor in maintaining low wood moisture contents with reduced and no ventilation was maintaining adequate ground cover. At the reduced ventilation level, ground coverage somewhat greater than 75% could assure moisture content levels below 20%. With no ventilation, coverage of about 90% or better provided adequate protection against elevated moisture levels.

These results generally confirm those from many different regions of the United States reported in previous publications cited in Quarles' paper [*28*]. In particular, Duff conducted two separate investigations in the Southeast in a test home built over a well-drained soil [*29,30*]. He reported that excessive moisture content conditions (traditionally defined as those in which the wood moisture content exceeded 20%) were avoided as long as at least 90% of the ground was covered, even when the perimeter stem wall vents were completely closed. Moody et al. [*31*] also reported that closing crawl space vents in a Tennessee home did not result in excessive wood moisture content. All these results reinforce the need and importance of using a ground cover vapor retarder, even if imperfect, especially when reduced or no ventilation is used. They further suggest that crawl space ventilation is not necessary for moisture control and may even be detrimental in humid regions. Unvented crawl spaces are, of course, better from an energy efficiency standpoint than vented ones.

Quarles' results also showed that wood moisture contents could vary significantly within a relatively small crawl space, suggesting that if moisture problems do occur, they often are localized, as also was noted by Choong and Cassens [*32*].

Measurements of Moisture in New Jersey Crawl Spaces

Wood and crawl space air humidity measurements were made in 15 crawl spaces in a New Jersey development [*33*]. Six of the crawl spaces had their masonry block walls insulated with 1-in.-thick extruded polystyrene panels. At the same time, the ground was covered with polyethylene sheets to reduce moisture transport from the wet ground below these houses. In three of the retrofitted houses, the vents in the crawl space were sealed, while in the others vents were left open. The remaining houses did not receive any crawl space retrofits and had open vents. Periodic visits were made to measure air humidity and wood moisture in these crawl spaces over the period of a year. Seasonal variations of wood moisture content were noted with higher values occurring in the summer months. The relationship between air humidity and wood moisture content in crawl spaces was determined.

For the insulated crawl spaces, there was little difference in moisture content between crawl spaces with vents open and those with vents closed; in both cases, moisture contents stayed within safe limits. In three of the six untreated crawl spaces, however, the average wood moisture content exceeded 20% for at least part of the year, with very high levels at some locations. The results suggested that if the ground has been covered with a vapor retarder (i.e., ground cover), leaving crawl space vents open is not necessary to contain moisture within safe levels. While most code jurisdictions require crawl space ventilation, this study suggests that it may not be necessary.

Tennessee Valley Authority Survey of Weatherized Homes

Thirty-six existing homes that had been weatherized and had complaints of subsequent moisture problems were visited and examined in the early 1980s [*34*]. The problems were found to be more common and varied than anticipated. Three types of excessive moisture problems were found, mainly inside or under homes, with the most serious being related to improper crawl space ventilation, improper control of either surface or free water, or a combination thereof. Discussion included the deleterious effects of dimensional changes caused by excessively rapid drying when a crawl space ground cover was installed. Moisture contents of the substructure of each house were measured and generally fell close to or below the fiber saturation range of wood. However, visible signs of condensation or surface water were noted in 78% of the houses, often located in floor insulation. One sixth of the homes had visible decay in floor joists or other floor members. There was no indication of whether or not the floor condensation was related to air conditioning of the indoor space.

Field evidence from various unpublished sources suggests that such crawl space wood decay problems occur relatively frequently in southern climates, but relatively infrequently in northern climates. In published studies directed by the author of hundreds of both new and older existing crawl space homes in the Pacific Northwest [*6,7,20*], wood members in crawl spaces were inspected for high moisture contents or wood decay. Yet in all those cases, there was never a single case of elevated moisture contents (near or above the fiber saturation point of about 30% [*4*]) or wood decay, except in a few isolated cases where wood members were in direct contact with the ground.

In the Northwest, the winter air is cold and dry, and normal infiltration of that air into the crawl space and floor probably keeps the wood members dry. In the summer, the air is warm but dry, which again keeps the wood fairly dry. However, in southern climates the summer air is quite humid and a source of moisture in ventilated crawl spaces. The moisture can easily condense on the floor in air conditioned homes since the floor surface is then often below the dew point temperature of the air. It is probably best not to ventilate crawl spaces in such climates. If so, the codes that require crawl space ventilation should be changed.

National Research Council Saskatoon Study

Moisture contents were monitored in the wood members of three floor insulation configurations in an outdoor test facility in Saskatoon, Saskatchewan, Canada from mid-December 1989 to mid-May 1990 [*35*]. The three configurations included: floor joists with a polyethylene vapor barrier about 30% through the batt insulation and caulked extruded polystyrene on the inside face, floor joists with caulked extruded polystyrene on the inside face, and floor joists with caulked extruded polystyrene on the inside face and a polyethylene vapor barrier on the cold side of the rim joist. The room's indoor relative humidity was maintained at 50%, and the room was pressurized 20 Pa above ambient to maintain an airflow through the building envelope from inside to outside to provide high moisture stress conditions. Further details of the study are presented in the later section on wall moisture field tests.

In all three configurations, the moisture contents were low, with maximum values in all three cases of about 10%. However, in the third case the moisture pin was located on the warm side of the rim joist, not on the cold side against the vapor barrier. Thus, there is the possibility that the moisture content is considerably higher on the cold side of the rim joist.

Canada Mortgage and Housing Corporation Study

A study of crawl space moisture problems in western Canada provided answers regarding a variety of both successful and unsuccessful techniques for curing moisture problems and maintaining satisfactorily dry crawl space conditions [*36*]. One house had a spring in the crawl space, so the builder installed extra vents to the outdoors and a ducted supply of warm air. Both approaches were ineffective in attempting to dry the crawl space.

Another house had high humidity levels throughout the house and a persistent musty odor in the living room. The crawl space had a concrete slab but no ground cover beneath it. There was so much water pooling on the crawl space floor that the builder suspected a leak. In was then noted that the brick chimney terminated at the subfloor level above the crawl space. It appeared that moisture-laden air from the crawl space was rising up the chimney and forming condensation which then dripped down onto the crawl space floor.

The builder first installed a high-capacity exhaust fan with dehumidistat control, but that was not able to reduce the relative humidity in the crawl space. Apparently the rate of evaporation just increased. Next the insulation was removed from the crawl space walls to make them warmer and hopefully reduce the amount of condensation. But that did not solve the problem either.

Sheltair Scientific (the research group performing the study) installed a 6-mil polyethylene ground cover over the concrete slab and then poured a second slab over the ground cover. The relative humidity in the crawl space dropped to an acceptable level, and the moisture content of the sub-floor, joists, and header were substantially reduced to safe levels.

FIELD STUDIES OF BASEMENT MOISTURE CONDITIONS

Underground Space Center Basement Foam Insulation Study

The thermal performance of both exterior and interior full wall R-1.8 $m^2 \cdot K/W$ (R-10 $ft^2 \cdot h \cdot {}^\circ F/Btu$) extruded polystyrene insulation was examined in a new foundation test facility in Minnesota while also investigating the effect of adding wall insulation on moisture transport into the basement [*37,38*]. Both poured masonry and concrete block walls were examined with the basement temperature maintained at 20°C (68°F). No waterproofing or dampproofing measures were applied. Great care was taken to seal the basement ceiling and maintain a zero temperature gradient across it. A constant rate of dehumidification was provided in each 20 by 20-ft (6 by 6-m) basement test module to measure the moisture transport into the basement.

The interior and exterior foundation insulation applications of the same thermal resistance and covering equivalent surface areas yielded almost identical energy savings on an annual basis. In contrast, the water vapor transport-retarding properties of the exterior and interior insulation placements showed a significant difference.

The uninsulated poured concrete mode allowed almost 50% more moisture into the test cavity than its uninsulated concrete block counterpart due to its higher effective permeability. The uninsulated concrete block module had a dehumidifier condensate weekly volume that ranged between 3.6 and 6.6 gal. In comparison, the block module insulated on the exterior yielded only between 2.5 and 5.7 gal per week, which was 23% less on average than its uninsulated counterpart. However, the module with exterior insulation allowed 2.3 times as much water to pass through the below-grade envelope as did the module with interior insulation at a constant rate of internal dehumidification. This also resulted in a lower average relative humidity of 49% in the internally insulated module compared with 55% for the externally insulated module. Thus, interior extruded polystyrene insulation placement is preferable because of its superior vapor transport retardation capability. The results do not apply to fiberglass foundation insulation nor do they consider the effect of frost penetration into the basement wall.

It should be noted that these research results may have relevance to a common basement moisture problem wherein a dehumidifier is needed in the summertime to control musty odor or mold and mildew associated with elevated relative humidities. The application of interior foam insulation to an existing basement wall may help reduce summer moisture transport into the basement so that a dehumidifier is needed less or even not at all. Since summer dehumidifier operation consumes energy, applying interior insulation may reduce the associated energy cost and make the retrofit insulation more cost effective as a winter heat energy savings measure. This possibility should be investigated.

LABORATORY AND FIELD STUDIES OF ATTIC CONDENSATION

The studies discussed in this section deal only with condensation in attics in northern climates. The author does not know of any published attic moisture problem studies undertaken in southern climates. The studies presented are aimed at developing a better understanding of the dynamics of moisture in attics to help develop improved guidelines to prevent attic moisture problems.

Moisture problems in attic wood members have been a source of concern for the structural integrity of homes. One of the major problems is the migration of water vapor from the living space into the attic. Moisture can potentially condense in cold parts of the attic, thus possibly leading to mold growth, wood decay, and structural damage. Dutt [*39*] has shown that moisture transport in and out of attics via air movement greatly outweighs moisture transport by diffusion, showing that the best way to keep moisture out of attics is to seal possible air infiltration routes between the living space and the attic. Recent research has focused on the role of moisture storage in the attic wood members.

National Bureau of Standards Laboratory Study

A series of attic ventilation tests were carried out by Burch et al. [*40*] in a small test house with a pitched roof/ventilated attic, all of which was located inside an environmental chamber. The attic was exposed to a series of steady and diurnal outdoor temperature conditions. For some of the tests, the attic was closed off without ventilation and house air was induced to exfiltrate through the ceiling into the attic.

An unexpected finding was that attic condensation at the roof sheathing did not occur under any of the test conditions. The attic wood surfaces adsorbed water vapor and maintained the wood surface dew point temperature below the roof surface temperature, thereby preventing condensation. It was noted that it would take long periods of adsorption (more than three months) before condensation would occur. Because the roof also was found to actually give up moisture, this experimental study confirmed the dynamic nature of roof adsorption and desorption.

These results should not be construed to imply that condensation will not occur. It is often noted in the field, especially when large attic leaks exist in houses with high indoor humidity levels. The importance of ceiling leaks was recognized in this study. It is conjectured that a higher indoor relative humidity than the 44% used in the study coupled possibly with localized attic leaks might have resulted in localized condensation, as is often seen in the field.

Princeton Attic Field Studies

Harrje et al. [*41*] measured the seasonal variations in wood moisture content in two New Jersey attics. Wood moisture levels were measured using two types of electrical resistance probes. In one house's attic, measurements in wood sheathing revealed large seasonal variations. The moisture content was highest in winter, fell in the spring, reached its lowest value in the summer, and increased again in the fall. The north sheathing moisture content was high—approaching 19%—in the cold part of the year, compared to 10 to 11% for the ceiling joists, roof rafters, and the south-facing sheathing. However, it dried out at a rapid rate in early spring and became identical in moisture content to other attic wood. One important factor in the drying seems to be the increased solar radiation on the north-facing roof. Measurements in a second attic showed extensive condensation and very high moisture content in the winter with rapid drying in the spring and no sign of wood decay.

In addition, the attic wood moisture adsorption/desorption rate averaged over a season was shown to make a small but noticeable contribution to the total attic moisture balance, which was dominated by airflow to and from the attic. In order to relate long-term trends with short-term variations, measurements of attic air humidity were also attempted, but proved to be unreliable.

Lawrence Berkeley Laboratory Attic Humidity Field Studies

Cleary and colleagues at LBL monitored the attic of a single-family unoccupied house in the mild climate of Oroville, California over the four-month period of January through April 1984 [*42–44*]. The purpose was to provide measured data that would help develop a model of the dynamic moisture characteristics of attics so as to help develop better guidelines for attic moisture control, including ventilation needs.

While in the past it has been assumed that an attic was an inert structure on which moisture would either condense or pass through unaffected, these studies conclusively showed that the wood members in an attic are in constant flux, absorbing and releasing moisture. This moisture cycles on a daily basis and also seasonally. Furthermore, there is considerable flow of water into and out of the roof sheathing. Part of the flow of water into the sheathing is from ventilation air. A simple model to predict the seasonal variation of the wood moisture content was developed using hour-by-hour measurements of wood resistance, attic, and outside dew point and meteorological variables to validate the model.

Northwest Wall Moisture Study

The attics of 86 newly constructed homes in Washington (66 homes) and Montana (20 homes) were inspected during the 1987 winter for signs of moisture damage, and measurements were made of the moisture content of roof sheathing and rafters [*20*]. Generally speaking, the wood moisture contents were less than 20% except in a few cases where exhaust fans were exhausting into the attic air space rather than outside the attic. In one such case, the roof was severely rotted. There were a few cases of mold and minor frost coatings on the underside of the sheathing, but it was not considered deleterious.

Alberta Building Envelope Moisture Accumulation Field Study

Tests were carried out during the 1988–1989 and the 1989–1990 heating seasons on a single-story instrumented house with a full basement and gable end attic in Edmonton, Alberta, Canada [*45*]. A dual tracer gas technique was developed to monitor indoor infiltration and attic ventilation rates and to infer indoor-attic exchange rates. The house was monitored in two attic ventilation configurations: one with gable vents and the other with soffitt eaves and a roof-mounted turbine ventilator. Moisture contents of the wood members were measured with moisture pins.

Attic ventilation rates varied linearly with wind speed, with considerably larger rates for the soffit-turbine configuration. Any stack effect was small by comparison. Indoor-attic exchange rates, which convected large amounts of moisture into the attic, varied up to a maximum of 40% of the indoor infiltration rate. The exchange rate did not depend on the wind speed, but it did show a weak dependence of the indoor-outdoor temperature difference (the stack effect).

The roof sheathing moisture content remained below 10%

moisture content by weight without any seasonal accumulation of moisture. Instead, short-term (on the order of a week) moisture accumulation occurred during cold weather followed by drying when milder temperatures prevailed. The attic ventilation during periods of warmer temperatures removed all of the moisture deposited during the cold weather and so was effective in controlling attic moisture deposition.

Weatherization Studies

The author has been involved with state low-income housing and utility weatherization programs throughout the northern United States. It has become clear that attic condensation occurs nearly always only when there is a leak in the ceiling that allows humid indoor air to enter the attic due to the stack effect or room pressurization caused by operation of a forced air distribution system. As the indoor air enters the attic, the water vapor in that air condenses on some cold surface. Unfortunately, there are numerous ways and places where indoor air leaks into the attic, including attic bypasses, ventilation fans that exhaust directly into the attic rather than the outside air, leaks in attic forced air system ductwork, and leaks around vent pipes, electrical fixtures, and attic hatches. Wet insulation, elevated wood moisture contents, and even wood decay are often noted during weatherization inspections. The lesson is that careful air sealing to decrease air leakage from houses to their attics in order to reduce space heating costs will usually greatly reduce and even eliminate most such moisture problems. In addition, while most weatherization programs emphasize adding attic ventilation whenever attic insulation is installed, proper ceiling air sealing is probably much more important. If done properly, there would be little or no need for additional attic ventilation, and more energy would be saved.

FIELD STUDIES OF ROOFING MOISTURE PROBLEMS

Flat Roof Condensation/Leak Study

An investigation was undertaken in June 1985 to determine the cause and resolution of existing roof moisture damage in three large flat-roofed buildings near Medford, Oregon [46]. The roofs were wood-framed with plywood inner and outer deck surfaces, R-1.9 $m^2 \cdot K/W$ (R-11 $ft^2 \cdot h \cdot °F/Btu$) batt insulation, and a thin rubber membrane covering the outer plywood surface. The buildings were constructed in the early 1970s. Roof moisture damage problems included numerous cases of water dripping from ceilings into the interior of the buildings, a hole in the outside surface of the roof of one of the buildings, and ice damage inside a building with a freezer room.

The two major candidate causes were a leak of water from the outside into the roof cavity that was causing leakage into the buildings and possible structural damage due to wood decay, or an accumulation of moisture in the roof cavity from condensation of water vapor migrating in the wintertime from the inside of the building toward the outside. As a result of inspection, including making openings into the roof cavity, and moisture measurements, numerous leaks of water from the roof cavities into the interiors of the buildings were observed as were high wood moisture contents in some locations and even some wood decay and structural damage. The roof ventilation system also was found to be impaired because ventilation air was inadvertently blocked during construction.

All the evidence strongly suggested that the roof moisture damage was caused by the fact that, while not easily observable, the exterior rubber roof surface deteriorated to such an extent that water was slowly leaking into the roof cavity. It was decided that the flat roof natural ventilation system, even if not impaired, would not have been able to provide enough airflow to dry out the moisture from a leak. Finally, while condensation is often blamed for roof moisture damage, the evidence in this case indicated that it was not a factor. Sometimes it is, and sometimes it isn't. This is obviously not a unique case, but rather is one of many that happens to be documented in the literature.

LABORATORY STUDIES OF ROOFING MOISTURE PROBLEMS

Building Research Association of New Zealand Study

A laboratory investigation of solar-driven moisture transfer through absorbent roofing materials was undertaken because moisture problems were noted in the field in cases where cellulose-fiber-reinforced cement shingles were used in cathedral-type roof applications in New Zealand [47]. It was speculated that the moisture transfer through the roofing was caused by solar heating rather than leaks or other causes. Thus, the purpose of the research project was to try to determine the cause of the moisture transfer that was occurring as well as any possible remedial actions.

A laboratory test rig was developed to simulate rain that would wet different types of absorbent roofing materials and then simulate solar heating such that any moisture transferred through the roofing into the closed roof cavity below could be isolated and measured. Testing verified that the shingles absorbed considerable moisture from the rain and that solar heating indeed did result in substantial moisture transfer through the roofing material. While the presence of conventional breather-type building paper underneath the shingles did not greatly impede the transfer of moisture into the closed roof cavity below, it was found that interleaving nonbreathable building paper with poly attached between the layers of shingles dramatically reduced and nearly eliminated the moisture transfer into the roof cavity. This remedial approach has been adopted by the roofing material manufacturer and is recommended for future applications involving cathedral roofs.

Tests of other less successful remedial measures as well as other common absorbent roofing materials also were undertaken. There appears to be considerable need to do a followup study of solar heating moisture transfer through wooden shingles since they were found to exhibit the largest moisture transfer of all the absorbent materials tested in this study. Solar heating moisture transfer may very well be responsible for the premature degradation of roofing shingles applied over plywood sheathing rather than spaced battens.

FIELD STUDIES OF MOISTURE PROBLEMS INSIDE EXTERIOR WALLS

Older Existing Homes in Northern Climates

Potential Wall Moisture Problems When Retrofitting Wall Insulation

During the mid- to late 1970s and the early 1980s when retrofitting of wall insulation became very popular, there existed a prevalent theory that by adding wall insulation, the outer wall layers would get colder, and hence water vapor migrating through the wall from the inside to the outside would be more likely to condense and accumulate. If so, minor effects might occur, such as mold/mildew/staining, siding warping, paint blistering, and wet insulation and greater heat loss. Moreover, the worst effects postulated were condensation and resultant liquid water accumulation, subsequent wood decay (dry rot), and structural damage.

In 1979 Weidt [*48*] opened the walls of 33 existing homes in Minnesota to examine insulation characteristics and somewhat surprisingly noted the absence of any liquid accumulation or decay in that cold climate. An additional similar study of 159 homes [*49*] found the same surprising result in homes throughout the northeastern United States. In order to determine if the prevailing theory or the limited field findings were correct, two major field studies were completed (under the technical direction of the author).

The Portland and Spokane Studies

In Portland, Oregon (4732 DD) and Spokane, Washington (6835 DD), 93 and 103 older homes, respectively, with and without retrofitted wall insulation, were carefully inspected for moisture problems and their walls opened in three or four places to measure wall cavity moisture levels and look for moisture damage [*6,7*]. The homes were typical of the existing housing stock.

As noted earlier, interior moisture problems were very prevalent, in large part due to lack of satisfactory indoor moisture control. The average indoor relative humidities were 56% for the Portland homes and 47% for the Spokane homes, with many homes having relative humidities in the seventies.

From the wall-opening measurements, no high wood moisture contents were noted out of 5234 wall cavity wood member readings, except where leaks or "splashback" was found. In the 103 Portland homes, no moisture contents above 20% were measured. Splashback in this case was excessive wetting of walls with shingles from water splashing on the ground and back onto the shingles—due to lack of gutters. Even with splashback, only 0.2% of the moisture content readings were above the fiber saturation point of wood, and no wood decay was observed, except where leaks were found. Even then, only a few cases of wood decay were seen.

In 681 wall openings, condensed liquid or frost was never observed inside a wall cavity. In addition, those walls that had insulation added actually had a lower incidence of most moisture-related problems within or outside the walls.

The major conclusion of the two field studies was that retrofitting wall insulation in older, leaky homes in climates like those of Portland and Spokane does not create or accelerate moisture damage. Any moisture damage within the wall cavities was always caused by leaks. Furthermore, because there are no associated wall moisture problems, there is no need to add a vapor barrier when retrofitting wall insulation in older existing homes.

It is important to note that these results may or may not be applicable in other climates. Many other climates are less forgiving in that there is far less drying potential. In other words, there is less opportunity for wetted walls to dry out during warm weather (e.g., summer), which is the only time wood decay can occur. Yet, surprisingly to some, the author knows of no cases anywhere in the continental United States where the installation of blown-in insulation has created wood decay. The installation of blown-in cellulose has in one instance been documented to cause siding problems; this case will be discussed shortly.

The walls of older homes stay dry because even though moisture enters the wall cavities from inside the house, the moisture drys out due to the relatively leaky exterior portion of the walls. Recall that most of the wall sheathing in the Portland and Spokane studies was board-type wood with substantial air leakage rather than more airtight plywood panels. The results might have been different if the homes had plywood sheathing. In fact, five of the Spokane homes had plywood sheathing, and their walls had among the highest moisture contents. However, there was no moisture-related damage.

Based on these field study findings, it is recommended that any wall airtightening primarily involve sealing the interior portion of the wall, such as by caulking the inside wall-floor joints behind the baseboard molding, and installing electrical switch plate/outlet gaskets. However, neither of these measures are likely to be cost effective, except if done by the occupants. It is not a good idea to caulk the wall exterior portion except to reduce or prevent rain or snow intrusion or leaks. If the wall insulation addition clearly leads to substantial paint blistering, then insert siding wedges available from paint stores between the horizontal siding laps to make an air space that provides a capillary break as well as air circulation and drainage. That should prevent further blistering.

Does Weatherizing Homes Create Moisture Problems?

Weatherizing existing, older homes generally does not create moisture problems around the building envelope exterior (attics, crawl spaces, and wall exterior surfaces). If anything, it reduces their incidence. Moreover, based on the results of the Portland and Spokane field studies and others, retrofitting wall insulation does not create moisture problems inside the exterior wall cavities.

As far as moisture problems inside the homes, many types of weatherizing such as adding storm windows or adding wall insulation can actually reduce the incidence of such moisture-related problems. However, some types of weatherizing such as airtightening or incorrectly insulating can change conditions enough to lead to moisture problems inside homes. Many low-income homes, for example, are prone to such weatherization-induced moisture problems since they typically are homes with a high occupancy and small living space with poor heating and ventilation that are more prone to moisture problems. In fact, about 10% of the low-income housing stock that recently has been considered for weatherization falls below the latest building tightness limits set to prevent indoor air quality problems, including moisture problems. A large portion of the recently weatherized homes are tightened right to the limit, so that moisture related problems are more prevalent and often actually caused by weatherization efforts.

Tri State Homes

As noted in an earlier section, one of the most unique and severe cases of moisture damage in residential walls occurred in the large group of manufactured homes known as the Tri State homes [*10*]. Between 1970 and 1982, more than 5000 such homes were manufactured, 3400 of which were made in Wisconsin. After 1986, extensive wall wood decay was reported. The manufacturing company declared bankruptcy and was liquidated just before reports of moisture damage surfaced.

Site visits and a home inspection program revealed decay in fewer than half the homes. Nonetheless, the number of homes with decay was substantial. Typically, wall decay is very rare and usually caused by leaks. Most decay in the Tri State homes was in the plywood sheathing, with far less damage to the wall framing.

According to Merrill and TenWolde [*10*], a survey of homeowners and airtightness measurements indicated that the damage was primarily due to excessively high indoor relative humidities, which led to condensation in the walls during winter. The homes were very airtight, leading to very low ventilation rates during winter. Insufficient ventilation, combined with a relatively large number of occupants, appeared to have led to high humidity conditions; the authors found a direct relationship between occupant density and the incidence of moisture problems. Other features, such as the type of heating system, were not found to be a significant influence.

It should be noted that part of the sheathing decay was caused by shower water leaking into the wall cavities. The bathroom windows were located in the shower space and were known to leak shower water that collected in the window tracks into the wall cavity. This introduced water into the wall cavities, where it was then able to migrate into other stud spaces through large holes drilled for wiring. This cause, however, did not account for all the damage in other walls of the homes.

It is believed that while the houses are tight (about 0.3 ACH from blower door tests using the LBL methodology [*22*]), they were not extremely so, and many others in that region are every bit as tight without any wood decay. Moreover, other houses in the area and elsewhere had similar occupant densities. In fact small, airtight homes with high occupant densities are not uncommon in most areas of the northern United States, and yet decay in walls is seldom seen. Something had to be different in the Tri State homes.

It was concluded in a court case that the installation of a very good *exterior* vapor retarder (low perm building paper) between the plywood sheathing and the siding in the absence of an effective interior vapor retarder was *the* significant contributing factor in the creation of conditions conducive to wood decay. Actually, the problem was most likely caused by the combination of fairly high indoor moisture levels (no one has argued that the homes were dry indoors) and the exterior vapor retarder that trapped moisture within the wall cavities. While the wetting potential of the walls was relatively high, the drying potential was rather poor.

The one major factor that is different about these homes is the unusual wall construction. Had no cold exterior vapor retarder been present, the problem probably never would have happened. At any rate, this case of extensive wall decay is unique. There are numerous examples of similar heavily occupied, poorly ventilated, and airtight homes (often in multi-family housing), and yet decay in such walls is seldom observed in any other U.S. northern cold winter climate location. It is indeed fortunate that such wood decay in walls is in fact very rare.

Cleveland Siding and Paint Failures

This project involved investigating numerous moisture-related siding and paint failures in Cleveland, Ohio that appeared a year or two after blown-in insulation was retrofitted in existing homes [*50*]. In addition, complaints of paint peeling and actual wood siding failures in new homes where wood siding was installed over insulating sheathing were examined. A survey of 150 homes with problems was undertaken, including some detailed wall investigations where sidings, sheathings, and insulations were removed. Peeling paint ranged from extensive to minor on both the exterior of the siding and the interior of the wall.

The key factor in all cases was that the failures were moisture related, and after cavity insulation was added the "drying potential" of the exterior portion of the walls was sufficiently reduced to ultimately cause paint peeling and blistering problems. Problems often were worse on south or west-facing walls where solar heating created a strong vapor pressure gradient that drove moisture into the walls. That result is contrary to popular thinking wherein it is believed that such walls should be drier because of the solar heating and therefore have fewer moisture problems. Installation of plastic siding wedges available from paint stores between horizontal siding laps proved to be a very effective means of providing a capillary break and increasing drainage and drying.

No definitive answer was found as to why there appear to be more such problems occurring with blown-in insulation and not with batt insulations. This author theorizes that the difference may be due more to the air leakiness of the wall cavities of the older retrofitted homes. Many of them have rough-sawn wooden 1 by 4-ft (0.30 by 1.2-m) or 1 by 6-ft (0.30 by 1.8-m) or 1 by 8-ft (0.30 by 2.4-m) sheathing boards nailed horizontally or diagonally to 2 by 4-ft (0.60 by 1.2-m) studs. The walls are much leakier than those with panel type sheathing (e.g., plywood or fiberboard), and the board-type sheathing has a considerable moisture absorption capacity. In the Cleveland study, those homes with such sheathing did not experience paint or siding problems. In fact, most of the test homes in the Portland and Spokane studies [*6,7*] had such sheathing. Statistical analysis of the data in those studies found in one case that houses with insulation blown in had slightly more blistering paint, whereas in the other the opposite was true. In neither case were the siding problems considered severe. There was no decay noted in either of those studies, and the statistical analysis did indicate that other indicators of wall moisture problems actually were lower with the insulated walls compared to those without insulation.

It also was recognized in the Cleveland investigation that an interior moisture source could not be conveniently cited in all cases as is popularly done. Moisture entering the wall from the outside was deemed to be very important in many cases, and especially in the cases with exterior insulating sheathing. In a more recent study of new Northwest homes directed by the author and described shortly, moisture entering wall cavities from the outside was found to be *the most important factor* in causing wood members of walls to have elevated moisture levels. As a consequence, in the Cleveland study it was realized that employing strategies and techniques that were aimed at effectively eliminating moisture entering the wall from the interior could not always be relied upon to eliminate the paint and siding problems.

Finally, it was recognized that the addition of exterior insulating sheathing to a wall cavity does increase the drying potential of all the wall components to its interior, but it is ironic that its installation may lead to an increase in siding or exterior wall moisture problems. In the Northwest Wall Moisture Study [*20*] wood members in wall cavities with exterior insulating sheathing were in fact found to be significantly drier than those without. However, there was no evidence of any type of paint or siding problems in those new homes, possibly in part because most of them had exterior stain applied rather than paint. Nonetheless, there was almost no siding damage such as cupping or warping or splitting.

Newly Constructed Homes in Northern Climates

National Bureau of Standards Insulating Sheathing Tests

Burch et al. [*51*] ran laboratory tests of a wall with and without low-permeability exterior insulating sheathing to determine if it resulted in accumulation of moisture within an insulated wall cavity during winter conditions. At the time it was not clear whether its addition would increase or decrease wall moisture levels. The test results showed that the addition of a low-permeability exterior insulating sheathing retrofit reduced moisture accumulation within the existing wood siding and sheathing. It was further determined that increasing the water vapor resistance of the exterior portion of the wall by adding the insulating sheathing had only a small effect on the rate of moisture accumulation from the inside of the wall cavity.

U.S. Forest Products Laboratory Field Test

Small, unoccupied test structures were constructed near Madison, Wisconsin to test exposure of eight types of insulated wall panels at controlled indoor conditions and typical outdoor weather conditions [*52,53*]. One test panel was framed with 2 by 6-ft (0.60 by 1.8-m) studs and full fiberglass batt insulation. All the remaining panels were framed with 2 by 4 ft (0.60 by 1.2-m) studs. There were no very high *R*-value walls tested as is now becoming common in many cold climates.

The primary variables were the sheathing material and the vapor retarder. Sheathing materials included fiberboard, plywood, extruded polystyrene foam, and foil-backed polyisocyanurate foam. The vapor retarders were either continuous polyethylene film or asphalt-impregnated kraft paper backing on blanket insulation stapled between studs. The panels were instrumented with moisture sensors and tested without (Phase 1) and with (Phase 2) penetrations (electrical outlets) in the indoor surface to examine the relative effects of diffusion and air movement as mechanisms of moisture migration.

Continuous inside vapor retarders effectively prevented cold weather condensation in all the panels. Installation of an electrical outlet with subsequent air leakage resulted in somewhat elevated moisture levels. Although condensation occurred for limited time periods in some panels at both test sites, the moisture content of framing did not rise to critical levels. It was concluded that there is no high potential for decay in any of the materials of any of the walls tested.

It should be noted that the test panels were never actually opened and inspected during the winter when "condensation" supposedly occurred. "Condensation" was simply presumed to occur when the wood moisture content measurement probe readings were over their maximum limit of 20%. "Condensation" also was presumed to occur because a dark substance was noticed running down on the outside of the painted lap siding, seemingly from between the laps. It is possible that condensation did occur. What that presumably means is that there were liquid water droplets on wood members or foam sheathing within the wall cavity.

Yet the author has inspected about 1200 wall cavities that were opened up in about 300 homes in winter climates ranging from mild and moist to that of Montana, which is more severe than Madison, Wisconsin. He has never observed liquid water or frost in any normal insulated wall cavity nor any evidence of an accumulation of liquid water that is often referred to. In fact, the author is not aware of any scientific study where liquid or frost has been observed in an insulated wall in the continental United States. He has observed mold and dark staining of plywood sheathing inside wall cavities, but no actual liquid or frost.

The dark coffee-colored stains observed in the Madison, Wisconsin tests have also been observed on more than one occasion by the author. However, after removing the siding to check for moisture behind the siding, none was found. They were all very dry on the back side. It is presumed that the staining is a phenomenon related to a combination of moisture transfer and the natural tannins in the wood itself. It does not appear to be caused by "condensation" and an accumulation of liquid water between the siding laps, at least in the cases observed by the author in the Northwest.

In conclusion, there is a very common belief that water vapor condenses in wall cavities and is present in liquid or frost form. That belief does not appear to be supported by field observations. "Condensation" perhaps does occur, but if so, the liquid appears to be immediately absorbed into wood. Interestingly, as noted later in this chapter, Forest [*54*] has observed that moisture in wood members of insulated walls appears to be absorbed in cold weather but desorbed (dried out) in somewhat milder winter weather, with a time constant of the order of a week. Thus, condensation is apparently followed by regular drying that prevents an accumulation of liquid or frost.

Surprisingly, to the author's knowledge, condensation has never been observed on the warm side of exterior insulating foam sheathing, in spite of the fact that in very cold weather temperatures at that interface in the wall are probably below the dew point temperature. Kane and Titley [55] noted that increasing the sheathing/insulation temperature by using insulating sheathing can significantly increase the capacity of air to contain moisture, which clearly helps reduce condensation.

Canada Mortgage Housing Corporation Wall Drying Study

Three highly instrumented test huts, including 48 test panels, were constructed in three locations representative of climatic conditions found in Atlantic Canada. The purpose was to investigate the cause of moisture damage in walls of wood-frame housing in Atlantic Canada and to suggest practical solutions. Monitoring the moisture conditions in the test huts was especially aimed at examining the drying of walls with different constructions that were initially wet, including investigating the use of furring strips between siding and the exterior sheathing as a means of enhancing drying or keeping walls dry [56,57]. The wall panels were constructed of locally supplied lumber, all of which had moisture contents above 26%. Data collection occurred between March 1986 and August 1987.

A joint task force comprising representatives of Canada Mortgage and Housing Corporation, the Canadian Home Builders' Association, and the National Research Council of Canada (Atlantic Region) was formed to oversee the field research project and the production of a good-practice, advisory document ("Construction Principals to Inhibit Moisture Accumulation in Walls of New, Wood-Frame Housing in Atlantic Canada"), and to visit housing with moisture problems. In conjunction with these activities, a survey was conducted to measure the moisture content of framing lumber typically used in new housing.

The task force presented a number of results, conclusions, and recommendations, as follows. All of the 48 test panels exhibited some degree of drying during the monitoring phase—south walls more than north walls. Test panels with sheathing systems that were more permeable to water vapor dried more quickly than those with less permeable sheathing systems. Statistical analysis results indicated that the permeability of the sheathing systems to water vapor was the most significant factor in the rate of drying and the final moisture content of the test panels. The use of exterior sheathing materials with a very low permeability in combination with "wet" framing lumber or insulation materials having a high moisture content puts walls to a high degree of risk of moisture problems.

Most test panels which stayed wet for an extended period of time exhibited some fungal growth on the framing lumber and wood-based sheathing materials. The frequent occurrence of conditions that theoretically can lead to condensation on the back of the siding suggests that the use of furring strips may be beneficial in preventing moisture accumulation in wood and wood-based siding and sheathing materials. Furring strips installed behind vinyl siding had no significant effect. The entry of water from the exterior, due to poor detailing, poor installation of siding systems and flashing, inadequate exterior air barriers, plus lack of regular maintenance were frequent factors in walls damaged by moisture, as was noted in the Northwest Wall Moisture Study [*20*].

Many of the houses visited exhibited mold, mildew, and condensation on the interior surfaces of exterior walls and relatively low indoor temperatures in the troubled areas. It was noted that householders do not have suitable information on the operation and maintenance of houses to avoid moisture problems. Further, design professional, building scientist, subcontractors, material manufacturers, builders, and inspectors do not have a sufficient understanding of the causes and prevention of moisture damage in walls. Finally, framing lumber surveyed in Atlantic Canada typically exceeded a moisture content of 19% and in most cases exceeded the fiber saturation moisture content. The lack of availability of dry framing lumber is a significant contributor to the moisture load in wall systems. Using the field test data, a wall drying model has been developed.

Dow Chemical Canada Study of Walls with Exterior Foam Sheathing

Moisture contents were measured by Kane and Titley [55] in the wood studs of seven occupied homes that had a low permeance foam sheathing, with or without a noninsulating sheathing such as plywood, in four Canadian cities. Moisture contents were measured over a period of one to six years, depending on the home, with Delmhorst moisture elements and then read with Delmhorst moisture meters. While both insulating and noninsulating sheathings were not installed in the same house for the best side-by-side comparison, nonetheless the results indicate that moisture levels were not excessive regardless of the exterior sheathing installed. Stud moisture contents were generally less than 15% and always less than 25%. The water vapor permeance of the walls studied was shown to be an insignificant factor in controlling the moisture content in studs. The use of extruded polystyrene as external sheathing did not cause moisture accumulation in the wood studs. In fact, the author of this chapter does not know of any documented case of moisture accumulation or damage occurring as a result of the installation of exterior low permeance foam sheathing. In the next study described, its use was actually shown to result in drier walls.

The Northwest Wall Moisture Study

The exterior walls of 86 newly constructed houses in the Pacific Northwest were cut open and examined to determine if building them to energy-efficient standards with more insulation [at least R-3.3 $m^2 \cdot K/W$ (R-19 $ft^2 \cdot h \cdot °F/Btu$)] and an air-vapor retarder causes unacceptably high levels of moisture or moisture damage within walls [*20*]. The test houses were located in three climate regions: 50 in the metropolitan Seattle-Olympia area, 16 on the rainy Washington coast, and 20 in the cold Montana region.

Measurements of the moisture content of wood members within the wall cavities were first made between January and March 1987. Over half of the test homes had at least one wall wood member with over 20% moisture content. On average the highest readings occurred in sheathing and sill (mud) plates. More than one third of all the sheathing measured had moisture contents over 20%, while more than one half of all the sill plates were over 20%. The highest moisture content measured was approximately 55%.

There were significant differences between regions, with the homes in the mild and humid Washington coastal area being the wettest and those in the cold Montana region being the driest. However, the cold region homes were often still very wet. Since the coastal climate is mild with relative humidities that average about 90% throughout the fall, winter, and spring, and since the equilibrium wood moisture content at a relative humidity of 90% is about 21%, the high wood moisture contents in the coastal homes are not too surprising.

The 28 homes with the wettest walls were reopened during the 1988 summer to see if the walls had dried out enough to avoid wood decay. The wall cavity wood members of the cold region homes had thoroughly dried out such that there is no reasonable likelihood of wood decay occurring there, except in the case of leaks.

On the other hand, many of the walls in the coastal and metro (Seattle-Olympia) homes had not dried sufficiently to rule out the possibility of wood decay and subsequent structural damage occurring in the future. How long it takes for wood decay to develop is unknown, although many of the walls are wet enough to decay during warm weather.

While there were no cases of wood decay observed in any of the wall cavities during any part of this study, sometimes it takes many years for decay to develop and be noticed, as for example in the Tri-States Homes case [*10*]. In those homes, severe wall structural damage occurred due to wood decay, but the homes were about a decade old before the damage was discovered. Incidently, in the Northwest study there were no cases of condensed moisture or liquid water accumulation observed within any of the 258 insulated wall cavities.

The walls of the 16 coastal and metro test homes that were still wet during the summer were again reopened during the 1989 winter. While the walls were generally drier, they were still wet enough to be of concern. The drying that occurred between the 1987 and 1989 winters appears to be the result of a period of abnormally cold, dry, and extremely windy weather just before the 1989 wall openings. Record low temperatures and strong winds were recorded all across the region for almost three weeks.

Thus the question of whether the high moisture contents will lead to wood decay and subsequent structural damage is still unresolved. The walls of one or two of the worst test homes should be regularly opened and checked for a few years to see if they are, in fact, slowly drying or if any decay occurs.

What also is unclear is whether similar results would occur in the walls of newly constructed current practice homes in the region and perhaps even in the new energy-efficient Super Good Cents manufactured homes. There is reason to believe that those homes could be worse because they have similar insulation levels and are nearly as airtight, but they lack an AAHX or dehumidifier. Moreover, there is a good possibility that wall moisture levels will be as high, if not higher, in the many multi-family homes recently built in the region. That is because the individual units are smaller, have less exposed exterior wall area, and generally have less expensive/effective ventilation systems. Thus, the finding of moisture-related problems in this study of single-family homes may only be the tip of the iceberg.

Statistical Data Analysis—Statistical analysis of the field data was undertaken to try to find out what caused the high wall moisture contents, and a number of factors were found to be significant. Wet walls were strongly associated with high indoor relative humidities. The wettest walls and highest indoor relative humidities were in the humid coastal region. Many homes had indoor relative humidities that were clearly too high. Thus, one of the major factors contributing to high wall moisture levels was the lack of indoor moisture control. Reducing indoor relative humidities with improved moisture control systems that are presently available but seldom used should reduce wall moisture levels. One of the main conclusions of this study is that better indoor moisture control is a major programmatic need in new Northwest housing and probably in most other similar new housing [*20*].

Most of the wettest walls were in homes with T1-11 plywood panel siding and shingle siding. These siding types are especially prone to what is called "splashback" because their lower edges and back sides are often not satisfactorily painted or sealed. They readily absorb rainwater or melted snow that splashes up from the ground, and that moisture is transmitted into the wall cavity wood members. Walls with insufficient clearance between the bottom of the siding and the ground were especially prone to splashback; many of the homes had siding whose bottom edge was within a few inches of the ground. Walls also were significantly wetter if they did not have an exterior air barrier such as Tyvek or a moisture barrier such as building paper behind the siding that provided resistance to capillary action. These findings point out that while moisture is generally believed to enter wall cavities from the inside, significant amounts of moisture leading to elevated wall moisture levels also can enter from the outside. Thus, control of exterior moisture may be at least as important as interior moisture.

To avoid high wall cavity moisture levels when T1-11 and shingle siding materials are used, the lower edges need to be much better protected, the ground-to-siding clearances need to be maintained above some minimum level, such as about 2 ft (0.60 m), and an exterior moisture barrier or possibly an air space behind the siding needs to be installed. Adding exterior insulating sheathing also may be wise.

In addition, high sheathing moisture contents often were found at sites where moist indoor air leaked through the wall cavity, such as through electrical outlets and a variety of penetrations in the polyethylene air-vapor retarder, indicating the need for better sealing on the inside of the wall. A further discussion of this topic will be presented in the next section.

The high sill plate moisture levels were likely caused in part by moisture from the wet ground wicking up by capillary action through the crawl space or basement concrete foundation walls into the adjacent sill plates and in part by the effects of splashback wetting.

Another programmatic problem was noted by comparing moisture levels in walls with different amounts of cavity insulation. It was found that building walls with more cavity insulation definitely lead to increased moisture levels in them. Fortunately, that adverse finding is balanced by the positive finding that walls with exterior insulating sheathing are significantly drier than walls without it [58]. Burch et al. [51] conducted laboratory tests and found a similar result. In the field study, almost none of the wettest walls had such sheathing and half of the driest had it.

These walls are drier because the insulating sheathing keeps the wall cavity wood members warmer and also because the sheathing is an excellent exterior moisture barrier or break that keeps wet siding from transmitting or wicking moisture into the wall cavity better than other moisture barriers. The results of this study indicate that the use of exterior insulating sheathing is one way of providing additional wall insulation while at the same time reducing the potential for wall moisture problems.

While the walls of homes with a polyethylene air-vapor retarder were slightly drier than those without, or with polyethylene only on the walls and not on the ceiling, the differences were not statistically significant. However, there were almost no homes with wet or very wet walls that had both a polyethylene air-vapor retarder and external insulating sheathing. Furthermore, the airtightness of the home was not significant.

Statistical analysis of the effect of the age of the homes on wall moisture levels was undertaken to see if the high wall moisture values were caused by the use of wet construction materials in the relatively airtight walls that are slow to dry out. There were no indications that this was a factor (i.e., the newest homes in each region were not wetter). However, the initial material wetness may still be an important factor. Continuous field monitoring of wall moisture levels is needed to find out.

In order to make these research results useful to the building community at large, specific recommendations were made to builders and contractors, building code officials, and energy-efficient home occupants [20]; they are too extensive to be repeated here.

Northwest Study of Correlation of Air Leakage and High Moisture Content Sites

In the Northwest Wall Moisture Study [20] of 86 new energy-efficient Pacific Northwest homes with relatively airtight construction, walls were opened up and unacceptably high wood sheathing moisture contents were measured in numerous wall cavities. A separate field investigation was undertaken at one Helena, Montana home in an effort to determine the cause [59]. The moisture content of the wall sheathing was measured from the outside of the wall, both high and low, in every stud cavity of two walls (120 locations). Three locations were found with more than 40% moisture content, four locations with between 30 and 40%, and eleven locations with between 20 and 30%. Because evidence suggested that the source of the winter moisture buildup in the wood sheathing was moist indoor air migrating out through penetrations in the polyethylene air/vapor barrier, infrared thermography was used during house pressurization and depressurization to locate air-leak sites and paths. Numerous air leaks were observed both on the inside and outside of the exterior walls even though the house was found to be *very* airtight (1.2 ACH at 50 Pa). Many of the leaks resulted from improper sealing or poor workmanship and could have been avoided. What is most important is that a definite correlation was found between the locations of many of the major air leaks and the locations of sheathing with high moisture content. In almost every one of the 18 places where the sheathing moisture content was more than 20%, there was a noticeable air leak in the wall cavity. Thus, the air leaks on the interior portion of the walls introduced moisture into the tightly built wall cavities that could not dry out during the winter. In the study, suggestions were made to help minimize the effects of air leakage and keep tightly built wall cavities dry. A number of recommendations for further study also were presented.

Alberta Building Envelope Moisture Accumulation Field Study

Tests were carried out during the 1989–1990 heating season on a single-story house with a full basement and gable end attic in Edmonton, Alberta, Canada [45]. Four south and four north wall panels were monitored, half of which had glass fiber insulation while the other half had sprayed cellulose insulation. Each insulation type had two types of exterior sheathing: one was conventional plywood and the other had a vented air gap between the insulation and the exterior plywood sheathing. Each panel had a small leakage site through the interior drywall which allowed air to exfiltrate or infiltrate depending on ambient conditions. Moisture contents of the wood-based wall components were measured hourly with moisture pins, while airflow through the wall panels was measured directly with a small orifice plate flowmeter.

Infiltration flows were generally higher than exfiltration flows, and the direction of flow was determined mainly by the wind direction. After the cellulose dried, it had a 20 to 30% higher flow resistance than glass fiber. That is in agreement with the earlier results from a field study involving blower door tests on older homes before and after having wall insulation of different kinds blown [6].

Sheathing moisture contents in the glass fiber panels showed a cyclic moisture absorption-desorption pattern with peak moisture contents reaching 16% moisture content in the north panels. Absorption was correlated directly with periods of large exfiltration through the leakage site during cold weather while desorption occurred during subsequent mild periods. There was no evidence of a steady increase in sheathing moisture content associated with diffusion of water vapor from indoors to the sheathing.

The cellulose panels exhibited a rapid initial increase in sheathing moisture to a peak of 36% moisture content, associated with redistribution of moisture within the wall cavity (the cellulose initially had 50 to 60% moisture content). However, there was gradual drying throughout the heating season. Direct solar gain on the south panels resulted in much lower sheathing moisture contents.

Edmonton, Canada Field Monitoring of Wet-Sprayed Cellulose in Walls

Seven different wall sections or orientations of a typical home insulated with wet-sprayed cellose were instrumented to evaluate the rate of drying and the effect of moisture on wall building components and to evaluate the effect of wet-sprayed cellulose on air leakage [60]. Point-in-time monitoring of wood moisture contents took place for one year. Installation of the cellulose increased the initially dry wood component moisture contents to approximately fiber saturation within 30 days of installation. The framing dried to near preinstallation levels within six months. Factors affecting the rate of drying were determined. It was concluded that the cellulose cannot be considered an air barrier. The exterior sheathing provided the majority of the air resistance across the wall sections tested. Examination of sections of the exterior walls one year after construction gave limited evidence of deterioration.

National Research Council Saskatchewan Field Study

Tests were conducted that involved monitoring moisture levels in the wood members of six different wood-frame construction north-facing wall panel sections in an outdoor test facility at the Prairie Regional Station of the Institute for Research in Construction in Saskatchewan, Saskatoon, Canada [*35*]. The insulation levels in the walls were relatively large, ranging from a nominal value of R-3.9 to R-7.1 $m^2 \cdot K/W$ (R-21.9 to R-39.9 $ft^2 \cdot h \cdot °F/Btu$); that is essentially the same range as the 86 test homes examined in the Northwest Wall Moisture Study [*20*] in which it was found that increased cavity insulation levels led to increased moisture contents in the cavity wood members (as high as 55% in one case).

The indoor relative humidity was kept at 50%, which was felt to be not atypical of that in future tightly built houses in the region. The pressure inside the room was set to approximately 20 Pa above ambient to maintain a relatively constant airflow through the panels from inside to outside. That is about as much room pressurization as one would expect from the operation of a typical forced air heating system. Moisture contents of wall wood members were measured manually from moisture pins using a moisture meter at two week intervals during the period from mid-December 1989 to mid-May 1990. The walls were constructed of kiln-dried wood that was initially between 8 and 13% moisture content. Two of the wall panels had special calibrated orifices inserted to measure the flow rate through the walls.

It was found that five of the six wall panels exhibited wood moisture contents above 20% during the winter. In fact, all five had readings above 40%, with one having a reading as high as 70%. However, just as in the Montana homes tested in the Northwest Wall Moisture Study, the walls all dried out over the summer months. Thus, in such climates that have relatively warm and dry summers, there would not appear to be any likely structural degradation in new homes with heavily insulated walls. Furthermore, the results suggest that room pressurization may lead to rather high moisture levels during the winter, but nonetheless the walls will probably dry out in such climates. That may not be as true in less forgiving climates with less drying potential, such as northern marine climates.

Older Existing Homes in Southern Climates

Gulf Coast Masonry Wall Field Study

Trechsel, Achenbach, and Conklin [*19*] conducted a field study of moisture problems in the exterior walls of a masonry housing development in Pensacola Naval Air Station, Florida from September of 1982 to May 1983. As noted earlier, indoor moisture problems included moist and waterlogged wallboard and mildew on walls and in furnishings. Most of the problems occurred below or adjacent to windows. Measurements of temperatures, relative humidities, air infiltration, and water leakage were made on several houses, and an occupant survey of 86 houses was undertaken to assess and resolve the existing indoor moisture problems. Standing water was observed in concrete block cavities.

It was concluded that rainwater penetrating through cracks in the masonry walls and at windows was the major source of moisture observed in the gypsum board and the wall insulation. Inadequate ventilation, particularly in bedrooms, and possibly capillary rise of moisture from the foundations may also have contributed to the moisture problems.

Newly Constructed Homes in Southern Climates

U.S. Forest Products Laboratory Wall Panel Tests

TenWolde and Mei [*61*] conducted tests on an air conditioned test building with nine instrumented south wall panels of different constructions in the warm, humid climate of Beaumont, Texas. All panels had 89-mm (3½-in.) fiberglass batt insulation and hardboard siding over either wood fiberboard sheathing or aluminum-faced molded expanded polystyrene sheathing. A polyethylene sheet was installed between the fiberboard sheathing and siding in one panel, whereas another contained a ventilated airspace between the fiberboard sheathing and siding. Two of the panels contained a polyethylene vapor retarder on the room side of the batt insulation. Temperatures and humidity conditions in the panels were recorded from early spring until late fall in 1984.

Generally speaking, all the wall panels showed little or no evidence of condensation, and walls with an outside vapor retarder as well as walls without any vapor retarders remained dry throughout the study period. The results did not clearly show a need for a vapor retarder on the outside of the wall. The siding in walls without the aluminum or polyethylene between the siding and the sheathing generally was drier and experienced less fluctuation in moisture conditions than the siding installed over the aluminum facing or the polyethylene sheet. An interior vapor retarder was found to be somewhat undesirable unless an exterior vapor retarder is installed as well. The ventilated airspace had little effect on moisture conditions in the siding or the rest of the wall, but the results might have been different with foil-faced sheathing. Taping of the joints between sheathing panels had no effect on moisture conditions in the walls.

A somewhat similar study was conducted by monitoring eight test panels in an unoccupied building in Gulfport, Mississippi [*52*]. The building and test panels were the same as those previously reported in the section on "Newly Constructed Homes in Northern Climates." In fact, the results were essentially the same. Although condensation occurred for limited time periods in some panels, the moisture content of framing did not rise to critical levels and so the potential for deterioration of materials was deemed to be minor.

CONCLUSIONS

Indoor Excess Moisture Problems

It should be stressed that indoor moisture problems have not been particularly well documented, in part because they are often considered more of an aesthetic nuisance than exterior or wall cavity moisture problems that may involve structural damage, which is clearly more severe. Based on the Iowa survey experience, it is also likely that some type of indoor moisture problem exists in almost all houses, and in most instances in the past the right questions of occupants simply have not been asked to accurately determine the degree to which moisture-related problems exist.

The situation may be very similar with health effects related to indoor moisture problems. We probably haven't done a good enough job of asking the right questions and so likely have underestimated, perhaps significantly, the degree to which such problems exist. In years past, things like mold and mildew were mainly considered a nuisance, whereas now it is increasingly being recognized that mold and mildew can have serious health repercussions. Thus, indoor moisture "problems" need to be taken much more seriously than they have in the past.

Certainly, in the author's experience, as well as judging from the studies discussed in this chapter, indoor moisture problems are vastly more pervasive than exterior or wall problems in the United States. Generally speaking, indoor moisture control has not been a serious concern of the building community or the building science research community. As a result, indoor moisture problems are fairly commonplace, both in older existing and newly constructed homes. At the other extreme, wall moisture problems are relatively rare.

Most of the indoor moisture problems are related to excessively high indoor relative humidities caused by the lack of satisfactory indoor moisture control. Moisture control has occurred mostly by chance rather than by proper design. Ventilation systems have not provided reliable moisture control and probably should not be relied upon to do so, especially in mild weather when ventilation is relatively ineffective. Dehumidification for general moisture control, in combination with spot ventilation and automatic control of exhaust fans for source control, along with continuous whole house ventilation for control of all other indoor air pollutants appears to be a very workable solution.

There appears to be a dramatic need for better indoor moisture control in both new and existing residences. Moisture control should have a much higher priority in programs involving weatherization of existing homes and in the design, construction, inspection, and ongoing operation of new homes. Without increased emphasis on substantially improving indoor moisture control in all homes, moisture problems will only get worse, leading to reduced durability of the homes and increased health problems for the occupants.

Exterior Excess Moisture Problems

One of the major findings of the research noted in this chapter is that crawl space ventilation is not necessary in most climates and in fact may even cause severe moisture problems in warm, humid climates, especially in air conditioned homes. Yet in spite of the overwhelming scientific evidence to that effect, building code agencies do not seem to be aware of this situation and almost uniformly require crawl space ventilation. This needs to be changed, especially when it is realized that eliminating ventilation will save energy and reduce construction costs. Of course, in some situations, ventilation may be desirable, such as to help mitigate radon.

Attic moisture problems have been found to be strongly related to the exfiltration of moist indoor air through a variety of ceiling bypasses or penetrations, especially when the installation of attic insulation results in relatively cold roof sheathing that acts as a condensing surface. Sealing the bypasses and penetrations should greatly help reduce attic moisture problems. As with crawl spaces, there is a growing feeling within the building science community that the present code levels of attic ventilation have little relevance today and need to be reconsidered.

It also is important to again stress that exterior moisture problems do not occur anywhere as often as indoor moisture problems. Yet, the vast majority of research is related to either exterior or wall moisture problems rather than indoor moisture problems. What few research results that are available regarding the health effects of indoor moisture problems, in combination with the fact that indoor moisture problems appear fairly commonplace, strongly suggest that the health effects of moisture-related biological contaminants could be vastly more serious than has generally been recognized. Our priorities appear to be incorrect and in need of major change.

Excess Moisture Problems and Damage Inside Exterior Walls

These problems have received considerable attention, and yet wood decay and resultant structural damage inside exterior walls is relatively rare, albeit expensive when problems do occur. However, again this author believes our priorities are wrong. Our first priority in dealing with housing should be the health and safety of the occupants. Houses should not make the occupants sick! Only after we have learned to make healthy buildings should we turn our attention to the second highest priority, which is maintaining the durability of buildings. Designing buildings that we live in should not result in the failure of the buildings themselves. It seems we have placed most of our emphasis on durability or even affordability (saving energy used in buildings). However, the major emphasis for building scientists should be to develop methods to provide satisfactory health and safety of the occupants of the homes that are constructed. We need to recognize the need to reorder our priorities and focus more of our efforts on providing healthy indoor environments. One major step in that direction would be to start paying considerably more attention to assessing and solving indoor moisture problems.

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APPENDIX

RESIDENTIAL MOISTURE PROBLEM ASSESSMENT CHECKLIST

Name:______________________________ Date:__/__/__
Address:______________________________
Home phone #:______________ Work phone #:______________
Service #:______________ Tech #:______________ House ID#:_______

Excess Moisture Symptoms/Problems

Interior: Occupant/Auditor Comments

- ☐ Mold/mildew/stains on surfaces (e.g. walls, ceiling)
  Note room type and location:______________________________
  - ☐ In bedroom closets: ☐ Mold/mildew on clothing
  - ☐ Behind furniture (poor air circulation)
  - ☐ Mold/mildew/staining on ceiling below attic insulation voids
  - ☐ Mold/mildew/dampness in carpet
- ☐ Mold/mildew/staining on window frames
- ☐ Mold in furnace humidifier water tray (a potential major health problem)
- ☐ Musty or damp odor
- ☐ Condensation on window glass/frames
  - ☐ Almost none
  - ☐ Only on very cold winter days
  - ☐ Often throughout the winter
  - ☐ Often during the fall and spring
  - ☐ Only on a few windows
  - ☐ On most windows
  - ☐ Water sometimes runs down onto sill
  - ☐ Water often runs down onto sill
- ☐ Sill condensation damage (staining, rot): minor[ ], major[ ]
- ☐ Sweaty pipes (note location and season)
- ☐ Basement dampness and leakage
- ☐ Efflorescence (white powdery substance), mold and/or dampness on foundation walls
- ☐ Other (describe)

Exterior:

- ☐ Evidence of splashback (explain)
- ☐ Attic condensation and/or frost
- ☐ Water stains on roof sheathing
- ☐ Attic nail halos (dark rust stains around nails) indicating long term chronic moisture
- ☐ Attic bypasses/air leaks (including dark stains of insulation or moist insulation)
- ☐ Roof leaks; ☐ ice dams
- ☐ Blistering/peeling paint (note side of house)
- ☐ Buckled siding (note type and location)
- ☐ Crawl space mold/mildew
- ☐ Wood decay (describe and note location)
- ☐ Wood member moisture content greater than 30%
- ☐ Other (describe)

Basic House Characteristics

House age (yrs):_____; # of occupants: day_____, nite_____; # of smokers:_____
Heated area (sq ft):____________; 1st floor ceiling height (____ft, ____inches); # stories:____
Window glazing: single[ ], double (or single w/ storm)[ ], triple[ ], dbl low-e[ ]
Window frames: wood[ ], metal[ ], TIM (thermally-improved metal)[ ], vinyl[ ]
Wall insulation: Y__, N__; ceiling insulation: Y__, N__
Floor type: basement[ ](heated:_____%, unheated:_____%), crawl[ ], slab[ ], mixed[ ]
Foundation wall type: concrete[ ], conc. block[ ], stone/brick[ ]
Space heating system: electric resistance[ ], heat pump [ ], forced air furnace[ ],
    vented space heater[ ], unvented space heater (e.g., kerosene heater)[ ]
Wood stove, fireplace insert, or fireplace regularly used for space heating: Y__, N__
Gas or propane range (oven) regularly used for space heating: Y__, N__

Monitoring and Occupant Interview Results

CFM50: pre-air sealing______________, post-air sealing______________
Thermostat settings: heating______°F; cooling______°F (NA if not applicable)
Measured temperatures (dry bulb)[2]: living room_____°F, master bedroom_____°F,
    heated basement_____°F, unheated basement_____°F; outside air_____°F
Measured RH: living room_____%, master bedroom_____%, heated basement_____%,
    unheated basement_____%, other (location:___________________)_____%,
    outside air_____%
Primary bathing/showering bathroom exhaust fan: Y__, N__; rated cfm_______;
    # showers per day:_____
Other bathroom exhaust fan: Y__, N__; rated cfm_______
If bathroom fan(s) exist(s):
    Exhaust fan blades clogged with dust/dirt/grease: primary bathroom Y__, N__;
        other bath Y__, N__
    Exhaust fans work (toilet paper test): primary bathroom Y__, N__;
        other bath Y__, N__
    Measured exhaust fan cfm: master bathroom_____, other bath_____
    Bathroom fans used when bathing/showering: seldom[ ], sometimes[ ], whenever needed to clear windows or mirror[ ], almost always[ ]; occupants limit use because fan is too noisy: Y__,N__
    Bathroom fan typically operated more than 15 minutes: Y__, N__
    Bathroom mirror stays fogged after showering: never[ ], seldom[ ], often for a few minutes or less[ ], often for more than five to ten minutes[ ]
Bathroom and kitchen exhaust fans ducted/vented: to attic[ ], to outdoors[ ]
Kitchen exhaust fan: none[ ], recirculating, nonvented type[ ], vented type[ ]
    Vented kitchen fan works: Y__, N__; filter screen clogged with grease: Y__, N__
Kitchen exhaust fan used: seldom[ ], whenever needed to clear windows or odors[ ], almost always when cooking[ ]; occupants limit use because fan is noisy: Y__,N__Forced air system return duct leak test w/ smoke generator: leaking[ ], well sealed[ ]

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[2] Basement and outside air temperatures and relative humidities should be measured year round; in the other room locations they should be measured only during the heating season (fall, winter, spring).

Monitoring and Occupant Interview Results - Continued

Dehumidifier: none[ ]; # in basement[ ], used summer[ ], used spring/fall[ ], used winter[ ]; # in other locations[ ], used summer[ ], used spring/fall[ ], used winter[ ]; locations:____

Brands, model #s, and capacities (pints/day):____

Method of control: on continuously[ ], operates as needed[ ]

Water (condensate) removal method: drain line[ ], manually as container fills[ ]

If manual removal, gallons per day of water removed (occupant's best guess):_____

Other (describe):____

Potential Moisture Sources

☐ Unvented space heater (e.g. kerosene, propane, or gas heater)
This can be one of the largest moisture sources in a home.
☐ Humidifier: portable[ ], furnace[ ]; used during heating season: almost always[ ], sometimes[ ], seldom[ ]
☐ Clothes dryer vented indoors; loads of wash per week:____
☐ Plugged dryer vent (look from outside)
☐ Clothes dried indoors
☐ Firewood stored indoors, including basement
☐ Crawl space without ground cover
☐ Water pooling on crawl space ground cover
☐ Poor grading-water ponds/puddles near house or water drains toward house
☐ Basement flooding
☐ Open concrete block cores in basement walls
☐ Liquid water seepage through foundation walls
☐ Open sump pump hole
☐ Exposed dirt/hole through basement concrete floor (e.g. for well or water pipe entrance)
☐ Gutter downspout not connected to sewer or suitable drain or otherwise ineffective
☐ No gutters
☐ Plumbing leaks
☐ Poorly caulked tub or shower enclosure grout
☐ Cooking without lids
☐ Cooking without using kitchen exhaust fan
☐ Gas stove: for cooking[ ], for space heating[ ]
☐ Forced air heating system return duct leakage
☐ Kitchen or bathroom fan(s) exhausting into attic (not to outside)
☐ Aquariums
☐ Recent remodeling or construction

Occupant/Auditor Comments and Additional Remarks

Recommended Moisture Control Strategies

- ☐ Indoor moisture source control
    - ☐ Discontinue use of unvented space heater, including oven for space heating (major source of indoor air pollutants)
    - ☐ Vent clothes dryer outside
    - ☐ Clear plugged dryer vent
    - ☐ Dry clothes outside
    - ☐ Store firewood outside
    - ☐ Cover aquariums
    - ☐ Discontinue use of humidifier or vaporizer, especially in spring, summer, and fall when not needed
- ☐ Install crawl space ground cover
- ☐ Improve grading so that water drains away from house
- ☐ Install gutters
- ☐ Improve existing gutter drainage (low cost option is to add 8-10 foot downspout extensions to move the gutter water flow away from the foundation)
- ☐ Dampproof basement
- ☐ Seal/caulk basement cracks
- ☐ Cover/seal sump pump opening
- ☐ Cover/seal exposed dirt in basement concrete floor hole
- ☐ Seal forced air return duct leaks with mastic (NOT duct tape)
- ☐ Seal attic bypasses and other air leaks into attic
- ☐ Eliminate attic insulation voids
- ☐ Educate occupants regarding need to increase use of ventilation systems
- ☐ Install bathroom fan automatic control: timer[ ] or dehumidistat[ ]
- ☐ Clean/vacuum dirty/clogged exhaust fan blades/filters that constrict air flow
- ☐ Install bathroom exhaust fan: quiet (2 sone minimum), 80 cfm minimum rated capacity
- ☐ Dehumidifier (40 pint per day minimum)(use existing model only if it has automatic defrost control)
- ☐ Improve closet air circulation (leave doors open or install louvered doors) or heat closet (leave light on)
- ☐ Clean mold from furnace humidifier water tray
- ☐ Other (describe)
- ☐
- ☐
- ☐
- ☐

Moisture Control Actions Already Undertaken by Occupants

Action Description With Approximate Date and Results of Action:

☐

☐

☐

Checklist designed by George Tsongas; version 4 (revised 11-3-92)

Part 3: Construction Principles and Recommendations

15

General Construction Principles

by Paul R. Achenbach[1]

MOISTURE CONTROL OBJECTIVES

SINCE MOISTURE IS PRESENT to a greater or lesser degree in all climates and because it has been shown to be a factor in most deterioration processes in building materials, it is important that building designers and builders take moisture problems into account in the design and construction of buildings. Also, the moisture content of indoor air has a significant effect on the comfort of building occupants, on the properties of various materials, and on the effectiveness of many material-processing techniques. Therefore, control of moisture transfer processes is an important design consideration for buildings. Furthermore, the control of moisture in buildings can have a significant effect on the energy use [*1*] of a building and on its initial and maintenance cost.

Therefore, the objectives of the designer and builder with respect to moisture control can be stated as follows:

1. To avoid premature deterioration of the building.
2. To provide desirable indoor air conditions.
3. To provide economy in the use of energy and materials.

MOISTURE CONTROL AS A SYSTEMS PROBLEM

Background

About 40 years ago, before the techniques of air infiltration measurement had been developed, it was generally accepted that hidden condensation in building walls and the resulting deterioration was caused principally by diffusion of moisture from the indoor air into the building envelope. This emphasis on the importance of diffusion led to building practices that required or recommended the use of a vapor retarder in the major building envelope components to protect them from hidden condensation, without much attention being given to whether or not the moisture generated indoors was adequately removed from the building. Of course, energy was relatively inexpensive in that period and building construction did not emphasize airtightness, so high indoor relative humidity was not a significant problem.

With the need for energy conservation becoming important in the early 1970s, builders began to put more insulation in the envelope of building; air infiltration and ventilation were reduced by installing air barriers in walls and ceilings and by weatherstripping windows and doors and by sealing cracks, joints, and openings in the building envelope. The continuity of vapor retarders was also improved to reduce diffusion of indoor moisture into the insulated envelope. In some cases, these practices have led to excessively high indoor relative humidity and to an inadequate indoor air quality because of the lack of movement of sufficient fresh air through the building. There has been a significant number of installations [*2,3*] where early decay in walls and ceilings occurred because of condensed moisture, accompanied typically by the growth of mold and mildew in areas of high relative humidity.

Out of these experiences has come the realization that the control of moisture in buildings is a systems problem; that is, the designer must find methods to prevent excessive diffusion and air transport of moisture into the building construction, to control the entry of rainwater from the outside, and to protect the foundation and lower walls from moisture in the earth, while concurrently providing a healthy indoor humidity and avoiding unnecessary energy use and construction cost. As a part of the design process, the building must be equipped with the means for disposing of the moisture load generated by the people and processes occupying the building.

Moisture Control Methods

Chapter 8 of this manual has identified and discussed the sources of moisture affecting a building, namely, indoor generation, climate, groundwater or moisture, sprinkler water, and construction moisture.

The various methods for moisture control in buildings are the following, used singly or in combination:

- infiltration
- chimney effect
- ventilation, natural and mechanical
- indoor/outdoor pressure difference
- humidification/dehumidification
- cyclic absorption and desorption of moisture by building materials
- drainage of water
- vapor retarders and air barriers
- caulking and sealants
- landscaping

The moisture transfer processes that are more likely to affect building deterioration are seasonally variable in direc-

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tion of flow, in magnitude, or in continuity. They are indoor/outdoor air exchange with building cavities, diffusion of moisture through materials, migration of groundwater upward into building foundation and walls, excessive indoor relative humidity, leakage of rain, and solar effects on absorbed moisture.

Indoor relative humidity is an everyday condition that conveys a sensory message to the occupants about the moisture condition in their building. The indoor relative humidity level is the result of balance between the indoor generation and inward flow of moisture and the outward flow of moisture produced by various transfer processes. The principal factors influencing the humidity level at which this balance occurs are the indoor generation rate, the seasonally variable exchange of moisture with the outdoors through infiltration and ventilation, and humidification or dehumidification.

Technical Knowledge and Data Required

The building design team can satisfactorily reach the objectives in moisture control cited earlier in this chapter by having available the following types of information:

1. Reliable climatic data, average and extreme.
2. Best available information on the rate of indoor moisture generation by occupants and process operation.
3. A reliable schedule of building occupancy and process operation.
4. Knowledge of where and how to install air barriers and vapor retarders and the best techniques for attaining satisfactory continuity at joints.
5. Knowledge of the best practice in sealing penetrations of the air barrier and vapor retarder and the joints between major elements of the building.
6. Reliable data on the moisture absorption and desorption rates for the materials to be used.
7. Information on the cyclic absorption and desorption of moisture by hygroscopic materials and their moisture storage capacities under conditions of use, and the techniques for draining accumulated moisture from wall constructions without incurring decay.
8. Guidelines for a ventilation system that will provide adequate, but not excessive, outdoor air to all parts of the building, that will be responsive to known changes in use of different parts of the building, and that can be used to counteract undesirable air exchanges through the building envelope in different seasons.
9. Knowledge of the water table, water permeability of soils, and subsurface water flow in the vicinity of the building site.
10. The roof drainage, landscaping, and grading requirements for the site.

The availability of the various classes of information itemized above is highly variable. For example, climatic data for major cities are reasonably complete for the United States and Canada, and the guidelines for roof drainage, landscaping, and grading have been adequately published. On the other hand, published information on the moisture absorption and desorption rates of hygroscopic materials and the safe storage capacities of various constructions under conditions of use are almost nonexistant. Use of the moisture storage concept by the building designer and builder is essentially unplanned at present and has been fortuitous in many situations.

It should be noted that good workmanship in the application of some of these procedures and intelligent use of the building by its manager or occupants are also important in some aspects of effective moisture control in buildings.

PROTECTION OF BUILDING COMPONENTS

The important moisture transfer processes that need to be considered or protected against in building construction are the following:

1. Rainwater or snow leakage, with or without wind impact pressure.
2. Rise of moisture from the earth into foundations, walls, and basement floors by capillarity or absorption.
3. Diffusion of indoor moisture into walls or ceiling with attendant concealed condensation in cold climates.
4. Diffusion of outdoor moisture into walls or ceilings and roofs, with or without solar exposure.
5. Transport of moist indoor air into elements of the building envelope, with or without static pressure difference accompanied by transfer of moisture to the envelope materials.
6. Transport of moist outdoor air into elements of the building envelope, with or without wind pressure, accompanied by transfer of moisture to envelope materials.
7. Impact of sprinkler water or water splashed from trees and shrubs.

Not all of the above moisture transfer processes apply equally to all of the components of the building envelope. For example, wind does not generally have access to floors except for residences with well-vented crawl spaces or apartments or commercial buildings built on columns. Also, floors are not subject to direct solar heating except through windows.

ASTM Practices for Increasing Durability of Building Construction Against Water-Induced Damage (E 241) provides guidelines in a qualitative format in three sections: (a) major principles to consider for design and construction; (b) examples of constructions that enhance durability; and (c) examples of constructions and conditions that should be avoided.

Walls

Walls can be subject to all the potentially deleterious moisture transfer processes listed above.

The lower few feet of a wall at the foundation can become wet by capillary rise of water from the earth in areas of high water table or in buildings that have not had the appropriate site grading and preparation for draining off surface or rain water. A capillary break is needed between the foundation and the bottom of the wall to prevent this source of wetting. Frequent impingement of water on the wall from lawn sprinkling or splashing from the ground and plants can also wet the lower part of the walls, and, of course, this source of water bypasses the capillary break.

Air leakage into building envelopes has been shown to be a more powerful mechanism for transporting water vapor into the building envelope than diffusion caused by vapor pressure differences. Research information summarized in the *1989 ASHRAE Fundamentals Handbook* [4] shows that walls account for a third or more of the total air leakage, on the average, in a mixture of old and fairly new residences. Table 1 shows the range and mean values for air leakage of various building elements, as published by ASHRAE. Data collected on a limited number of commercial buildings [5,6] indicated that the air leakage rate per unit of wall area was of comparable magnitude to that for residences.

The relatively high level of wall air leakage indicates the need to limit the transfer of air into the building from either the interior or exterior. In cold climates, an air barrier is frequently installed on the inside of the wall framing. The material chosen is usually a plastic film, which permits the air barrier to function also as a vapor retarder. Care must be taken to provide continuity of the air/vapor barrier at floor, ceiling, and wall joints and at window and door frames, and to ensure that the barrier is sealed around electrical outlets, plumbing connections, and utility service penetrations. Joints of the air/vapor barrier must be lapped and sealed. An interior air barrier is only partially effective in limiting entry of air into the wall from the exterior.

The air barrier can preferably be placed on the outside of the wall framing, but in cold climates it must have a moisture permeance high enough to transfer the moisture reaching it from the occupied space, or, alternatively, it must be located at a plane where its inner surface temperature during the coldest weather is as high or higher than the dew-point temperature of the indoor air. This latter alternative can be attained by installing a board insulation that is an air-vapor barrier and which has sufficient thermal resistance to cause its inner surface temperature to be higher than the indoor dew point temperature. If the air barrier installed outside the framing has little thermal resistance, then a well-sealed vapor retarder must be placed on the warm side of the framing to limit the moisture transfer to a level that can be dissipated as vapor through the air barrier, the sheathing, and the siding. Both air barriers and vapor retarder films must be physically supported to prevent dislodgement by wind pressure. In situations where building materials are wet at the time of installation, the vapor retarder must be located so the materials can dry either to the inside or outside.

Air-conditioned buildings constructed in the humid climates bordering the Gulf of Mexico and the South Atlantic Ocean, Hawaii, and Puerto Rico and in other warm humid areas of the world should have a vapor retarder and air barrier installed as close as possible to the exterior of the wall to prevent condensation occurring on the inside cladding of the wall during the summer [3]. Dew-point temperatures averaging 80°F (26.6°C) or higher for a month or more can occur during the summer in these humid climates.

TABLE 1—Air leakage distribution in residential buildings.[a]

Building Element	Range of Observed Leakage, % of Total	Mean Observed Leakage, % of Total
Walls	18–50	35
Ceiling details	3–30	18
Heating systems	3–28	18
Windows and doors	6–22	15
Fireplace	0–30	12
Vents in conditioned space	2–12	5
Diffusion in walls	. . .	<1

[a] *1989 ASHRAE Handbook, Fundamentals Volume*, Chapter 23.

Air-conditioned buildings constructed of masonry blocks and finished with furring strips, insulation, vapor retarder between furring strips, and plasterboard interior [7] frequently experience condensation on the back of the vapor retarder and softening of the plasterboard interior in humid and rainy climates. Even though the masonry block is painted, expansion and contraction can cause many hairline cracks in the painted surface. During heavy rains, water is absorbed into the cracks and is stored in the masonry block. Subsequent solar radiation drives the water vapor inward to condense on the vapor retarder and to be transferred through the furring strips to the plasterboard, causing it to soften and discolor. Enough solar heat can be stored in the masonry blocks during the day to continue vapor transfer to the vapor retarder and the plasterboard throughout the night. A surface coating on the masonry block that retains sufficient elasticity to avoid cracking under the temperature changes to which it is exposed would alleviate this problem. A saturated sheathing paper installed between the masonry block and the insulation would also protect the insulation and the interior plasterboard.

A limited amount of research on moisture transfer in buildings located in the fringe climates north of the humid climate zones, described in the *1989 ASHRAE Fundamentals Handbook*, Chapter 21 [4], indicates that areas of the country with moderate winter temperature and less extreme humid summers may perform satisfactorily without any vapor retarder in the wall construction [8]. Neither extreme summer or winter conditions last long enough to cause condensation problems, and the absorption and desorption cycle in the wood and other hygroscopic materials in the walls is effective in preventing premature decay. More research is needed on this hypothesis, and better guidelines for the use of this practice are needed.

Experience and limited research indicates that some absorption and desorption of moisture in the hygroscopic materials in a wall construction on a seasonal basis can be allowed without decay of materials. However, the percent of saturation, its duration, and the associated temperature of the wet materials all influence the onset of decay. Some of these limitations are known approximately in a laboratory setting, but very little published information exists on what the conditions are in actual buildings under natural climatic exposure. It is probable that temporary moisture storage in walls has allowed some inadequately sealed walls to get by without excessive deterioration.

Exterior walls must be designed to shed rain or snow, wind-driven or not, without allowing it to enter or penetrate the insulated portions of the wall. Overhanging eaves provide protection for the upper parts of the wall except for extreme winds. In climates with wind-driven rain, the "rain screen" concept [9] is used. This concept utilizes an exterior cladding or siding backed by an air space, ½-in. wide or more, which is vented top and bottom to the outside air. Venting the air space to the outside air tends to equalize the wind pressure across the cladding or siding, thus reducing the amount of water transported through cracks and holes. The air space, open at the bottom, allows water that penetrates the cladding to drain to the ground outside. An air and water barrier must be placed on the inner side of the air space to prevent water and moist air from being forced into the insulation.

In drier climates, a "rain screen" may not be required; water penetration can be prevented by application of building paper, plywood, or similar sheet material over the exterior of the wall framing.

Windows and Doors

The principal potential moisture problems with windows and doors are the following:

1. Poor sealing of the wall air barrier and vapor retarder at window and door joints with the wall.
2. Penetration of rainwater into the wall construction beneath the windows.
3. Condensation of moisture or frost formation on the inside of windows in cold weather and subsequent drainage of the water onto the sill and into the wall construction.
4. Excessive leakage of warm moist air into the building in summer weather to add to the air conditioning load.

Air barriers and vapor retarders must be carefully sealed at window and door openings to prevent air leakage into the wall construction at the window and door frames. Likewise, the design of the window sills and the sealant techniques must be such that rainwater drainage is diverted to the outside without wetting the insulated construction beneath the windows.

Double and triple windows should be used where there are extended periods of cold weather to reduce surface condensation and drainage. Research by Wilson [*10*] has shown that indoor relative humidity of 40% at a temperature of 70°F (21.1°C) can be maintained without excessive condensation on double-glazed windows for outside temperatures down to −26°F (−32.2°C) and on triple-glazed windows for outside temperatures down to −40°F (−40°C). The drainage of window condensation should not be allowed to remain on the window sills or to run down the inside walls.

Excessive window and door leakage can be avoided by specifying the maximum acceptable leakage observed when windows and doors are tested in accordance with ASTM Test Method for Rate of Air Leakage Through Exterior Windows, Curtain Walls, and Doors (E 283) or ASTM Method for Field Measurement of Air Leakage Through Installed Exterior Windows and Doors (E 783), whichever is applicable. Air leakage around doors and window sash affects heating, cooling, humidification, and dehumidification loads, but does not directly contribute to the amount of concealed condensation in the walls.

Floors

Moisture problems with floors are likely to be confined to the following conditions:

1. Capillary rise of earth moisture through concrete slabs on grade and foundations.
2. Indoor condensation at the perimeter surface of concrete slabs on grade.
3. Transfer of moisture from the earth through wood floors over crawl spaces by diffusion and air leakage.
4. Mold and fungus growth on wood members including decay in crawl spaces due to high humidity.
5. Leaky return ducts for heating systems located in crawl space bringing moist air into the living space.
6. Inadequate slope of earth surrounding the building to drain away surface water.

Concrete slab floors should be underlaid with a 4-in. (0.1-m) layer of gravel to serve as a capillary break for groundwater. The gravel should be covered by a continuous vapor retarder of sufficient strength to prevent puncture by the gravel during construction. The subfloor vapor retarder should be turned up and sealed with the vapor retarder in the walls. The vapor retarder should be placed underneath the grade beam in that type of construction.

Water impermeable rigid insulation of sufficient thickness to prevent winter condensation on the perimeter of concrete floor slabs should be placed outside of the slab edge to a depth of at least 2 ft (0.61 m) or horizontally inward under the slab for a distance of 2 ft (0.61 m) or more.

Crawl spaces underneath a building should have the earth covered with a continuous vapor retarder of 6 mil (0.15 mm), polyethylene or equal, to reduce moisture migration from the earth. In vented crawl spaces, the vapor retarder needs to be turned up several centimeters on the wall perimeter. In unvented crawl spaces, the ground cover vapor retarder should be continued up the inside and over the top of the foundation wall. Ventilated crawl spaces should be provided with distributed vents with an area equal to 1/500th of the floor area of the building [*4*] and should be open only during spring and fall seasons.

Floors over ventilated crawl spaces require insulation between joists and a vapor retarder covering both the insulation and the joists on the underside to prevent condensation on the underside of the floor in summer. In winter, air leakage is typically from the crawl space to the living space due to the stack effect of the heated building. Unless well sealed and insulated, ducts for warm air heating systems should not be placed in ventilated crawl spaces because leaks in the ducts will cause an undesirable exchange of heat and moisture both in winter and summer. Care must be taken to seal penetrations of floors over crawl spaces and basements for plumbing and water lines, electric service, ducts, and other utility services to prevent passage of warm, moist air and soil gases into conditioned space under the influence of chimney effect or mechanical ventilation.

Floors located below grade level need to be protected from water leakage, especially in wet climates or on generally flat terrain. Such floors need a layer of coarse gravel underneath the floor covered by a heavy weight vapor retarder carefully overlapped and sealed at the joints. In addition, a perforated drain pipe surrounded by several centimeters of coarse gravel may be required around the building at the level of the foundation. The drain pipe must be connected to the storm sewer or to an outlet at lower level, or sump.

Ceilings and Roofs

One of the principal functions of a roof is to prevent rain and melted snow from entering the ceiling, walls, and foundation of a building. Roofs are exposed to all the elements of exterior climate: rain, snow, hail, wind, solar radiation; forces resulting from expansion and contraction due to wide temperature changes; and foot traffic, in some cases. Most roofs fail before the expected lifetime of the building and have to be repaired or replaced.

There are many types of roofs: pitched roofs with attics on residences, low-sloped roofs on row houses, Mansard roofs on residences and institutional buildings, low-sloped and flat roofs on commercial, institutional, and industrial buildings.

In Chapter 16 of this manual, Tobiasson has classified roofing systems in four categories: (a) compact membrane, (b) compact water-shedding, (c) framed water-shedding, and (d) framed membrane roofing systems.

The principal moisture control problems encountered by roofs are:

1. Direct water leaks due to long-term deterioration of roof materials caused by solar exposure, ultraviolet radiation, expansion and contraction, and wind action.
2. Improper disposal of rainwater due to inadequate drains, gutters, downspouts, and water run-outs.
3. Ice dams formed at the eaves of overhanging roofs in climates experiencing heavy snows followed by cold sunny days and with excessive heat loss from below.
4. Condensation or frost forming on the underside of roofs due to inadequate roof ventilation or excessive entry of moist air through the ceiling, or both.
5. Snow entry.

Pitched roofs, low-sloped roofs, and flat roofs should be ventilated by providing an air space between the underside of the roof and the insulation and openings for air inlet and outlet. Either a difference in elevation between inlet and outlet or wind promote circulation. Except in calm weather, the ventilating air carries out water vapor that penetrates the ceiling insulation and prevents condensation or frost from forming on the underside of the roof. The inlets and outlets must be distributed to assure that the entire roof area is ventilated. The *1989 ASHRAE Handbook, Fundamentals Volume* summarizes recommended practice for various types of roofs.

Most building standards, good practice guidelines, and association manuals recommend or require that a vapor retarder with a permeance equal to or less than 1 perm (0.66 metric perm) be installed on the inside of the ceiling in moderate and cold climates [*11*]. This vapor retarder, also serving as an air barrier, should be made continuous at the top of the walls by overlapping and sealing, and all penetrations of the retarder by utility services should be carefully sealed. The exception to this broad requirement for a vapor retarder is the cathedral ceiling with a plank deck exposed to the interior. Experience indicates that the moisture absorption capacity of the planking is able to accommodate seasonal moisture accumulations. In heavily insulated cathedral ceilings, a superior vapor retarder with permeance no greater than 0.1 perm (0.07 metric perm) is necessary.

Large flat roofs are probably the most difficult to protect from moisture damage. Such a roof built with a waterproof membrane on top of the insulation and a well-sealed vapor retarder on the underside of the insulation tends to provide a trap for moisture that enters the insulated space from either direction. An air space must be provided between the insulation and the waterproof membrane, as well as air inlets that will ventilate each joist space in the roof. Fans are sometimes used to assure ventilation of large flat roofs.

Inverted roof systems, in which the insulation and a layer of ballast are placed on top of the waterproof membrane, are being used to prevent or delay the deterioration of the membrane. In the inverted roof system, a closed-cell insulation must be used since the insulation is exposed to the rain. The layers of insulation and ballast reduce the temperature changes and the large-dimensional changes otherwise experienced by the membrane and also protect it from solar radiation and wind. The inverted system is used principally on commercial and institutional buildings.

Rainwater falling on a sloped or pitched roof should be collected in gutters and delivered remotely from the building by means of downspouts and drain tile to prevent soaking the earth at the perimeter of the building. The earth at the perimeter of the building should be sloped to drain surface water away from the foundation.

Ice damming at the eaves can be reduced or eliminated by decreasing heat transfer through the ceiling together with adequate ventilation of the roof through soffit and ridge vents to reduce snow melting, and by a waterproof membrane at the eaves. This waterproof membrane is an extension of the back side of the gutter or it overlaps the back side of the gutter and extends up under the roof shingles well past the intersection with the vertical walls, thus preventing the water from melting snow from draining into the top of the wall or onto the ceiling when an ice jam forms on the roof at the edge of the overhang.

In hot humid climates the ventilation air brought into the attic of a pitched roof of a consistently air-conditioned building will cause condensation on the upper side of the vapor retarder placed between the gypsum board ceiling and fibrous insulation. In such cases, a vapor impermeable rigid insulation should be installed on the underside of the ceiling frame above the gypsum board. This insulation should be of such thermal resistance that the upper side temperature is above the dew-point temperature of the ventilating air. A similar situation will occur in hot humid climates for low-sloped and flat roof constructions, and a similar remedy is applicable.

In pitched and low-sloped roofs with soffit air vents, a wind baffle must be placed at the perimeter of the roof where the ceiling insulation overlaps the wall top plate to prevent wind from penetrating the insulation at the soffit vent locations [*9*]. Air penetration of the insulation at these locations could deposit moisture at the top plate and adjacent ceiling gypsum board.

MOISTURE CONTROL, INDOOR RELATIVE HUMIDITY, AND INFILTRATION/VENTILATION

Indoor Relative Humidity

When all of the measures for control of moisture transfer, concealed and visible condensation, and water leakage from outside have been built into the exterior envelope, there remains the problem of disposing of the indoor moisture load that is characteristic of all occupied and some unoccupied buildings. Ventilation is required for all occupied buildings to supply air for respiration, for gas cooking, and/or for combustion of fossil fuels. The total ventilation required for these purposes may be sufficient to dissipate the moisture load in some buildings. In some cases, it may be the moisture load that determines the required ventilation rate; in other cases, it may be odor dissipation, heat dissipation, or air contaminant removal.

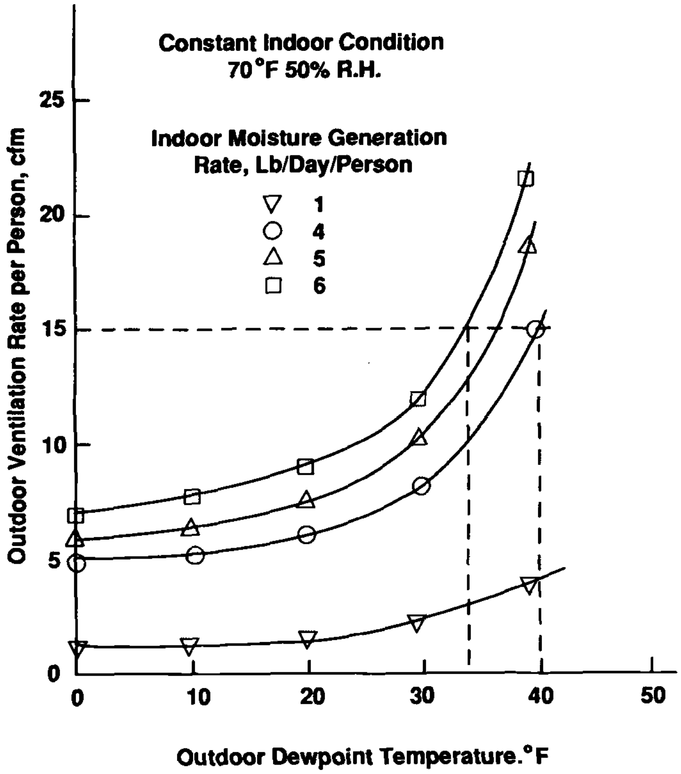
The indoor relative humidity of most buildings with climate control designed for human occupancy is maintained between 30 and 50% for comfort and health reasons. Fifty years ago, when insulation was just beginning to be used in building envelopes, little was known about measurement of air leakage in buildings, and air conditioning was in its infancy; indoor relative humidity was influenced mainly by outdoor climate, and indoor relative humidity fell below 10% during the winter in cold weather. Even today, many older buildings without humidification equipment may experience uncomfortably low indoor humidities in cold weather. On the other hand, the reduction of air leakage in modern residences can be so effective that very high indoor humidities can occur, resulting in mold and mildew formation, decay of building materials, and a decrease in comfort and health of the occupants.

In new residences and those built in the last 15 to 20 years, it is important to have a relative humidity indicator or controller installed in a location sensitive to most of the activities of the house. The relative humidity in a residence is a fairly good indicator of the adequacy of the ventilation process and the airtightness of the building. In winter, high relative humidity (above 50%) indicates that the building is tighter than can be tolerated for the moisture generation and that additional ventilation is needed to prevent concealed condensation, mold, and mildew. An unusually low relative humidity in winter indicates that too much outside air is entering the building and that excessive energy is being used to warm the building, or that some other factor than moisture may be dictating the ventilation rate, and that humidification is needed.

INFILTRATION/VENTILATION AND MOISTURE CONTROL

Many residences in use today rely on infiltration, a fresh air duct connection to the furnace blower and/or as-needed manual operation of kitchen and bathroom exhaust fans to control relative humidity and odor in their homes. Infiltration and most natural ventilation techniques are not efficient and effective methods for removing moisture from a residence. The quantity of air exchange produced by either process is affected by indoor/outdoor temperature difference and by wind velocity. The amount of cracks, apertures, and other openings in the envelope that would produce the required air exchange on a cold windy day would produce far too little air exchange on a mild calm day. Conversely, the amount of leakage area that would produce the correct amount of air exchange in spring and fall weather would be excessive and wasteful of energy in cold weather, especially if accompanied by a strong winter wind.

The amount of outdoor air at selected dewpoint temperatures that could dissipate various rates of moisture generated indoors can be calculated from the properties of moist air tabulated in the *ASHRAE Fundamentals Handbook*. Outdoor air is typically a moisture sink in winter and a source of moisture in all but arid climates in the summer. Various researches [*12,13*] have indicated that the average of the total moisture release in residences is likely to be in the range from 4 to 6 lb (1.8 to 2.7 kg) per person per day. The ventilation rates per person of outdoor saturated air at temperatures ranging from 0°F to 40°F (−18°C to 4.4°C) required to maintain a relative humidity of 50% at 70°F (21.1°C) indoors for moisture releases of 1, 4, 5, and 6 lb (0.45, 1.8, 2.3, and 2.7 kg) per person per day are shown in Fig. 1. Figure 1 shows that the value of 15 ft^3/min (7.1 L/s) per person recommended in ASHRAE Standard 62-81, Ventilation for Acceptable Indoor Air Quality for Human Occupancy, could dissipate all of the moisture generated at rates of 6 and 4 lb (2.7 and 1.8 kg) per person, respectively, for outdoor dew point temperatures of 34°F and 40.5°F (1.1°C and 4.7°C), respectively. At lower outdoor dew point temperatures for the same rate, the indoor relative humidity would decrease unless humidification was employed to maintain a humidity of 50%. Conversely, at outdoor dew point temperatures above about 40.5°F (4.7°C), indoor relative humidity would rise above 50% for the same ventilation rate unless dehumidification was employed. At an outdoor dewpoint temperature of 50°F (10°C), the ventilation rate required to maintain the same indoor conditions would



1 cfm = 0.472L/s
1 lb = 0.454 kg
5/9 (°F - 32) :°C

FIG. 1—Outdoor air ventilation rate per person versus outdoor dew point temperature for a range of indoor moisture generation rates.

be about ten times as great as for 40°F (4.4°C) because the dew point for indoor air 70°F (21.1°C) and 50% relative humidity is about 50.5°F (10.3°C). A ventilation rate of 15 ft^3/min (7.1 L/s) per person corresponds to an air change rate of about 0.5 per hour for an occupancy of four in a house with a floor area of 1000 ft^2 (92.9 m^2), or an air change rate of 0.25 per hour in a 2000 ft^2 (185.8 m^2) house.

Tight houses are being built with seasonal average air infiltration rates of 0.1 to 0.2 air change per hour. Such houses would operate at excessive indoor relative humidity most of the time and would require mechanical ventilation to comply with the ASHRAE Standard 62-81 requirement of 15 ft^3/min. (7.1 L/s) per person. Even an average size house with a seasonal air change rate of 0.5 per hour would probably be deficient in outdoor air exchange during summer, fall, and spring weather when the outdoor-indoor temperature difference was low.

MOISTURE STORAGE

Analytical studies by Tenwolde *[14]* of moisture transfer and moisture storage in hygroscopic materials in residential walls showed that lowering the indoor relative humidity by increasing the outdoor ventilation rate lowered the storage of condensed moisture in the walls. Thus, lowering the indoor relative humidity from 50 to 35% during the cold weather months would reduce the concealed condensation in building construction and would reduce the amount of humidification required for treating the required 15 ft^3/min (7.1 L/s) per person of outdoor air.

Using the ventilation system to depressurize the interior of a house in winter and to pressurize an air-conditioned house in summer is a useful way to reduce the entry of moist air into the envelope construction from inside and outside, respectively. However, it would only be partially effective in windy weather and would increase the total air leakage of the house somewhat. Depressurization of the living space may cause uncomfortable drafts under some conditions.

COMMERCIAL AND INSTITUTIONAL BUILDINGS

Many commercial and institutional buildings have lower indoor moisture generation rates per person than residences. There are some exceptions. Furthermore, many commercial and institutional buildings are not occupied or operational 24 h per day, so the cyclic nature of moisture generation may be useful in the moisture control procedures adopted. In large buildings, the moisture load is not likely to be dealt with on a per person basis. Large buildings should be zoned to group rooms or areas having similar utility requirements, including moisture control, close together whenever possible so that the special requirements of the zone can be accommodated with similar controls or zone controls.

Some envelope materials used in commercial and institutional buildings tend to be more tolerant to moisture and to suffer less decay. However, care must be used in the design of outside walls to prevent internal air circulation in hollow masonry units, to avoid penetration of air barriers by structural members, and to avoid leaks at the joints of dissimilar materials. For example, masonry cannot form an airtight joint with steel framing members.

Building design for high-rise buildings should seek to isolate one floor from another to eliminate or reduce cumulative chimney effect, thus avoiding high indoor-outdoor pressure differences to exist across parts of the building envelope. Special care in design of stairwells, elevator shafts, and utility shafts is needed to prevent these passageways from imposing a large chimney effect on the surrounding rooms.

Some types of rooms or buildings require or cannot avoid high indoor humidity levels. Examples are swimming pools, operating rooms, laundries, and gymnasiums. In such cases, exceptional care must be used by the designer and builder to provide well-sealed air barriers and vapor retarders and to choose materials that resist rusting and do not exhibit excessive dimensional changes with moisture content. Placing such rooms where they do not have walls exposed to the outdoor weather can sometimes reduce the vapor pressure differences and the static pressure differences that transfer moisture into the construction.

DRY CLIMATE EFFECTS

The effect of a dry climate on moisture control measures has not been discussed extensively thus far. Buildings in dry climates will probably entail less cost in moisture control design, labor, and materials, although a higher cost for humidification can be expected. In particular, the need for and the complexity of a "rain screen" should be reduced, the cost of a drain tile system and vapor retarder system at the foundation level may be reduced, and the cost of rainwater drainage from the roof may be less. Perhaps somewhat less labor and material would be required to seal the vapor retarder in dry climates.

In dry climates, one might choose to operate the interior at a 35% relative humidity rather than 50% to reduce the cost of humidification. Also, in a dry climate, there could be fewer problems with mold and mildew growth depending on construction practices and living habits.

Not much technical information has been published in U.S. literature on moisture control in dry climates and on the potential for lower building costs.

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16

General Considerations for Roofs

by Wayne Tobiasson[1]

TYPES OF ROOFING SYSTEMS

Water-Shedding Versus Waterproof

THE EXTERIOR WATERPROOFING ELEMENT of a roof can be a waterproof membrane or, if the roof has enough slope, a series of overlapping, water-shedding elements such as shingles or tiles. Since gaps exist between such overlapping elements, water must flow down them by gravity and sufficient headlap must exist to prevent water penetration by wind and rain forces, by air pressure, and by capillary suction [*1*].

Water-shedding systems work well on relatively steep slopes, but they have limitations in cold regions where icicles and ice dams may form at roof eaves. Water that ponds behind ice dams can rise above the headlap of the water-shedding elements and cause leaks. Those portions of water-shedding systems that might be subjected to ponding behind ice dams should be underlain with a waterproof membrane. Such membranes are also useful in roof valleys where snow may retard the flow of converging water. That water may rise in the snow above the headlap.

Waterproof membranes are required on low-slope roofs where water flow by gravity is not fast enough to allow use of water-shedding systems. Waterproof membranes can also be used on steep slopes, but complications such as downslope movement (i.e., slippage) can arise.

The waterproof membrane may be a bituminous built-up system (i.e., the so called "tar and gravel" roof) or one of the newer membranes of plastic, rubber, or polymer-modified bitumen. A plethora of components are available from which waterproof membrane roofing systems can be assembled [2]. Unfortunately, many components do not behave well together. Considerable knowledge of the art and science of roofing is needed to design and build viable systems. Fortunately, valuable guidelines have been written [*1,3–5*] and some excellent systems are available. Many poor systems are also marketed, and the phrase caveat emptor (let the buyer beware) is appropriate.

Waterproof membranes and their flashings should be totally sealed against water penetration. Since a total seal is almost impossible to achieve, even waterproof membranes should be provided with slope to preclude ponding of water on them [*1,3,6,7*]. A "dead flat" membrane is a design mistake. Fortunately, in most instances, a slope of 1:50 (i.e., about 1°; ¼ in./ft) is sufficient. It is usually best to create slope by sloping the roof itself rather than using tapered insulation.

Usually, the most inexpensive way to drain a membrane roof is over its eaves. Unfortunately, eaves and other terminations are often the weakest links in the waterproofing system and leaks are likely to develop there. In addition, ice dams may form along the eaves or at scuppers, causing water to pond on a large portion of the roof. Because of these problems, it is far better to drain low-slope membrane roofing using internal drains. Scuppers located a few inches above the membrane can be used for secondary (i.e., emergency) drainage in the event that the primary drains become blocked.

Some years ago, deliberately ponded roofs were promoted. Numerous problems occurred; they are no longer considered appropriate.

Membrane roofing systems suffer more than their share of moisture problems, but most of these problems are caused by entry of rain and snow meltwater at defects in the exterior waterproofing system of the roof, *not* by improper control of condensation. Flaws at flashings, penetrations, and seams are the primary cause of roof leaks for low-slope membrane roofs. Attention to these details is a critical design and construction issue. Moisture may also be built into the roof [*8,9*].

A relatively small number of moisture problems in membrane roofs are related to condensation [*10*]. Nonetheless, serious condensation problems do occur in some membrane roofs, and it is important to understand how to avoid them.

Older metal roofing formed of overlapping components was designed to shed water. Newer standing seam metal roofing systems have many of the features of membrane roofing systems [*11*]. However, it is wise not to think of metal systems as membranes since they are usually not watertight at their valleys, eaves, ridges, rakes, and penetrations. Standing-seam metal roofing systems perform very well in many areas, but they have some limitations in cold regions where water can back up behind ice dams and slush can form in valleys, along parapets, and where roofs abut higher walls [*12*].

For any kind of roof, the risks associated with moisture can be reduced significantly by utilizing proven flashing and penetration details, by constructing the roofing system properly, and by taking the job of preventive maintenance seriously.

Compact Versus Framed Systems

When studying condensation problems in roofs, it is important to distinguish between compact and framed roofing systems.

A *compact* roof with membrane waterproofing is shown in Fig. 1. The insulation is placed above the roof deck. There is

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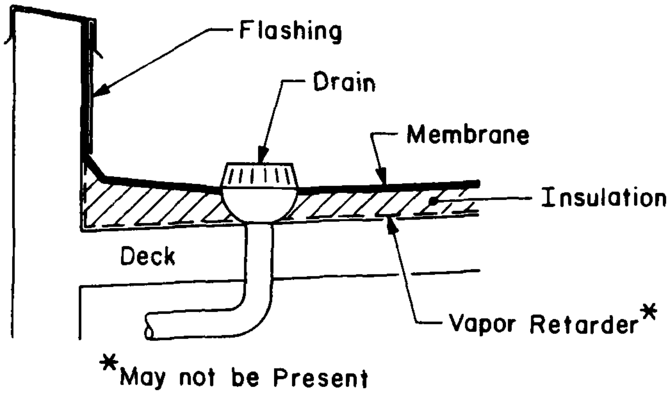

FIG. 1—Typical compact roof.

little opportunity for air movement within a compact system because (1) it contains no air spaces, (2) the rigid insulations used are usually of low permeability, and (3) wires and pipes are seldom routed within it. A compact roof topped with a waterproofing membrane is very resistant to air leakage. Because of this, such systems suffer few condensation problems. This is particularly true of systems that have their components adhered together in solid moppings of hot bitumen.

A *framed* roof is shown in Fig. 2. Such roofs are usually insulated below the deck between framing members. Often relatively inexpensive batts of permeable fibrous glass or rock wool insulation are used. A barrier to air and vapor may or may not be present. It is common for electrical wires to be placed among the batts and for fixtures to be recessed up into the roof. Many air leakage paths are present in such roofs. Framed roofing systems that leak a lot of air are apt to have condensation problems.

Water-shedding systems and waterproof membrane systems can be used on either framed or compact roofs, but it is common to have compact membrane systems and framed water-shedding systems as shown in Figs. 1 and 2.

Ventilation

To prevent condensation from accumulating in framed roofs, many contain a ventilated air space above the insulation as shown in Fig. 2. It opens to outside air at each end. When the air space is steeply sloped as shown and not inadvertently blocked, natural, stack-induced ventilation can be quite good. At lower slopes, natural ventilation diminishes significantly.

Ventilation can also promote flow of moist indoor air up into a roof. Occasionally, this can cause, rather than cure, moisture problems. Ventilation can also cause damp outdoor air to be drawn up into a roof where it is not wanted. These potential problems notwithstanding, ventilation of framed roofing systems is usually appropriate.

With snow on the roof, there is a second reason to ventilate roofs that drain to cold eaves: ventilation can minimize icings at eaves by removing building heat rather than letting it warm the underside of the roof. Building heat, not the sun, is usually the primary cause of ice dams. Heat from the sun may generate meltwater, but that heat also warms the eaves, reducing the tendency for growth of icings there. Periods during which building heat creates meltwater can be reduced by using *cold* ventilated roofing systems.

In cold regions, generally the best way to build framed roofs that slope to eaves is to make them cold ventilated systems. *Hot*, unventilated framed roofs that slope to cold eaves are apt to suffer from ice damming and from condensation.

ADVERSE EFFECTS OF MOISTURE

General

The common manifestations of moisture problems in roofs are annoying, damaging leaks into the rooms below. However, even when leaks do not occur, the roofing system can be suffering severe deterioration from the effects of water in the wrong places.

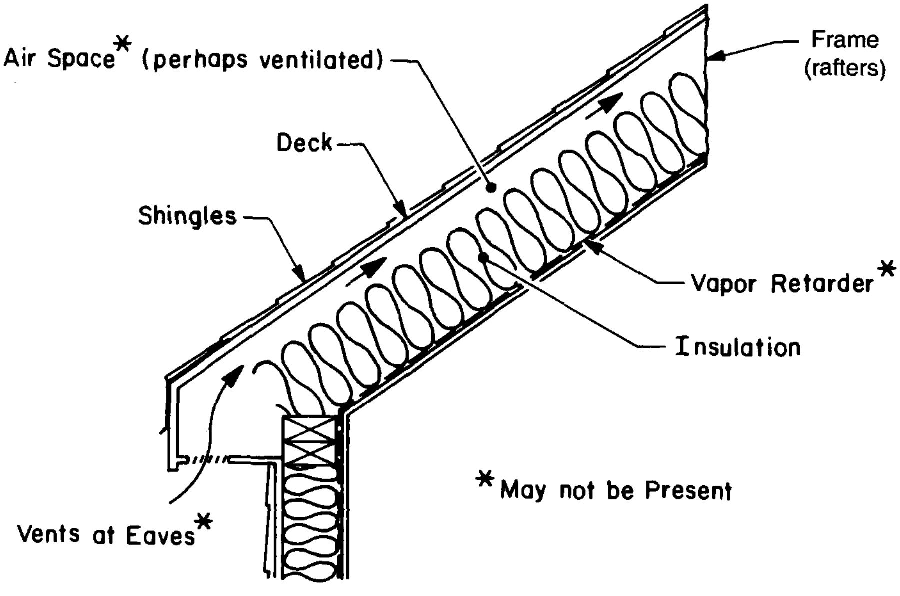

FIG. 2—Typical framed roof.

Excess moisture in a roofing system can weaken and eventually rot wood, corrode metal, cause leaching, efflorescence, and spalling of concrete and masonry and, by freeze-thaw action, delaminate or disintegrate roofing components [*1,3,13*].

Each 100 mm of wet insulation can contain up to 96 kg of water per square meter (i.e., 5 lb of water per square foot for each inch of wet insulation) [*7*]. This unknown, unwanted extra load can be enough to overstress or fail the roof structure in combination with snow or wind loads.

Membranes

The bitumen (asphalt or coal tar pitch) in a bituminous built-up membrane is essentially unaffected by moisture, but there are several ways in which moisture can deteriorate a bituminous membrane composed of alternating layers of bitumen and felts [*1,3,14*]. The felts give the membrane strength, the interply bitumen adheres them together, and that bitumen, together with the flood coat of bitumen on top, provides waterproofing. Although the ply felts are said to be "saturated" with bitumen in the factory, they are far from saturated. They can absorb water. "Saturated" felts with water contents in excess of 60% by weight have been measured [*15*]. The fibers in asbestos and organic felts are weakened significantly if they get wet [*16*]. The wet strength of such a felt and membranes containing wet felts may be less than 20% of their dry strength [*17,18*]. Organic and asbestos felts swell upon wetting and shrink upon drying. Swelling of 0.2 and 1.5% along and across the length of a wetted felt has been measured [*15*]. The difference is due to orientation of the cellulose fibers along the length of the felt. When a wet organic or asbestos felt is dried, its shrinkage can exceed its breaking strain [*19,20*]. Because of the moisture sensitivity of these felts and the health hazard associated with asbestos, felts made with glass fibers have gained in popularity. Glass felts are not much affected by moisture. In fact, membranes constructed with them may not require an immediate flood coat of bitumen on top.

To perform successfully, organic and asbestos felts must be isolated from moisture by bitumen. When they are not, the probability that the membrane will wrinkle, shrink, split, delaminate, or blister increases greatly.

Wrinkles may occur above insulation joints where moisture within the roofing system can condense on the bottom of the membrane [*21*]. If the bottom felt is not isolated from this moisture, the moisture is absorbed by any cellulosic fibers in the felt. When the membrane is hot and soft, these fibers expand, creating a wrinkle. With time, the wrinkle may grow, crease, and eventually split. Wrinkle-cracking was so pervasive in the 1950s that new membrane systems were developed to eliminate it. By using a coated felt (saturated felt with an additional coating of bitumen applied in the factory) for the bottom ply, the underside of the membrane was made more moisture resistant and the amount of wrinkle-cracking diminished significantly.

Unfortunately, voids were built into the roof at base ply overlaps (Fig. 3) and long, tunnel blisters occurred. In addition, the use of two types of felt in a membrane led to installation of the base ply at one time and the remaining plies at a later date. This is called "phased construction." Dirt and moisture deposited on top of the base ply in the interim led to blistering and delamination of the membrane.

Today, the trend is back to use of saturated felts for all plies, with glass felts the most popular. Organic felts now have a very small portion of the market, and asbestos felts have essentially disappeared.

Back when built-up membranes were solidly mopped to wet decks and to lightweight insulating fills that still contained moisture, blisters developed between the membrane and the wet substrate at gaps in the mopping. The practice of fully adhering a membrane to a wet deck is no longer practiced because of this.

Inadequate condensation control has been blamed for blisters in built-up membranes, but often that does not ring true. Almost all blisters develop between the plies of built-up membranes at flaws in the interplay mopping (Fig. 4) [*3*]. Thus, most blisters are indications of workmanship deficiencies. If a bituminous membrane is adhered to an insulation that contains a factory-applied surfacing (such as a felt), blisters may also develop between this surfacing and the bottom ply of the membrane. A mopping void is needed for a blister to form. When the air in that void is warmed, it expands. Since the surrounding materials are also warm, they are somewhat compliant, which facilitates expansion. When the surrounding materials cool, they stiffen and resist contraction back to their original position even when the air in the blister is cooled, creating a lower pressure there. If a void is completely encapsulated in hot bitumen, only the residual air and moisture in it can promote blistering. However, complete encapsulation is unlikely. High and low temperatures and a source of air are needed for blisters to grow [*22*]. Moisture is not necessary for blister growth, but when moisture is present, the pressure within the void can increase significantly,

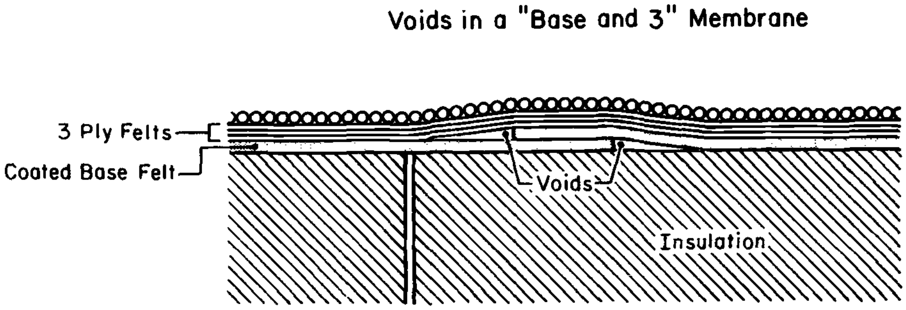

FIG. 3—Voids that may be created when a coated base felt is used for the bottom ply.

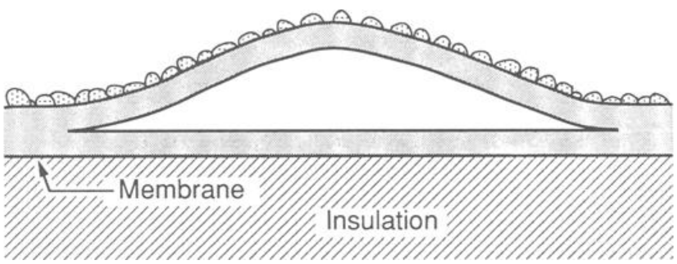

FIG. 4—Interply blister. Most blisters are interply blisters.

accelerating blister growth. The open, unsaturated nature of roofing felts, particularly those containing organic fibers, allows small quantities of air and water vapor to move toward the blister when the air in it is cool and has a negative pressure. This recharges the blister with additional air and water vapor, allowing it to grow when it is reheated.

A deliberate attempt is made to prevent air and water entry through the top of most membranes by the flood coat of waterproofing applied there. Since less attention is paid to encapsulating the bottom, it is logical that, at least initially, the source of air and water for most blisters is at the underside of the membrane at insulation seams where the felt may be exposed. Felts are not laid one on top of the other in a stack but in shingle-fashion (Fig. 5) such that each felt traverses the membrane from top to bottom (Fig. 6). Thus, each felt is in a position to absorb moisture from within the roof sandwich. This moisture may have arrived there due to inadequate condensation control [*21*], but it is more likely that it came from rainwater that entered the roof sandwich through flaws at flashings and penetrations.

Photo-oxidation at the top of the membrane can cause shrinkage of the bitumen and alligatoring (Fig. 7). These cracks can be deep enough to allow moisture to gain access to the felts, and thus the air and water necessary for blister growth can come from above as well as below.

Most of the rubber, plastic, and modified bitumen membranes are much less affected by moisture than their bituminous built-up predecessors. That is a major reason why they have become so popular. However, the contact adhesives used with rubber sheets can be damaged by moisture, and moisture may increase the rate of plasticizer loss of plastic membranes, increasing their tendency to shrink and become brittle.

But bituminous built-up membrane technology has also improved. The use of glass felts in such membranes has greatly improved their resistance to moisture.

Insulations

"Moisture, the ubiquitous roofing troublemaker," [*3*] also causes numerous problems with roof insulations. A few key issues are mentioned below.

Most insulations used in roofs can get wet and when wet, they get heavy, lose strength, swell, and deteriorate, especially during freeze-thaw [*1*]. Cellular glass insulation does not take on moisture. However, moisture that freezes in the cut cells at the edges of cellular glass boards can crack those cells, exposing others to similar action, which can eventually disintegrate the board. Extruded polystyrene insulation is quite resistant to moisture even in the presence of freeze-thaw [*23–26*], but there are situations where even extruded polystyrene insulation can become wet [*26,32*]. The other cellular plastic insulations used in roofs (expanded bead polystyrene, urethane, isocyanurate, and phenolic) take on moisture in the presence of temperature and vapor pressure gradients [*27–31,33*]. Insulation boards of fibrous glass, wood fiber, and perlite take on moisture rapidly [*28,29,31*]. When wet, the insulating ability of roof insulations is significantly reduced [*23–31,33*].

Since *essentially all insulations and most other components of roofs are adversely affected by moisture*, the normal goal is

FIG. 5—Felts laid shingle fashion.

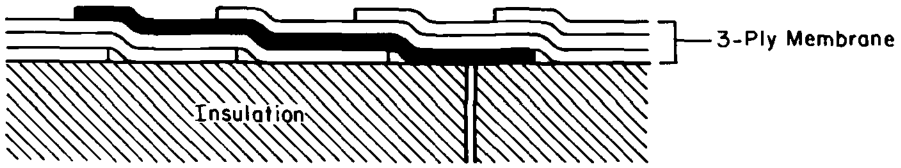

FIG. 6—Three-ply membrane. Each felt traverses the membrane from top to bottom.

to keep moisture away from them. The protected membrane roof (i.e., the "upside-down" roof) is an exception to this. Rainwater and snow meltwater are allowed to come in contact with extruded polystyrene insulation placed above the waterproofing membrane. The benefits and limitations of protected membrane roofing are discussed later in this chapter.

MOISTURE MOVEMENT

Chapter 1 describes various moisture movement mechanisms and explains why condensation occurs.

Perhaps the most important thing to realize about condensation control is that diffusion of moisture through the components of a roofing system is a very slow process that seldom causes problems. Where problems occur, movement of moist indoor or outdoor air into a roofing system is almost always present. By directing attention to the elimination of air leakage, most condensation problems can be avoided [34].

The following three quotes from the *ASHRAE 1989 Fundamentals Handbook* [35] are worth remembering:

1. ". . . rarely is vapor diffusion a major factor."
2. ". . . air movement carrying the water vapor with it is far more powerful in transporting water vapor within the building envelope."
3. "The first defense against condensation is . . . by airtight construction."

Once air leakage is acknowledged as the problem, it is clear why some types of roofs suffer condensation problems while others do not.

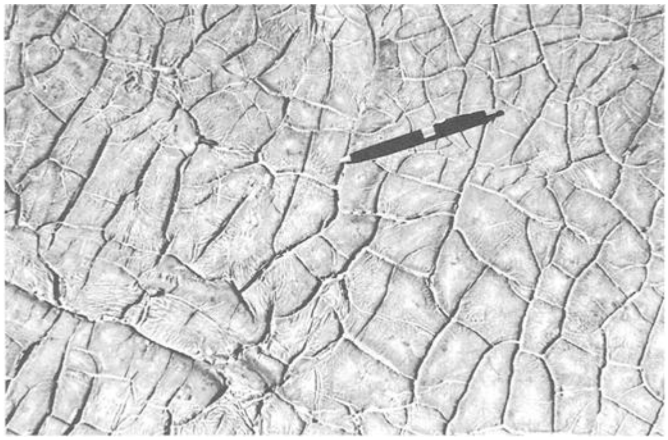

FIG. 7—Bitumen shrinkage. Photo-oxidation causes shrinkage, which produces "alligatoring."

In warm, humid climates, the primary vapor drive in roofs is downward because many buildings are air conditioned. The waterproofing membrane also serves as the vapor retarder. By not sealing the underside of the roof, any vapor that diffuses through the membrane can continue downward into the building rather than be trapped in the roof. Since roof membranes are essentially impermeable to vapor as well as to water [3], condensation problems in membrane roofs are relatively uncommon in warm, humid climates.

Most condensation problems in temperate and cold regions are generated in cold weather when the warm air in buildings usually has a higher vapor pressure than the cold, outside air. This plus wind effects, the tendency of warm indoor air to rise, and mechanical ventilation pressures cause internal moisture to move up through the roof. If an essentially impermeable membrane is present, it prevents the moisture from leaving. The dew point is reached within the roofing systems and condensation may occur there. A little condensation on the coldest day of the winter will do no harm, but when condensation occurs for many days, weeks, or months, the amount of moisture deposited can create major problems [36]. Moisture barriers may be installed near the underside (i.e., warm side) of the roof to reduce the flow of moisture to an acceptable level.

Since the primary purpose of such moisture barriers should be to reduce air leakage, not resist diffusion, it is far more important to build them with the continuity needed to resist air leakage than to use materials of very low permeability. The term *air and vapor retarder* more accurately describes their dual purpose than the term vapor barrier or vapor retarder. However, for simplicity, the term *vapor retarder* will be used in this chapter with the hope that you, the reader, will remember that this moisture barrier often must also resist air leakage. To do that, it must be built airtight.

The National Building Code of Canada [37] discusses "vapour barriers," the importance of sealing openings in them, and other measures, such as separate air barriers, to prevent condensation. In Canada the separate functions of air and vapor barriers are well established [38]. Unfortunately, American model building codes [39,40] say little or nothing about condensation control.

The importance of vapor retarder continuity is acknowledged in most technical publications, but little guidance is provided to designers and to the trades on what it takes to achieve the desired results. Consequently, many vapor retarders are not sealed or they are inadequately sealed. As an acknowledgment of the impossibility of creating a perfect vapor retarder, some roofs are ventilated just under their topside (i.e., cold side) to remove any moisture that passes their vapor retarder.

Valuable guidance on vapor retarders and ventilation is presented in Chapters 20 and 21 of the *ASHRAE 1989 Fundamentals Handbook* [35].

CONDENSATION CONTROL PRINCIPLES AND PRACTICES

Compact Membrane Roofing Systems

Description

A tightly sandwiched compact roofing system is shown in Fig. 8. The insulation is not interrupted by framing members, and there is seldom anything recessed up into a compact roof. Nor should any electrical wires or conduits be placed there. The primary reason compact membrane roofing systems suffer few condensation problems is that most are quite resistant to air leakage.

Compact roofing systems with their membrane and upper layer of low-permeability insulation fully adhered with hot bitumen are remarkably resistant to air leakage even if no deliberate vapor retarder is present.

Vapor Retarders

Since air leakage is the key issue, the resistance of the material to vapor diffusion (i.e., its permeance) is a relatively minor concern. Generally materials with a permeance of about 3×10^{-11} kg/(Pa·s·m^2) (0.5 perm)[2] or less are considered to be vapor retarders in roofs. Other guidance defines specific permeances for various climatic zones and occupancies [*4,35,41*]. Permeances recommended usually range from about 3 to 6×10^{-11} kg/(Pa·s·m^2) (0.5 to 1.0 perm), but some individuals feel a permeance of 0.6×10^{-11} kg/(Pa·s·m^2) (0.1 perm) or less is necessary [*3*]. It has also been recommended that the permeability of an air-vapor retarder should be no greater than that of the roof membrane above [*42*], but this can be very difficult to achieve.

Table 1 lists the permeance of several materials used in roofs. As shown in that table, steel is impermeable, but a steel deck should not be considered to be a vapor retarder since it contains numerous seams that permit air leakage. In fact, any system can only avoid condensation problems if it can resist air leakage. For that reason, even low permeance insulation boards, such as cellular glass, are not considered to be self-vapor retarders because an assembly of them contains numerous seams that may facilitate air leakage.

The permeances of bituminous built-up, plastic, rubber, or polymer-modified bitumen membranes are all quite low (see Table 1 in this chapter and Table 3 in Chapter 4). Because of this, calculations discussed in Chapter 1 indicate that all such membrane roofing systems would require vapor retarders if the dew point temperature of the indoor air is above the winter design temperature where the building is located. Figure 9 shows the distribution of winter design temperatures for North America.

As an example, indoor air at 20°C (68°F) with a relative humidity of only 20% would be uncomfortably dry for many people. It would have a dew point temperature of −3°C (26°F). If the indoor relative humidity were higher, which is likely for occupant comfort, that air would have a higher dew point temperature. However, even for the relatively dry indoor conditions of this example, almost all such roofs would require vapor retarders to avoid condensation problems since the dew point temperature of −3°C (26°F) is above the winter design temperature in Fig. 9 over most of North America.

In fact, most membrane roofs in North America do not have vapor retarders and they do not suffer condensation problems. It is clear that a small amount of moisture can defuse into airtight compact roofs during cold weather without doing any real harm.

Various guidelines on where to use vapor retarders for compact membrane roofing systems have been summarized [*41*]. Philosophical guidance ranges from "When in doubt, leave it out" [*3*] to "When in doubt, think it out" [*1*]. The broad differences that exist among vapor retarder guidelines for compact roofs and the lack of condensation problems suggest that the more stringent guidelines are excessive. Those guidelines range from the need for vapor retarders for the entire United States to only areas where the average January temperature is less than 1.7°C (35°F) or 4.4°C (40°F) or 7.2°C (45°F). Some guidelines recommend vapor retarders for all occupancies, while others call for their use only if the indoor relative humidity in winter exceeds 40% (or 45%) or where there is "excessive moisture within the building."

Perhaps the most commonly used guideline for compact roofs is to install a vapor retarder with a permeance of 3×10^{-11} kg/(Pa·s·m^2) (0.5 perm) or less when the average January temperature is below 4.4°C (40°F) (Fig. 10) and the indoor winter relative humidity equals or exceeds 45% [*4*]. This guideline has its advocates, but it indicates that buildings in the northern tier of states do not need vapor retarders unless they have an indoor RH of 45% or more. This does not fit with the collective experience of many researchers, designers, builders, and building owners in cold regions. Their experience indicates that, in those states, buildings with relative humidities as low as 30% in winter may need vapor retarders.

To better relate vapor retarder requirements to this experience, a series of maps of the United States, with each map representing a different winter vapor drive (i.e., a different winter condensation potential) have been developed [*43*]. Weather records were analyzed such that the entire winter was examined, not just the coldest portion. Seasonal wetting and drying potentials were determined. Figure 11 compares those potentials for roofs in Washington, DC, above spaces with a temperature of 20°C (68°F) and relative humidities of 45 and 75%, respectively. The drier occupancy (45% RH, Fig. 11*A*) has a small winter wetting potential (i.e., small "wetting" area) and a large summer drying potential (i.e., large"drying" area). The ratio of wetting potential to drying potential (i.e., the ratio of the shaded wetting and drying areas) is 0.2. When the relative humidity below the roof increases to 75% (Fig. 11*B*), the winter wetting potential increases significantly and the summer drying potential decreases. The ratio of wetting to drying increases to 1.1, which suggests that not all the moisture driven up into the roof in winter will make it back out during the next summer.

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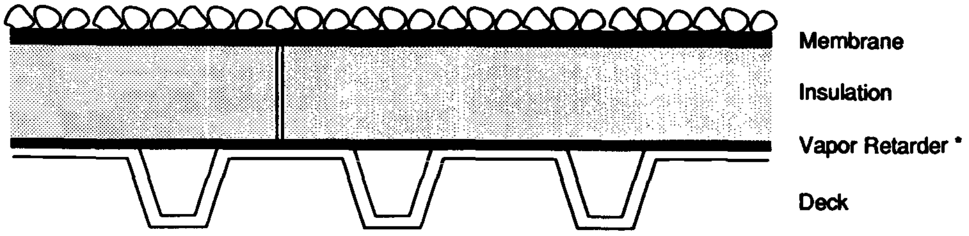
[2] A perm has units of grain/(h·ft^2·in. Hg). A grain is equal to 6.48×10^{-5} kg. One perm is equal to 5.72×10^{-11} kg/(Pa·s·m^2) or 57.2 ng/(Pa·s·m^2). The "old metric perm" has units of g/(24 h·m^2·mm Hg). One perm is equal to 0.66 "old metric perm."



* May Not Be Present

FIG. 8—Cross section of a compact membrane roofing system.

Figure 12 shows similar wetting and drying potential curves for roofs in Minneapolis, Minnesota, above 20°C (68°F) spaces with relative humidities of 45 and 75%. The wetting areas in both cases are much larger than those for the roof in Washington, DC. The drying areas are smaller and the wetting-to-drying ratio increases to 0.9 at 45% RH and 3.7 at 75% RH.

The information in Figs. 11 and 12 shows that both climate and indoor relative humidity greatly influence wetting and drying potentials.

Maps were made with winter wetting potentials of 0.67, 1.35, 2.03, and 2.70 kPa·month (0.2, 0.4, 0.6, and 0.8 in. Hg·month). With assistance from architects, engineers, roofing consultants, and contractors, the 2.03 kPa·month (0.6 in. Hg·month) map was selected as best representing the maximum winter wetting potential that can be allowed without installing vapor retarders in compact membrane roofing systems. That map is presented in Fig. 13.

Using this map, designers can see that buildings with a 20°C (68°F) indoor temperature and a 30% indoor relative humidity need a vapor retarder only if they are in very cold areas, such as northern Minnesota or most of Alaska. The indoor RH must be much higher in more southerly areas before a vapor retarder is needed (e.g., in Tennessee the indoor RH needs to be about 60% before a vapor retarder is needed).

The Fig. 13 map is for buildings with an indoor temperature of 20°C (68°F). If that is not the indoor temperature of a building being investigated, the mapped RH obtained from Fig. 13 should be corrected using Fig. 14. For example, in New York City the Fig. 13 map indicates that roofs need vapor retarders if the indoor relative humidity exceeds 50%. If the indoor temperature in a factory in cold weather is 24°C (75°F), the limiting relative humidity drops to 40%. The arrows in Fig. 14 show how this was determined.

When they are not needed, vapor retarders should not be used since they are expensive and allow "cancers" of wet insulation to grow within a compact roof having membrane or flashing flaws. Flawed roofs without vapor retarders tend to leak water into the building sooner, which often reduces the lateral extent of wet insulation.

Little guidance is available on how to seal compact-roof vapor retarders at flashings and penetrations. No particular attention is given to such seals in most situations. If a roof needs a vapor retarder it should be sealed at flashings and penetrations so that it can resist air leakage, which is usually the mechanism by which problematical levels of indoor mois-

TABLE 1—Permeance of some roofing components [35].

Material	SI Units kg/(Pa·s·m^2)	IP Units Perm[a]
Bituminous built-up membrane	0.0	0.0
1 mm (45 mil) EPDM	0.17×10^{-11}	0.04
1.5 mm (60 mil) EPDM	0.11×10^{-11}	0.03
Aluminum foil (no holes, no laps)	0.0	0.0
0.1 mm (4 mil) polyethylene	0.29×10^{-11}	0.08
0.15 mm (6 mil) polyethylene	0.23×10^{-11}	0.06
0.1 mm (4 mil) polyvinyl chloride (PVC)	about 5×10^{-11}	about 1.2
Kraft paper laminates	less than 1.1×10^{-11}	less than 0.3
No. 15 asphalt-saturated felt	4.0×10^{-11}	1.0
No. 43 asphalt-saturated and coated felt	1.1×10^{-11}	0.3
Steel deck (forgetting seams)	0.0	0.0
Steel deck (considering seams)	more than 4×10^{-11}	more than 1.0
Uncracked concrete, 150 mm (6 in.) thick	about 2×10^{-11}	about 0.5
Plywood, 6 mm (¼ in.) thick, exterior glue	2.9×10^{-11}	0.7
Gypsum wall board, 10 mm (⅜ in.) thick	189×10^{-11}	50.0
INSULATION BOARDS		
Cellular glass, 25 mm (1 in.) thick	about 0.0	about 0.0
Polyurethane, 25 mm (1 in.) thick	about 4×10^{-11}	about 1.0
Polystyrene, extruded, 25 mm (1 in.) thick	about 5×10^{-11}	about 1.2
Polystyrene, expanded, 25 mm (1 in.) thick	about 15×10^{-11}	about 4.0

[a] Grains/h·sq ft·in. mercury. See the second footnote in this chapter for permeance conversions.

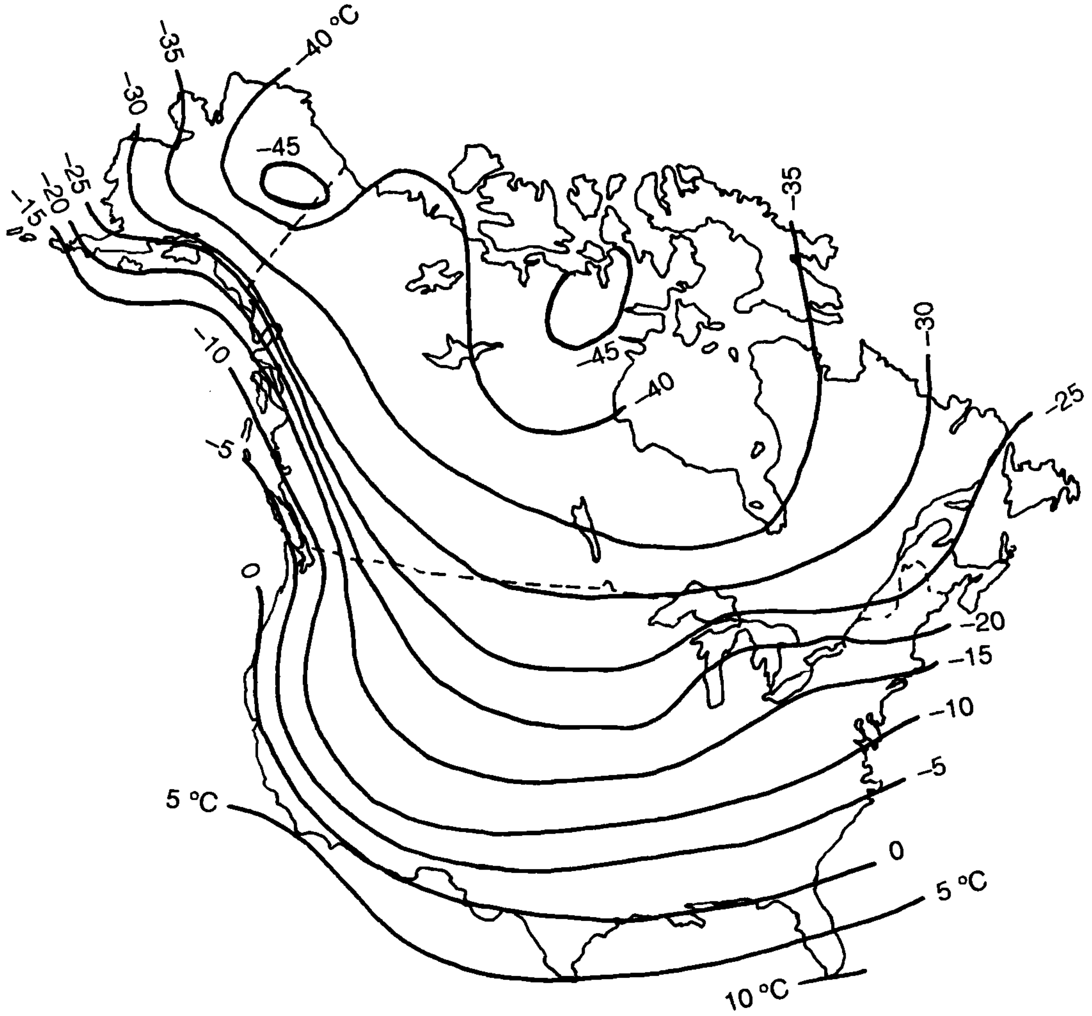


FIG. 9—Distribution of winter design temperatures over North America.

ture enter roofs. When the vapor retarder serves as a waterproofing membrane for some time during the construction process, excellent seals are often achieved, since, to serve as waterproofing, it must be flashed at all penetrations.

In warm, humid weather the low permeance of the waterproofing layer of a compact membrane roof prevents moisture in the outdoor air from entering the roofing system. In other words, the membrane then serves as a vapor retarder.

Vapor retarders are left out of many compact roofs not because of an understanding of condensation control but because of fear of fire and wind blow-off problems, which some vapor retarders have created. About 30 years ago a fire occurred within a large industrial building that had a compact roofing system on a steel deck. A bituminous vapor retarder had been adhered to the steel deck using hot bitumen. The gases and dripping bitumen from the retarder fueled the fire and a catastrophic loss occurred. That event prompted the development of other vapor retarders that would not fuel internal fires. Retarders made of asbestos felts, kraft paper laminates, and polyvinyl chloride (PVC) sheets adhered to steel decks with limited amounts of hot bitumen or with "cold" adhesives became popular. While these new systems improved the fire resistance of the system, they were difficult to adhere, and many roof splits and blowoffs were blamed on the vapor retarder. Some designers then chose to eliminate vapor retarders from roofs as a means of solving these problems. A better approach has been to continue to install vapor retarders where moisture calculations indicate they are needed. Asbestos felts are no longer available, and PVC sheets are seldom used when hot bitumen is on the job. Kraft paper laminates are popular and particularly effective in some of the "improved systems" to be discussed.

Vapor Traps and Ventilation

If a compact membrane roofing system has no vapor retarder, it should not be ventilated since ventilation may cause more harm than good by promoting air leakage [*44*].

The incorporation of a vapor retarder in a compact roofing system (Figs. 1 and 8) creates a potential trap for vapor between the waterproofing membrane and the vapor retarder. The need to vent potential vapor traps in roofs to prevent the accumulation of moisture within them and avoid the possibility of pressurization is considered essential by some [*1,3*].

It is difficult to ventilate a compact roof. Attempts to provide ventilation include the use of kerfed wood nailers

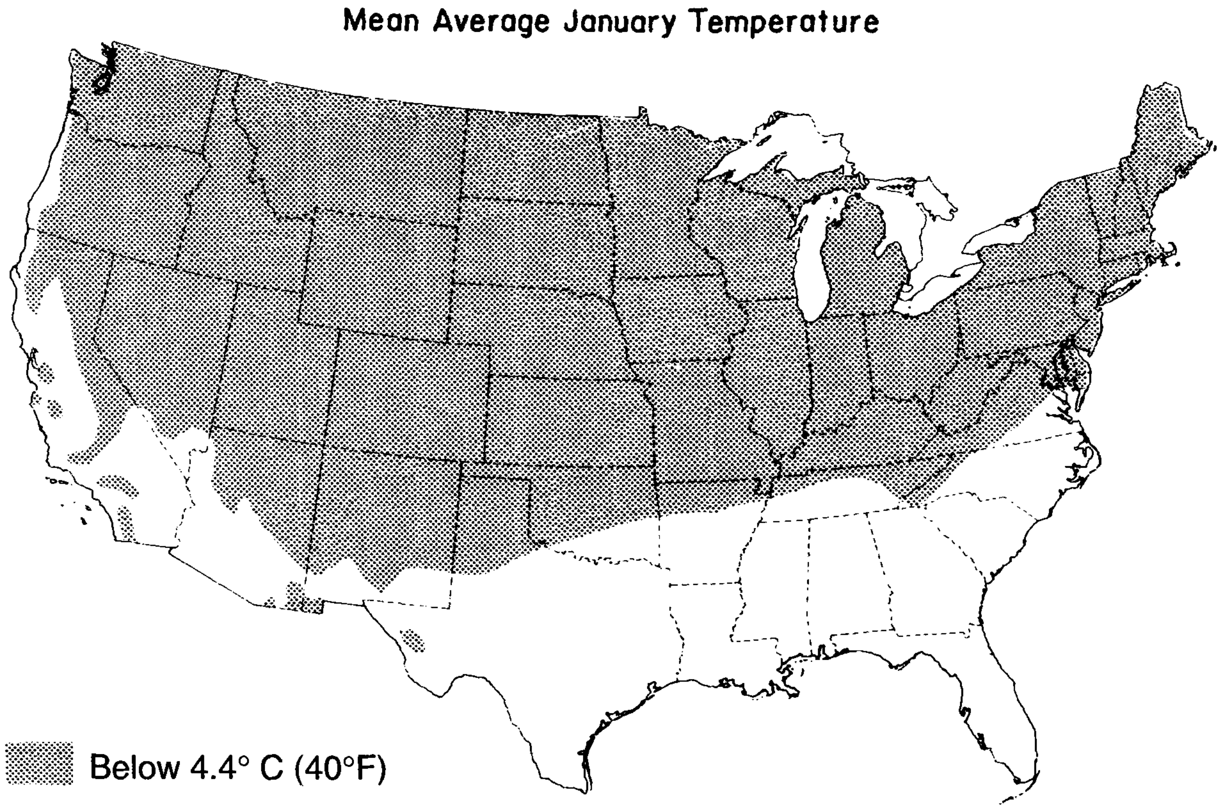


FIG. 10—Area of the United States that has a mean average January temperature below 4.4°C (40°F).

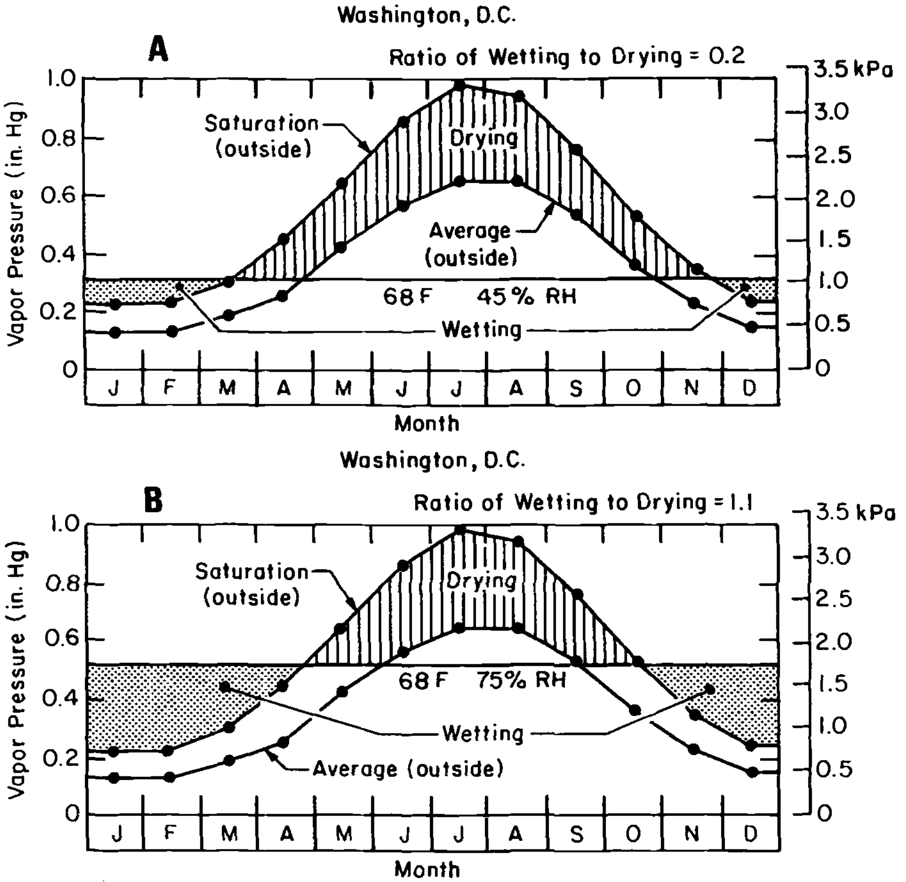


FIG. 11—Wetting and drying potentials for roofs in Washington, DC, with indoor relative humidities of 45 and 75%: (A) Indoor relative humidity 45%; (B) Indoor relative humidity 75%.

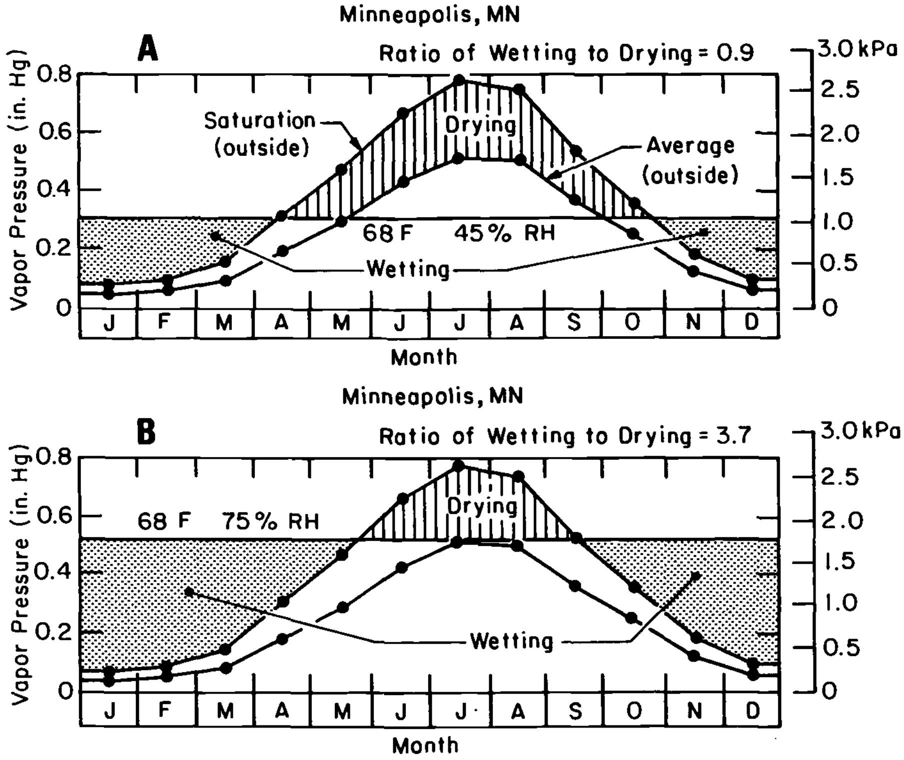


FIG. 12—Wetting and drying potentials for roofs in Minneapolis, Minnesota, with indoor relative humidities of 45 and 75%: (A) Indoor relative humidity 45%; (B) Indoor relative humidity 75%.

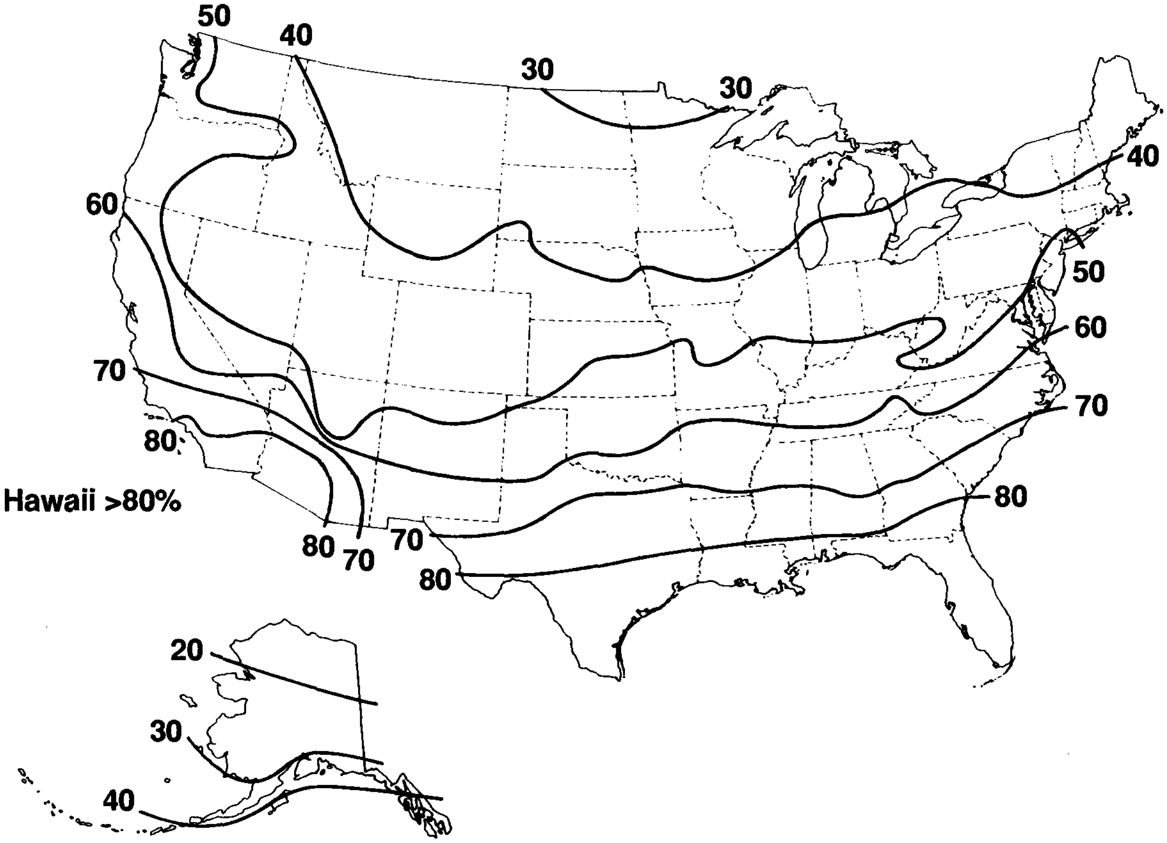


FIG. 13—Indoor relative humidities at 20°C (68°F), above which a vapor retarder is needed in membrane roofing systems. If the indoor temperature is not 20°C (68°F), use Fig. 14 to modify these values.

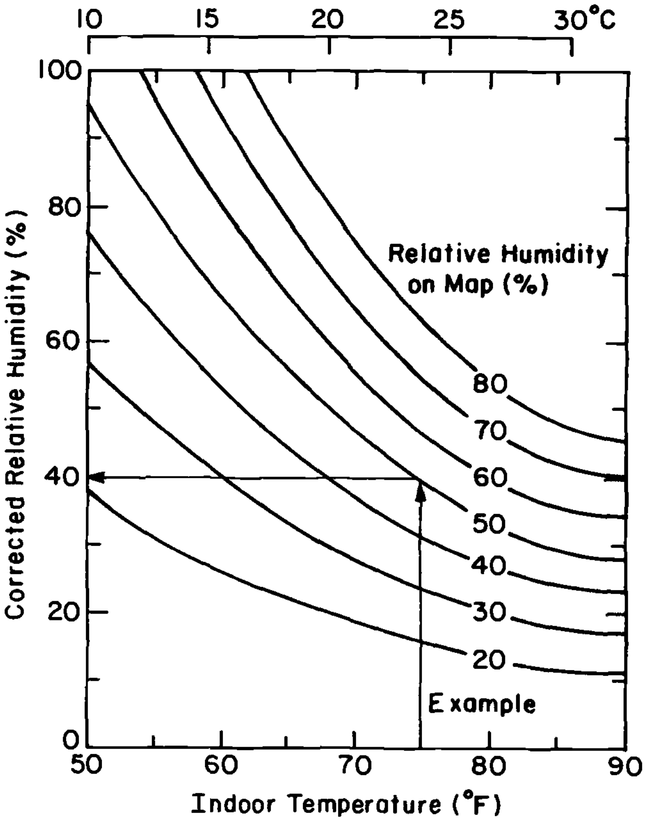


FIG. 14—Graph for correcting the mapped values in Fig. 13 for indoor air temperatures other than 20°C (68°F).

around the perimeter and the use of roof breather vents over the rest of the roof. One-way, two-way, and solar-powered breather vents are available (Fig. 15). The *two-way* roof vent is the simplest. It consists of a rain-shielded stack that allows air to move in or out without restriction. Some concerns have been expressed that two-way breather vents allow outside moisture to enter a roof. As a result of this concern, *one-way* roof breather vents have been developed. They contain a valve that opens only when the pressure within the vent exceeds that outside. This feature is purported to prevent entry of outside moisture. The *solar-powered* roof vent contains two one-way valves. One valve allows air from within the roofing system to enter the vent, and the other allows air within the domed vent to exhaust to the atmosphere. The two valves are separated by a transparent dome having a black horizontal base. When sunlight enters the dome, it is absorbed by the black base and the air in the dome is warmed. This air expands and a portion exits through the one-way valve to the atmosphere. When sunlight no longer enters the dome, the air therein cools and contracts, drawing air from within the roof into the dome. When the sunlight returns, this air warms and expands and a portion exits to the atmosphere.

The National Roofing Contractors Association (NRCA) recommends use of one breather vent for every 93 m^2 (1000 ft^2) of roof surface for roofs with vapor retarders [*4*], but this practice is seldom followed. Thousands of compact membrane roofs with vapor retarders exist without edge or breather vents. There is no evidence that these roofs perform any worse than others with vents.

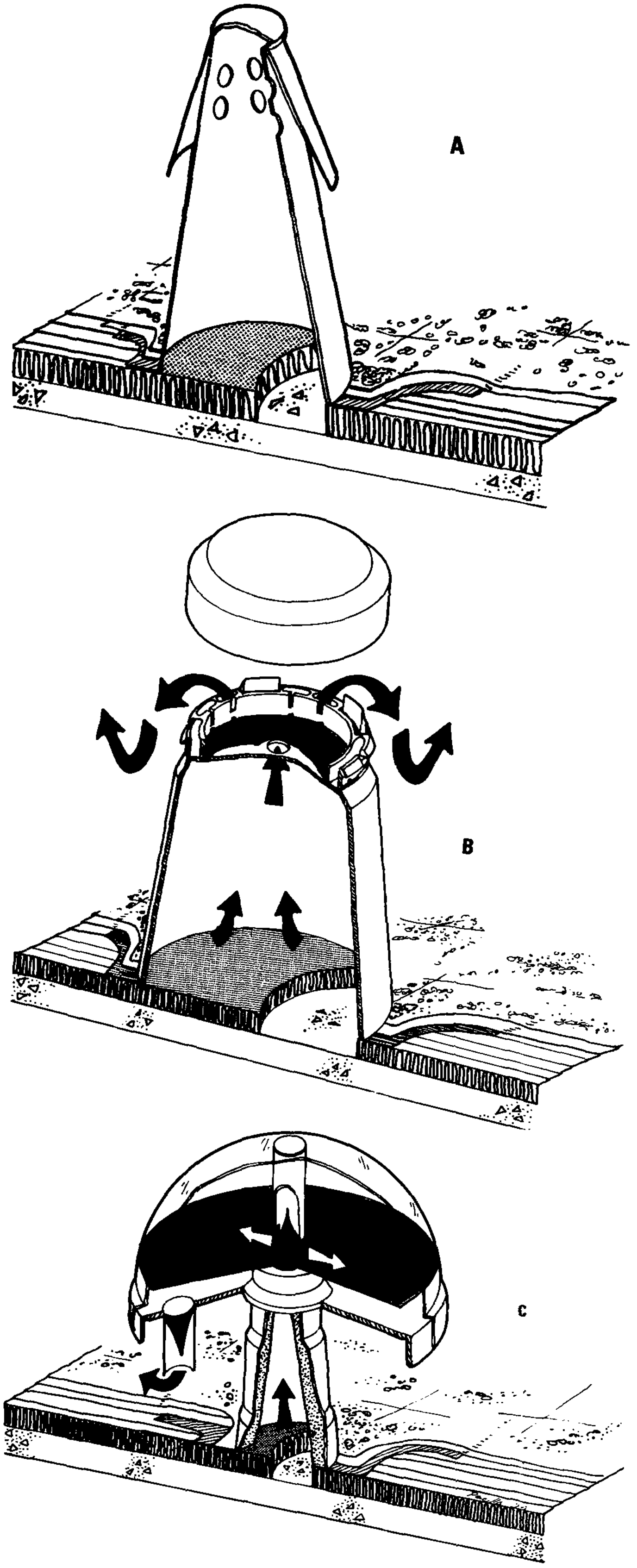


FIG. 15—Two-way, one-way and solar-powered roof breather vents: (A) Two-way vent; (B) One-way vent; (C) Solar-powered vent.

Flaws in an imperfect vapor retarder do allow small quantities of moisture to enter a compact roofing system in cold weather. However, those flaws do not close once the moisture has entered. When the vapor drive reverses in warmer weather, the system can dry out downward through the same flaws [*43*].

Concerns about pressurization of the unventilated space between the membrane and the vapor retarder in compact roofing systems because of changes in the temperature of that space are unfounded. Pressures that cause membrane blisters do not develop in that space [*45*].

A membrane perforated with a field of breather vents contains just that many more penetrations that may be flawed, allowing external moisture to enter the system. I have argued that the installation of breather vents or other venting features in compact roofing systems makes little sense [*46*].

As shown in Table 1, the permeance of a bituminous built-up membrane is essentially zero [*3,35*], but that of rubber and plastic single-ply membranes is somewhat higher [*2*]. This difference has been used by some single-ply manufacturers to promote the "breathability" of their products as a way to avoid trapping condensation within a membrane roofing system. Unfortunately, some such membranes have even been promoted for use over wet insulation, which supposedly will dry up through them. However, calculations [*42*], tests [*47*], and experience by the roofing industry [*48*] indicate that the amount of vapor these membranes can pass is very small and those materials should not be thought of as"breathable."

The permeance of loose-laid membranes made of ethylene-propylene-diene monomer (EPDM) rubber increases significantly when the membrane is hot [*49,50*]. It has been speculated that this is allowing outside moisture to enter compact roofing systems with EPDM membranes in warm weather. Since the permeance decreases when the EPDM is cold, that moisture may be trapped within the system. However, the study concluded that "moisture can accumulate, but not a significant amount [*49*]."

Compact membrane roofing systems should not be vented. They should be made as resistant to air leakage as possible even if this creates potential vapor traps.

Improved Systems

The trend toward mechanical attachment of insulation to decks—steel decks in particular—has somewhat increased the air leakage potential of membrane roofs. However, the concurrent trend toward two or more layers of insulation with joints staggered has compensated for this increase, and few condensation problems have resulted.

Using the Fig. 13 map and Fig. 14 graph, some compact roofs will be found to need vapor retarders. If the vapor retarder is placed between the deck and the insulation, it will be penetrated by mechanical fasteners. In most situations this will not pose a serious problem because the vapor retarder is squeezed tightly between the insulation and the deck by the fasteners, thereby resisting air leakage. However, where the indoor relative humidity greatly exceeds that determined from Figs. 13 and 14, or where air leakage potential is particularly high (e.g., in pressurized buildings, in high-rise buildings, or where the insulation has a high permeance), violating the vapor retarder with numerous mechanical fasteners should be avoided.

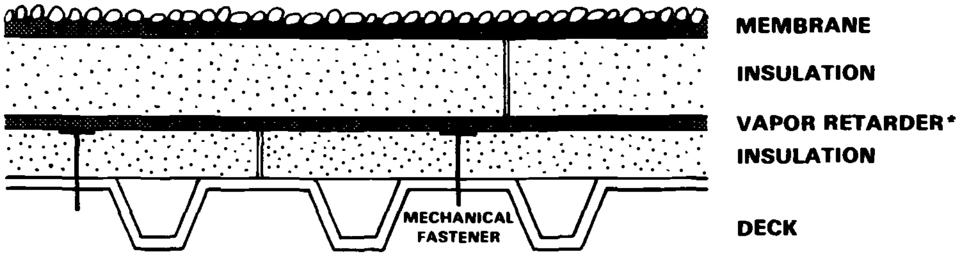
By installing the vapor retarder between the two layers of insulation as shown in Fig. 16, the vapor retarder is not violated by mechanical fasteners. This approach (with or without a vapor retarder) is known as the "nail-one, mop-one" method of constructing a compact roofing system with hot bituminous materials. This is an excellent way to achieve airtightness in a roof, increase its wind uplift resistance, and reinforce it against stresses and strains. The vapor retarder could be a kraft paper laminate or a ply or two of saturated felt adhered with hot bitumen.

Even if a deliberate vapor retarder is not installed in a nail-one, mop-one system, the bitumen used to attach the upper layer of insulation, which has its joints offset from those of the bottom layer, tightens and strengthens the roof and improves its moisture resistance. Whenever possible, the nail-one, mop-one method of construction should be used.

If Figs. 13 and 14 indicate that a vapor retarder is barely needed, it can be placed relatively close to the cold side of the roof and still do its job. If the expected indoor relative humidity is far above the mapped and corrected value from Figs. 13 and 14, the vapor retarder must be placed closer to the warm side of the roof in winter.

The approach used to develop Fig. 13 was used to develop the Fig. 17 graph, which defines the maximum percentage of the total thermal resistance of the roof that can be on the warm side of the vapor retarder [*51*].

For example, if Figs. 13 and 14 generate a value of 30% but the expected indoor relative humidity is 45%, then intersecting the 30% curve with a vertical 45% line and moving hori-



*MAY NOT BE PRESENT

FIG. 16—Cross section of a compact membrane roofing system with the vapor retarder installed between insulation layers.

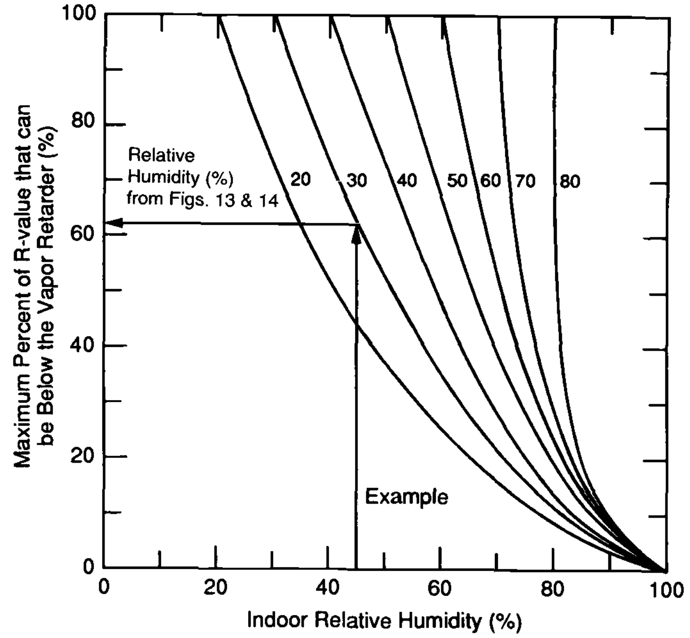


FIG. 17—Graph used with Figs. 13 and 14 to determine the maximum percent of the thermal resistance of the roof that can be on the warm side of the vapor retarder.

zontally to the left will show that up to 62% of the thermal resistance of the roof can be on the warm side of the vapor retarder.

A *protected membrane* roofing system is shown in Fig. 18. The filter fabric above the insulation "rafts" the system together and reduces the ballast needed over most of the roof to 50 to 60 kg/m^2 (10 to 20 lb/ft^2), no matter how much insulation is used. The filter fabric also keeps dirt out of the system, which facilitates drainage. The waterproofing membrane is below at least some of its insulation. There, it is not affected by most of the temperature variations, solar effects, and mechanical abuse that exposed membranes are subjected to. The membrane remains at a relatively constant temperature day and night, summer and winter. In winter the membrane is warmer than the surface of the roof; thus, any meltwater that reaches the base of the snow is warmed as it moves down to the membrane and then to the drains. This greatly reduces the potential of ice forming at the drains. A protected membrane can also serve as a vapor retarder, thereby eliminating the creation of a potential vapor trap. The amount of insulation that can be located under the membrane without introducing condensation problems can be found using Figs. 13, 14, and 17.

The insulation above the membrane is usually loose laid and protected from the sun and from being blown off by the wind by a ballast of stones or concrete pavers. That insulation is in a relatively harsh environment. All the surfaces of the boards are bathed in water during a rain, and moisture may remain between the ballast and the insulation, between insulation layers, and between the insulation and the membrane for some time. Because of this, the insulation above a protected membrane must be quite resistant to moisture. Laboratory and field studies [*1,24-26,52-55*] have shown that most insulations will become wet and thermally inefficient in such a setting, but extruded polystyrene can survive provided that the membrane is sloped to drain and the ballast layer is configured so that it promotes drying. In Denmark it has been shown that, surprisingly, loose-laid, unballasted rock wool insulation boards can also be used above a protected membrane [*56*]. However, in most circumstances, extruded polystyrene insulation should be used above protected membranes.

Where large arrays of pavers are used for ballast, they should be elevated on pedestals or otherwise made to discontinuously contact the insulation so that air can facilitate upward drying of the insulation [*53*]. Because crushed rock or stone ballast, if reasonably clean, allows rapid drying, these less expensive ballasts are usually preferred, except for walkways and around the perimeter of the roof where wind uplift forces are greatest.

The rain and meltwater that may wet the insulation above a protected membrane also may short-circuit some of its insulating ability [*25,57*]. A reduction in thermal resistance of 20% has been measured during a moderate rain [*57*]. The cooling of the membrane at such times can be enough to cause condensation on its underside if high humidities exist within the building. Other studies indicate that, year-round, a protected membrane roofing system is only a little less efficient than a conventional roofing system [*25,56*]. Design

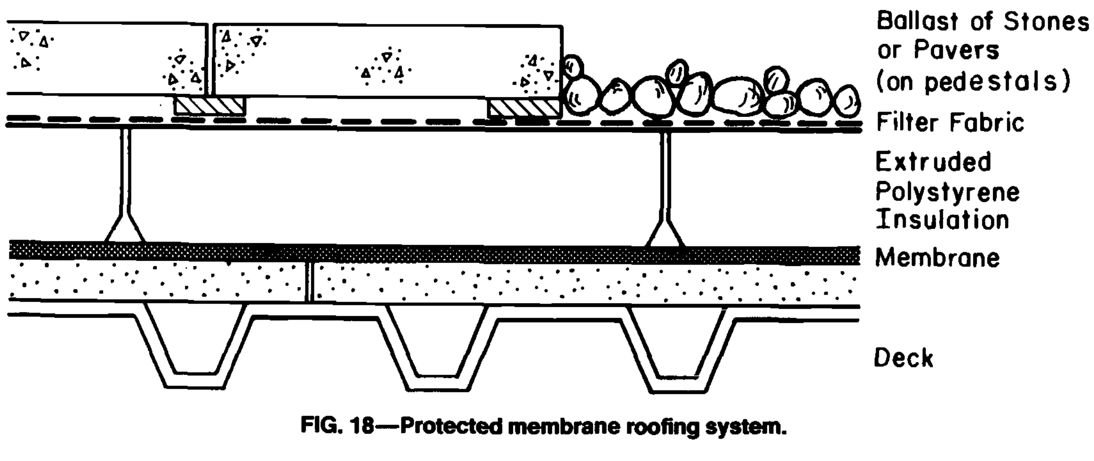


FIG. 18—Protected membrane roofing system.

guidelines for protected membrane roofing systems have been developed in Norway [52].

Protected membranes usually cost somewhat more than conventional membranes because of the premium paid for extruded polystyrene insulation and the need for ballast. However, they have an excellent performance record in cold and hot regions and for roofs that experience lots of traffic or vandalism [58]. Their life-cycle costs can be less than those of conventional membrane roofing systems. The sustained upward vapor drives in cold regions introduce potential condensation problems and vapor retarder requirements that protected membrane roofs handle particularly well.

Loose-Laid and Mechanically Attached Membranes

Loose-laid and mechanically attached single-ply roof membranes have some advantages because they are not as sensitive to substrate movements as are fully adhered membranes. However, their lack of complete attachment increases the potential for air leakage and condensation problems.

Air can move laterally under a membrane that is not completely attached, particularly during windy periods when localized suctions create a pumping action. When this is possible, warm, moist indoor air can be drawn up into the roofing system and condensation can occur on the underside of the membrane.

Beads of water are being found on the underside of an unexpectedly high number of loose-laid and mechanically attached EPDM rubber membranes. As stated previously, it is unlikely that the increase in EPDM permeance with temperature is responsible [49,50]. Probably leakage of indoor air, not diffusion of outdoor water vapor, has brought moisture to the underside of the EPDM. More evidence is needed to settle this matter, but air leakage is so very often present when problems occur that it is a prime suspect. In my opinion, control of air leakage into loose-laid and mechanically attached membrane roofing systems will resolve most of the moisture problems these systems are having.

Compact Water-Shedding Roofing Systems

Description

A compact water-shedding roofing system such as that shown in Fig. 19 has its insulation placed above the deck. It contains no air spaces or intermediate framing membranes. Because it is topped with a water-shedding system, not a waterproof membrane, it must be used only on relatively steep slopes.

Permeability, Air Barriers, and Vapor Retarders

The effective permeability of most water-shedding surfaces is relatively high. Thus, concerns related to the creation of vapor traps within such roofs usually can be dismissed. However, the benefits of air leakage control afforded by a watertight membrane may be lost by having a permeable upper surface. Since air leakage is the real concern, the net result is to create a system somewhat more prone to condensation problems than a compact membrane system. Providing the roof with an air barrier even if it does not require a vapor retarder can compensate for this weakness. The vapor retarder guidelines mentioned above for compact membrane roofs can also be used to determine when and where to use them in compact water-shedding roofing systems.

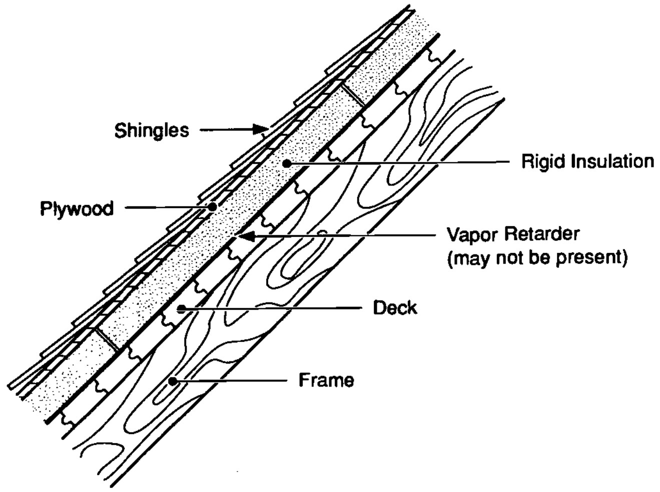


FIG. 19—Compact water-shedding roofing system.

Ventilation

Compact water-shedding roofing systems are commonly not ventilated but they can be. Where ventilation is desired (e.g., in cold regions to minimize ice damming), a framed roofing system is usually more economical. Ventilation is discussed in detail in the sections of this chapter dealing with framed roofing systems.

Framed, Water-Shedding Roofing Systems

Description

A framed water-shedding roofing system has its insulation below its sloping deck between framing members. The configuration may be a "cathedral ceiling" as shown in Fig. 2 or an attic with the insulation between ceiling joists instead of between roof rafters as shown in Fig. 20. The space between the roof deck and the insulation may be ventilated as shown in those two figures, or it may not be ventilated. The decision to ventilate or not to ventilate depends on indoor conditions, outdoor climate, and the air and vapor retarding characteristics of the system.

Air Leakage

Vapor retarder continuity is difficult to achieve and many air leakage paths are created in such roofs because permeable insulations are used and pipes, wires, and fixtures often interrupt that insulation. If a lot of indoor air can leak into a framed roof, it is apt to have condensation problems.

The many places where warm moist air within a building can enter its attic are shown in Fig. 20. Electrical wires run among the batts of insulation to fixtures that penetrate the ceiling. If hatches into the attic are not tightly sealed against air exfiltration, a lot of moisture can enter the attic there. Most hatches are not well sealed. Access holes around plumbing vent pipes may be passageways for moist basement air to rise into the attic. Several studies have shown that most of the moisture in attics does not arrive by diffusing through the

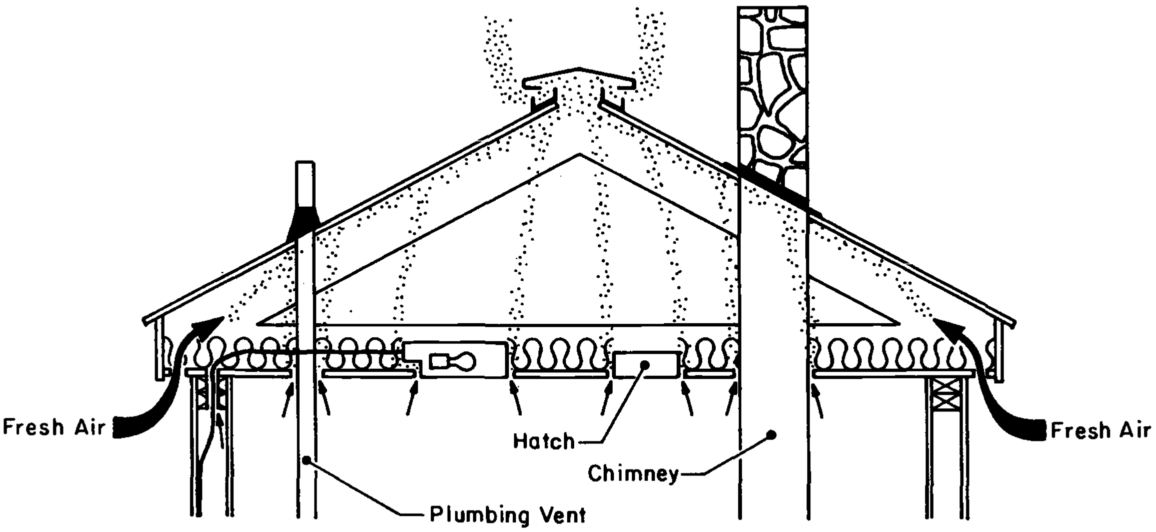


FIG. 20—Air leakage paths into an attic.

ceiling but by air leakage [*59–61*]. To reduce the amount of moisture that enters an attic, the first priority is to direct efforts at stopping air leakage, not installing a vapor retarder.

In temperate areas, attic ventilation may be able to remove all the moisture from exfiltrating air, but in cold regions large quantities of frost can grow even in well-ventilated attics when hatches, electrical fixtures, and pipes are not well sealed. Figure 21 shows what can happen. In warmer weather the frost melts, the insulation is soaked, the ceiling is damaged, and leaks occur in the rooms below.

Because of the importance of controlling air leakage, construction specifications should not only require that penetrations in the building envelope be sealed but they should also contain specific guidance on the type of seals needed. Such seals should be inspected and approved before other materials conceal them.

Unfortunately, current design and construction practices seldom include the sealing of penetrations: gaps often exist in ceilings through which indoor moisture enters the attic. Figure 22 shows a typical unsealed pipe penetration. Seals against air leakage are needed at these locations. Guidelines are available on how to achieve this for polyethylene vapor retarders used in wood-frame construction [*62,63*].

Vapor Retarders

For framed water-shedding roofing systems in cold regions, a vapor retarder having a permeability of 6×10^{-11} kg/(Pa·s·m^2) (1 perm) or less is usually required along with ventilation. In very cold regions, sustained periods of cold promote a significant flow of moisture into attics. In such places, great care must be taken to create a vapor retarder with few gaps and flaws [*62*]. Realizing that some moisture will pass by the best of well-sealed vapor retarders, it is also appropriate to provide ventilation to take it away.

In the warmer regions of the United States (i.e., in Condensation Zone III of Fig. 15 in Chapter 21 of the *ASHRAE 1989*

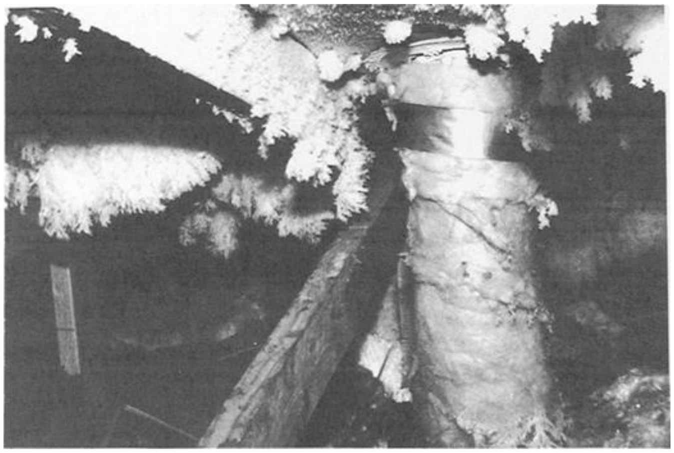


FIG. 21—Attic frost caused by leakage of indoor air by an unsealed vapor retarder, Fort Greely, Alaska.

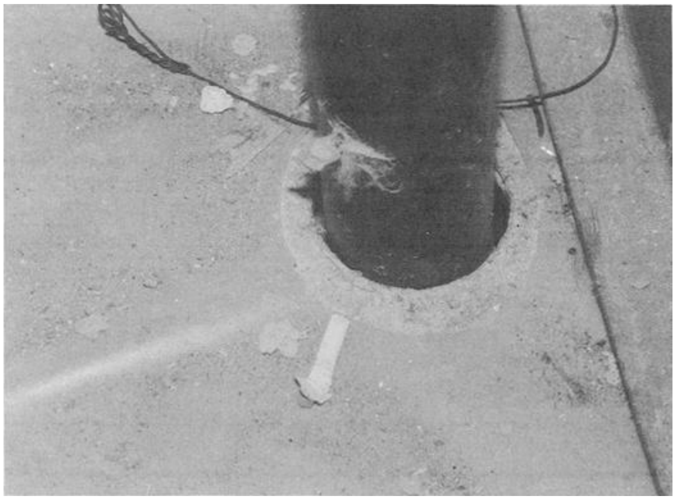


FIG. 22—Unsealed ceiling vapor retarder at a pipe penetration, Petersburg, Alaska.

Fundamentals Handbook [35]), it is common to omit ceiling vapor retarders if the attic is ventilated and the roof has a slope of 1:4 (i.e., 14°, 3 in./ft) or more. Such construction has been successful where air leakage is controlled. However, the lack of need of a vapor retarder has been mistakenly construed by some designers and builders to mean that no provisions need to be taken to control leakage of indoor air into the roof. In such cases some moisture problems have developed.

Ventilation

Condensation problems decrease as roof slope increases because stack-induced flow (i.e., chimney draft) increases with slope. It also increases in cold weather, enhancing ventilation. Cathedral ceilings can be ventilated by creating a continuous air space between the deck and the top of the insulation (Fig. 2). Some guidelines indicate that a 10-mm-(3/8-in.-) deep airspace will suffice [64]. However, since such narrow spaces are difficult to achieve, a better minimum is 38 mm (1.5 in.) and a better goal is 50 mm (2 in.). That space must extend unobstructed from the eaves to the ridge over the entire roof. Forms may be needed at the eaves to ensure that the insulation is installed without blocking the airway. If a chimney, skylight, dormer, or roof hip blocks ventilation, holes should be drilled in rafters to allow the air to complete its journey to the ridge. The structural implications of such holes should be considered.

Fifty-millimeter- (2 in.-) deep air spaces will usually provide enough ventilation to take away moisture that passes a reasonable vapor retarder in roofs with a slope of 1:4 (i.e., 14°; 3 in./ft) or more, provided that the airway is not much over 6 m (20 ft) long. At lower slopes, it is usually appropriate to interconnect all individual rafter spaces by installing purlins on the rafters before the deck is laid (Fig. 23).

The net areas open for ventilation at the eaves and ridge should be about the same size. Those two areas should sum to about 1/150 (i.e., 0.67%) of the area of the space that is the source of moisture. Commonly, this horizontal area is determined at the level of the eaves. When the exhaust ports of the ventilated space are at least 0.9 m (3 ft) above the intake ports, two American model codes [39,40] reduce the net area of openings from 1/150 (i.e., 0.67%) of the area of the source to 1/300 (i.e., 0.33%) of that area. ASHRAE [35] recommends 1/300 of the area of the source for all slopes. The National Building Code of Canada [37] also uses 1/300 no matter what the slope, but at slopes less than 1:6 (i.e., 10°; 2 in./ft) the requirement for interconnecting all the enclosed rafter spaces as shown in Fig. 23 is added. This important requirement should be used more, and wherever possible the net area of openings should approach 0.67%.

At slopes of 1:4 (i.e., 14°; 3 in./ft) or more, the requirement for ceiling vapor retarders is commonly omitted in ventilated wood-framed roofs in the warmer regions of the United States because of the improvement in natural ventilation achieved by slope. As stated previously, this approach will succeed only if leakage of indoor air into the roof is controlled.

When an attic is present below a sloped roof, it is relatively easy to ventilate away any moisture that moves upward through the ceiling. Continuous vents at the eaves and ridge are usually quite effective provided, once again, that leakage of moist indoor air is limited. The net open areas needed for ventilation at the eaves and ridge are the same as those for cathedral ceilings.

For small buildings, louvers having a total net area of 1/300 of the area of the source located on opposite ends of the attic near the ridge can provide the ventilation needed to avoid condensation. However, this configuration is less desirable since, by placing the intakes and exhausts at the same level, desirable chimney draft is eliminated. Whenever possible, intakes should be placed all along all eaves and exhausts all along the ridge.

Intakes and exhausts of roof ventilation systems must be designed to resist driving rain and blowing snow. It is relatively easy to prevent rain penetration at intakes located under eaves, but baffles may be needed there in windy regions to prevent snow ingestion (Fig. 24). Baffles are usually preferred over filters in the opening since filters can become blocked with dust and pollen.

A variety of metal and plastic continuous ridge vents are available. They should be configured to prevent ingestion of driving rain and blowing snow (Fig. 25). The "Boston Cap" [65] is a wooden version (Fig. 26).

Winds often keep portions of a continuous ridge vent clear

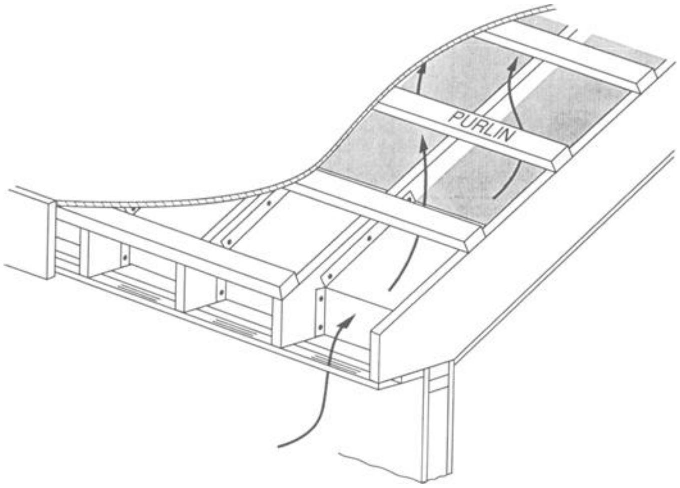


FIG. 23—Use of purlins to interconnect the ventilating airways of a low-slope framed roof.

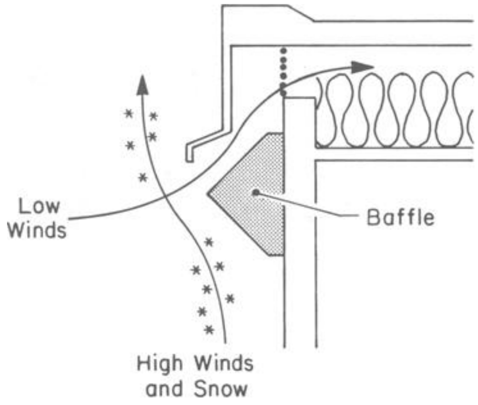


FIG. 24—Baffle used in Sweden to prevent vents from ingesting snow during high winds.

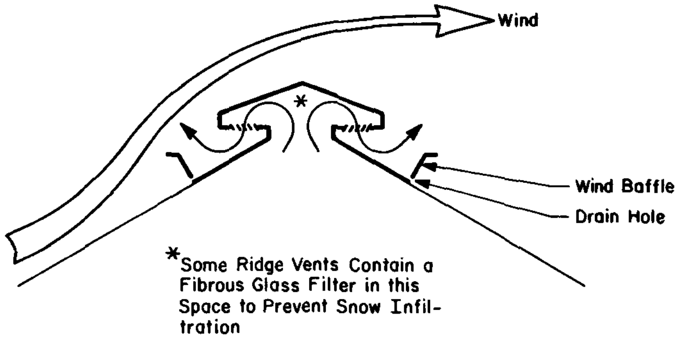


FIG. 25—Ridge vent configured to prevent ingestion of driving rain and blowing snow.

of snow. However, even when a ridge vent is covered by snow, air can pass out of the vent through the snow. In areas experiencing deep snowfall, sheltered roofs may need some additional provision to ensure adequate ventilation with the ridge buried under deep snow. By extending each end of a Boston Cap beyond the end of the roof and opening its underside there, secondary exits can be provided for the ventilation system. Alternatively, J-stacks or turbine ventilators can be installed above the continuous ridge vent but they may visually detract from the roof.

Additional information on ventilation of low-slope framed roofs is presented in the "Framed, Membrane Roofing Systems" section of this chapter.

Cold Versus Hot Roofs

Since snow is a good insulator, a warm (unventilated) roof tends to melt snow that forms on it even in relatively cold weather. This does not usually create problems if the meltwater produced moves to drains located above the warm building. However, if the meltwater moves to cold portions of the roof such as its cold eaves, icicles and ice dams will develop (Fig. 27) that can result in roof leaks. In areas where snow remains on roofs for long periods, roofs that slope to cold eaves should be cold (ventilated) systems to reduce the risk of eave icings [*7,65–69*].

Meltwater is produced less often when a ventilated roofing system is used. Building heat, not the sun, is usually the primary cause of ice dams because the sun also warms the eaves. The amount of ventilation needed to prevent condensation problems is usually enough to minimize icings at eaves in reasonably well-insulated buildings. However, if heat-producing equipment is located in a ventilated attic, additional ventilation may be required [*7,12*]. Very large attics may also require additional ventilation.

FIG. 27—Icings from roof meltwater.

As cold, dry, outdoor air moves from the eaves to the ridge of a cold (ventilated) attic-less roof, it picks up moisture and heat. By the time it has traveled about 6 m (20 ft) in the narrow spaces above the insulation, it is no longer very effective at keeping the surface of the roof cold [*70*]. This limits the size of cold (ventilated) attic-less roofs in snow country. The 6-m (20-ft) limitation can be increased somewhat by increasing the thermal resistance of the roof insulation above 3.5 K·m^2/W (20 F°·h·ft^2/Btu).

Preliminary experiments have been conducted to determine the ventilation rates needed to achieve a "cold" roof [*71*].

The *ASHRAE 1989 Fundamentals Handbook* [*35*] presents information for calculating the amount of ventilation needed to cool attics by stack-induced flow. Problematic icings have

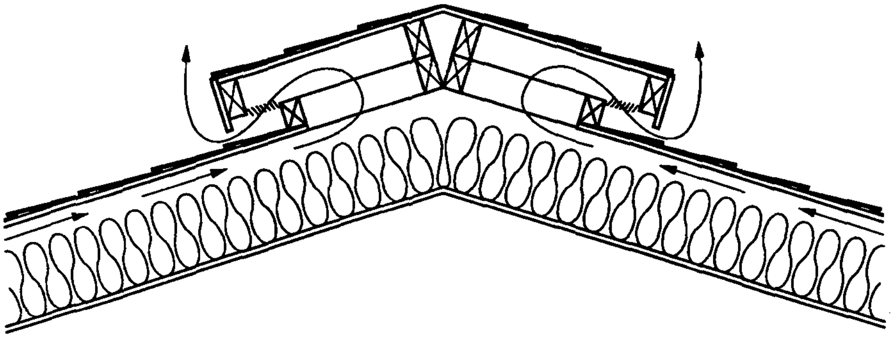


FIG. 26—Wooden "Boston Cap" continuous ridge vent.

been eliminated by sizing attic ventilation systems so that they are able to maintain an attic temperature of −1°C (30°F) when the outside temperature is −5.5°C (22°F) [*12*]. This particular outside temperature is used since problematic icings have been found to develop very slowly, if at all, when the outside temperature is above −5.5°C (22°F) [*12*].

Icings can also be reduced by increasing the amount of thermal insulation in a roof, by increasing the slope, by making the surface slippery so that snow slides off, by not installing gutters, and by reducing the overhang at the eaves. However, overhangs should not be less than 150 mm (6 in.) on roofs without gutters for fear of wetting the walls below or having icings form on them (Fig. 28).

Since some icings are still likely, it is appropriate to convert the lower portion of the roof from a water-shedding system (that will leak if water ponds on it) to a membrane system that can resist ponded water. A good way to accomplish this is to place a 0.7- to 1.2-m- (2.5- to 4-ft-) wide strip of modified bituminous sheet material (i.e., a rubberized asphaltic sheet) on the deck under the water-shedding system in valleys and along eaves.

In most cases, a properly designed roof will not require electrical heating cables zigzagged along the eaves. However, if large icings form on a roof, such cables can be used to melt holes through that ice to prevent water from ponding on the roof and leaking into the building. Hammers, hatchets, and salts used at the eaves usually do more harm than good.

In cold regions, framed water-shedding roofing systems may encounter problems on buildings with high indoor relative humidities. In such cases, a more moisture-resistant, compact water shedding system such as that shown in Fig. 19 may be needed. However, this system lacks ventilation. A ventilated alternative is shown in Fig. 29. It consists of a hybrid compact-framed ventilated system with better air leakage resistance than a framed system.

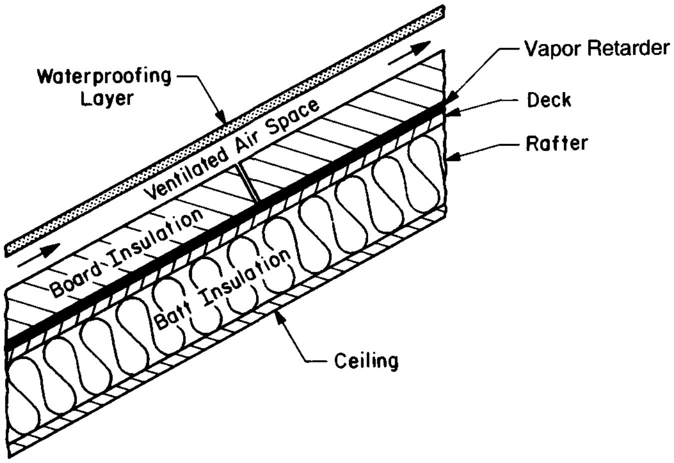


FIG. 29—Hybrid compact-framed, ventilated roof with a portion of its insulation above the deck to better resist air leakage.

Sliding Snow and Ice

The sliding of snow off a roof can be beneficial since it reduces snow loads. However, sliding snow can endanger people and damage property. Thus it may be necessary to install obstacles (snow guards) on the roof to prevent sliding. Several types of snow guards are available. They must be robust because snow and ice can exert great forces on them.

Design of snow guards is usually based on holding snow in place, not resisting large dynamic forces caused by snow that has slid some distance before it confronts the snow guard. To reduce the risk of subjecting snow guards to dynamic forces on slippery roofs, it is beneficial to place several rows of moderately strong snow guards up the roof rather than relying on one very strong snow guard in the vicinity of the eaves. Snow

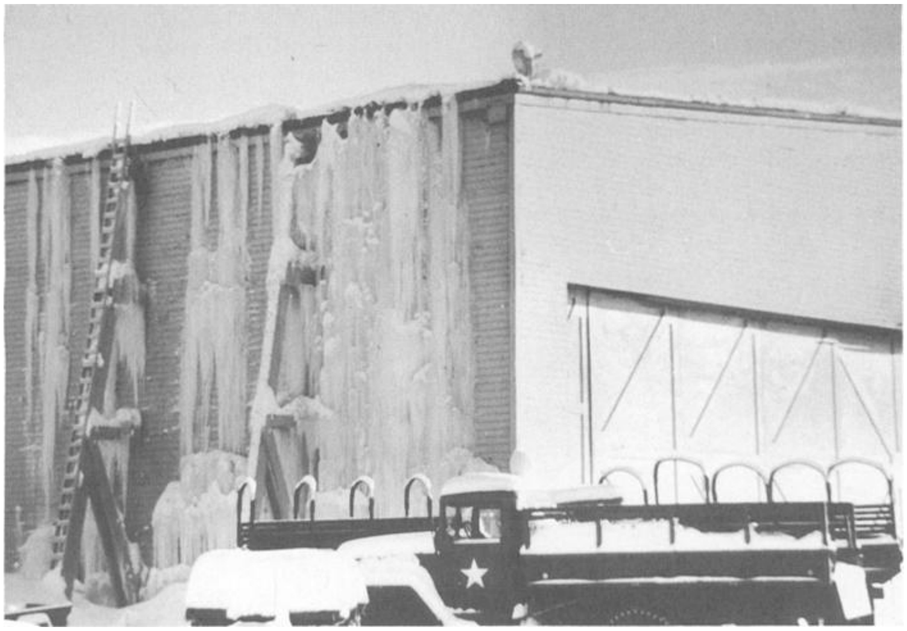


FIG. 28—Icings can form on walls if the eaves do not overhang far enough.

guards should not be placed at cold eaves because they may facilitate growth of ice dams there.

To compensate for thermal movements, the metal roof panels of many standing-seam metal roofing systems are fastened to the building frame only at one end (usually the eaves). They are secured to the rest of the roof frame with sliding clips to allow the metal roofing to expand and contract freely as its temperature changes. Unfortunately, some snow guards are being attached through the metal roofing to the purlins, thereby defeating the sliding-clip feature and causing leaks.

Except in areas experiencing very heavy snow loads, snow guards can usually be mechanically attached or adhered just to the metal roofing. Risks of leaks are reduced when mechanical attachment is made to the standing seam, not to the metal pan on which water flows.

In cold regions, standing seam metal roofing systems should be thought of as water-shedding (not waterproof membrane) systems [*12*]. When provisions such as snow guards are added to metal roofs to hold snow on them, the risk of leaks from the accumulation of slush, ice dams, and ponded water may increase at eaves and valleys.

Framed Membrane Roofing Systems

Description

A framed roofing system has its insulation below its deck between framing members. Most framed systems with membrane waterproofing have little slope. Such roofs may drain internally or over their eaves. There may be a ventilated airspace between the deck and the top of the insulation. Because such a space is nearly horizontal, there is no stack effect to cause a draft between the intake and exhaust openings. Thus, ventilation is slight except during windy periods. Ineffective ventilation, combined with the high air leakage many framed systems allow, explains why such roofs suffer so many condensation problems [*72–74*].

Air Leakage

Figure 30 shows air leakage paths in a typical framed membrane roofing system. It may be possible to solve moisture problems in such roofs by sealing such paths of air leakage. Although difficult, especially after the fact, it is often well worth the effort. Two Canadian booklets [*62,63*] provide a wealth of practical guidance.

Some years ago in Canada, moisture problems in such roofs were also solved by installing fans on the roof. In the winter, they forced cold, dry, outside air into the space above the insulation. This not only increased ventilation but also reduced the leakage of moist indoor air up into the pressurized space [*75*]. While fan pressurization has merit, it has not received wide acceptance because of initial and operating costs and maintenance obligations associated with reliance on mechanical devices.

Vapor Retarders

All leakage paths such as those shown in Fig. 30 are not eliminated by the installation of a vapor retarder on the underside of the insulation unless the vapor retarder is sealed at all penetrations.

For "flat" timber-framed roofs in the United States, guidelines commonly recommend a vapor retarder with a permeance of about 6, 3, or 0.6×10^{-11} kg/(Pa·s·m^2) (1, 0.5, or 0.1 perm) below the insulation. Past guidelines that recommended a very low permeance of 0.3×10^{-11} kg/(Pa·s·m^2) (0.05 perm) in heavily insulated wood-framed roofs without attics have been revised upward to 0.6×10^{-11} kg/(Pa·s·m^2) (0.1 perm) [*35*]. The need, in most cases, for a permeance of less than 3×10^{-11} kg/(Pa·s·m^2) (0.5 perm) is questioned [*34*] because vapor diffusion is a very slow process. No matter what the permeance, continuity (i.e., air leakage control) is essential.

Ventilation

Additional information on ventilation of framed roofing systems is presented in the "Framed, Water Shedding Roofing Systems" section of this chapter. The information in this section focuses on ventilation of low slope framed roofs.

Any moisture that moves up through a ceiling into a big open attic space, such as that shown in Fig. 20, is relatively easy to ventilate away. Decades ago, many low slope roofs contained vented lofts for that purpose (Fig. 31) [*1*].

When the attic or loft is removed and the deck and waterproofing are placed on top of the ceiling joists as in Fig. 30, little or no air space is available for ventilation.

For "flat" roofs with enclosed rafter spaces, guidelines on the net area of openings for natural ventilation range from $1/300$ (i.e., 0.33%) of the area of the space to be ventilated [*35,37*] to $1/150$ (i.e., 0.67%) of that area [*39,40*]. When the roof slope is less than 1:6 (i.e., 10°; 2 in./ft), the National Building Code of Canada [*37*] requires the air space to be at least 25 mm (1 in.)

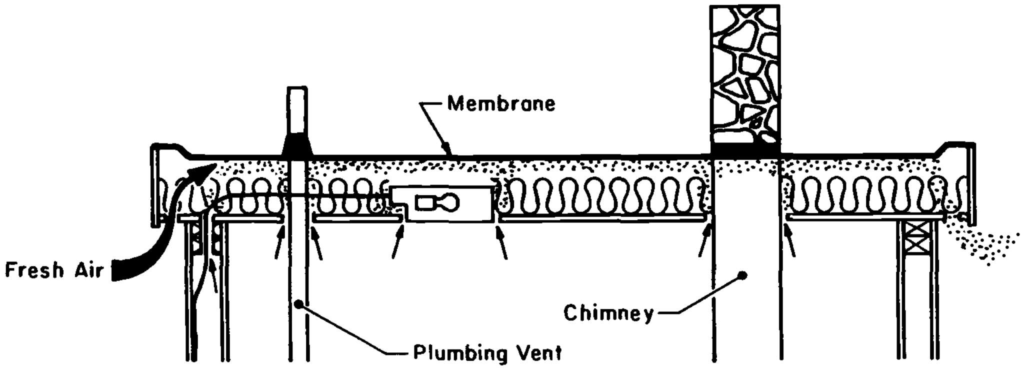


FIG. 30—Air leakage paths into a ventilated flat roof with below-deck insulation.

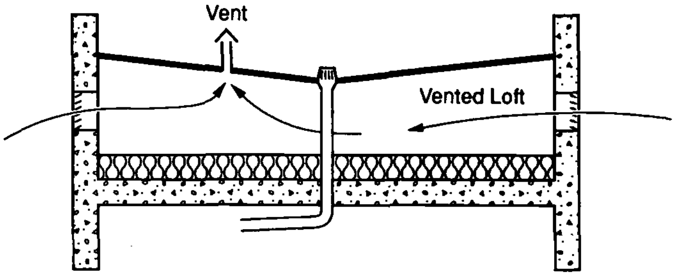


FIG. 31—Vented-loft roofing system.

high and also requires cross-purlins at least 38 mm (1.5 in.) high above the rafters. This interconnects all the individual enclosed rafter spaces to avoid dead spots where condensation is likely.

In England it is common to ventilate "flat" timber-framed roofs by providing openings totaling at least 0.4% of the roof plan area. However, problems are occurring that suggest that this should be increased to 0.6%. When such roofs have long spans (i.e., the moist air must travel laterally quite a distance before being exhausted) or when they are located above kitchens or other high-humidity occupancies, there appears to be a need to force ventilate the air space by installing fans [*76*].

Studies in Denmark [77] determined that the incorporation of a ventilated air space above insulation in a "flat" roof may do more harm than good since such ventilation promotes air leakage. Unvented panels above high-humidity "flat"-roofed buildings constructed as shown in Fig. 30 accumulated somewhat *less* moisture than did most vented panels. Some reduction in moisture was achieved when the space was force-ventilated with fans, but whenever the fans were stopped for a few days, moisture accumulated rapidly. The Danish study found that edge-to-edge ventilation of the type shown in Fig. 30 "seems to function satisfactorily" for "flat" roofs in the Danish climate [about 3700 heating degree days Celsius (6600 heating degree days Fahrenheit) and a winter design temperature of about −7°C, (19°F)] for homes and other small buildings having reasonably tight ceilings and an indoor-air dew-point temperature below 0°C (32°F). This corresponds to an indoor relative humidity in winter below 26% at a room temperature of 20°C (68°F). (Humidifiers are seldom used in Danish homes.) However, condensation problems are likely if similar roofs are used for larger buildings or buildings with high indoor relative humidities, whether the roofs are ventilated or not. Great care in installing the ceiling vapor retarder so that it is airtight reduces the risk of condensation, but with normal construction practices moisture problems are to be expected. The Danish study concluded that ventilated wood-framed "flat" roofs with below-deck insulation are inappropriate for buildings with a dew point temperature above 11°C (52°F) [this corresponds to 56% RH at 20°C (68°F) indoors]. They also indicate that some problems are likely in Denmark's climate for drier buildings.

Unventilated Systems

When unventilated frame construction is used, only a portion of the insulation should be placed below the deck. The rest of the insulation should be placed on a vapor retarder above the deck so as to create an unvented compact roof above the framed portion. This dual insulation method is shown in Fig. 32. As the relative humidity in the building increases, the amount of insulation allowed in the wood-frame portion decreases. In Denmark, for houses and other low-humidity occupancies, no more than half the insulation should be there. When the dew point temperature of the inside air is between 0°C (32°F) and 11°C (52°F), no more than one third of the total thermal resistance of the roof should be below the deck. If the dew point temperature is above 11°C (52°F), essentially all the insulation should be in the compact portion of the roof. The intent of these guidelines is to keep the dew point temperature of the indoor air above the deck and vapor retarder during most of the winter, thereby elimi-

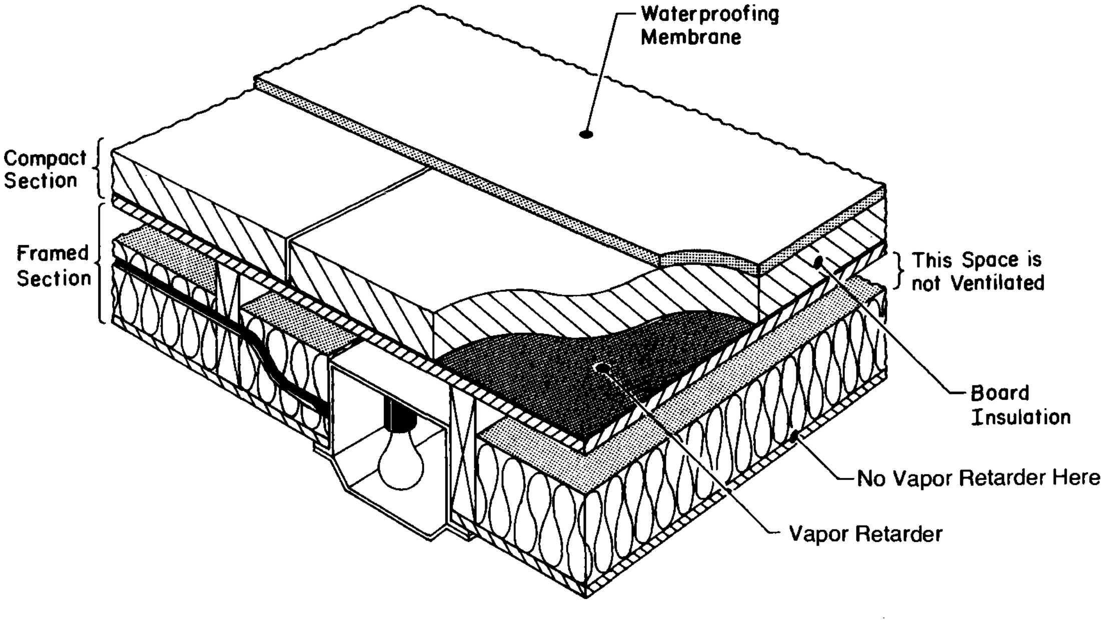


FIG. 32—Unventilated wood-framed roof with insulation in compact and framed portions.

nating the possibility of condensation in the framed portion of the deck where moist indoor air is likely to have access.

The above Danish guidelines allow less insulation below the vapor retarder than would be determined by using Figs. 13, 14, and 17. Those figures provide reasonable guidance in my opinion.

There is ample evidence that "flat" wood-framed roofs have a relatively high risk of incurring condensation problems. That risk can be reduced by installing a vapor retarder, by making the ceiling airtight at all penetrations, and by ensuring that the space above the insulation is well ventilated. However, it is probably better to place a portion of the insulation above the deck and vapor retarder in the form of a compact roofing system and not ventilate any air spaces below the deck. In fact, eliminating air spaces in such a hybrid roofing system is preferred to further reduce the chance of air leakage.

While the above Danish recommendation to convert cold (ventilated) roofs to hot (unventilated) roofs is applicable to internally drained roofs, it may not be the appropriate solution in snow country when drainage is to cold eaves. In this case it may be necessary to add a ventilated space above the insulation as shown in Fig. 29.

If enough insulation is placed above the deck and vapor retarder to cause the dew-point temperature of the indoor air to occur in the compact system above the vapor retarder at the winter design temperature, condensation problems are highly unlikely.

A compromise solution is also possible. It involves placing a vapor retarder and some insulation above the deck, but not the full amount required to keep the dew point temperature above the deck. Economics is the primary incentive to use less above-deck insulation since rigid insulation boards are a more expensive way of providing insulation than are batts. A sealed but admittedly imperfect second vapor retarder would be placed below the batt insulation to reduce the amount of moisture that can move up through it to the underside of the deck in cold weather. The combination of these two imperfect systems, provided they are both reasonably good, can work together to control condensation. The "trap" created by the two vapor retarders is not of much concern for the reasons already stated when discussing potential vapor traps in compact roofs.

Summer Condensation

Most framed-roof condensation problems occur in cold regions and are from indoor moisture. However, outdoor moisture can cause problems for air-conditioned buildings in hot humid regions. Air spaces for roof ventilation may allow outdoor air to enter the roof. If a vapor retarder is present below the insulation, "summer condensation" can form on it when its temperature is below the dew point of the outdoor air [*78*]. For this reason, vapor retarders are usually not wanted in framed roofs in hot, humid areas. There, ceilings should have a high permeance to water vapor to allow small amounts of moisture to pass into the occupied space below rather than accumulate in the roof. Although such ceilings should not contain a vapor retarder, they should be well sealed against air leakage.

Referring to the map in Fig. 13, few roofs in the warm regions of the United States need vapor retarders. However, the *ASHRAE 1989 Fundamentals Handbook* [*35*] recommends ceiling vapor retarders for flat roofs in these areas. Perhaps that is a response to the real need for air leakage control rather than a need for low permeance ceilings in hot, humid regions.

Improvements, Repairs, and Reroofing

Adding Insulation

It is often less expensive to add insulation below an existing roofing system than on top. This is particularly true for systems with suspended ceilings. Unfortunately, in most cases it is quite difficult to create an effective air barrier below the added insulation. While the new insulation will reduce heat flow, moisture flow is likely to continue about as before. The underside of the roof will become much colder and the potential for condensation there will increase [*79,80*].

For example, consider the roofing system shown in Fig. 33. The roof itself has a thermal resistance of about 0.53 $K \cdot m^2/W$ (3 $F° \cdot h \cdot ft^2/Btu$), and the air space and suspended ceiling below have a combined thermal resistance of about 0.53 (R3). If the building is located in Chicago where the design winter temperature is −19°C (−3°F) and the indoor air temperature is 20°C (68°F), the underside of the deck will be about 1°C (33°F) at the winter design condition. The relative humidity of the air within the building can be as high as 27% before condensation will form on the bottom of the deck. However, if insulation with a thermal resistance of 1.25 (R7) is placed above the suspended ceiling, the temperature of the underside of the deck will drop from 1°C (33°F) to about −11°C (13°F) and condensation will occur there if the relative humidity of the indoor air is above 11%, which is likely.

From this example it is obvious that before insulation is added below a roofing system, the possibility of introducing condensation problems should be investigated. Some suspended-ceiling insulation systems have been designed to reduce both heat and moisture flow [*81,82*], but many are not able to effectively reduce moisture flow.

Ventilating the space between the old and new system is not appropriate. Ventilating with indoor air short-circuits the new insulation, and ventilating with outdoor air short-circuits the original insulation.

When insulation is added above an existing roofing system, that system becomes warmer in cold weather and the risk of condensation on or in it diminishes. This incentive to add insulation above an existing system is counteracted by the cost and complexity of doing that because the new system must not only provide insulation but also resist wind, rain, and snow loads and provide waterproofing. Economic studies usually indicate that it is not cost effective to increase the thermal resistance of even rather poorly insulated roofs from the exterior. Thus, adding exterior insulation to a roof is usually done only when other problems (usually leaks) indicate that the waterproofing system also needs attention.

To build a roofing system on a new, stable deck is not a simple matter. It is far more complicated to reroof over existing materials whose performance is poor enough to warrant reroofing. In our litigious society this is a strong reason why many roofing consultants and contractors recommend replacement of roofing systems instead of adding another system on top.

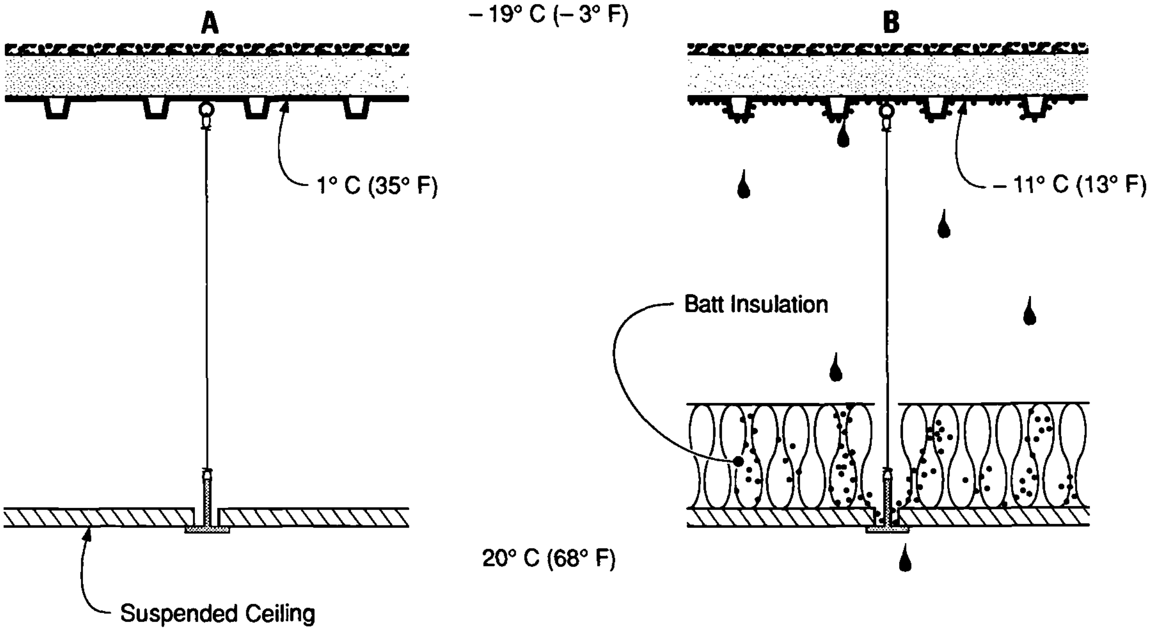


FIG. 33—Adding insulation above a suspended ceiling. This increases the risk of condensation on the underside of the roof deck: (A) existing roof and ceiling; (B) after adding insulation above the suspended ceiling.

If new materials are added above old, it is important to divorce the two systems so that the problems of the old system are not transmitted to the new system. Moisture problems are often of major concern, but other issues such as movements (e.g., splitting) and inadequate wind resistance of the old system also must be addressed. While divorcement is often an appropriate way to solve such problems, the new system may have to be attached to, or through, the old to hold the new system in place. These complexities lend appeal to use of loose-laid ballasted membrane systems over existing low-slope membrane systems whenever the roof structure can support the additional ballast load.

Adding any type of new system over an old system is only appropriate if all the wet components of the existing system can be eliminated and the existing system can provide a stable substrate for the new system. Some old systems will dry out downward once the flaws in their waterproofing layer are eliminated. If such systems have not been damaged by being wet, they can be left in place. Many other existing systems will not dry out downward. Most systems with warm side vapor retarders are in this category. In such systems wet materials should be removed before a new roofing system is placed above. Even if they could be dried, other old systems have been damaged by moisture such that they would not provide a suitable substrate for new materials.

Some individuals feel that it is necessary to slash an existing membrane and install a venting base sheet on it before new material is added above. The idea is to allow any moisture in the existing system to move upward to the underside of the new system but to prevent it from entering the new system by ventilating that space [*83*]. However, if the existing system is dry (a prerequisite for saving it), the slashes and vents only open air leakage paths in the old system, allowing additional moisture from within the building to enter the roof during cold weather. Instead of slashing the old membrane, it seems appropriate to repair any flaws in it so as to enhance its ability to serve as a vapor retarder for the new system.

Finding Wet Insulation

It is virtually impossible to determine the extent of wet insulation in roofs visually, but nuclear meters, capacitance meters, and infrared scanners can locate wet insulation in compact roofing systems [*84,85*].

Nuclear meters (Fig. 34) and capacitance meters (Fig. 35) take readings at the spots on a roof where they are placed. It is common to mark a grid on the roof with points spaced from 1.5 to 3 m (5 to 10 ft) apart. Nuclear meters sense the amount of hydrogen in the roofing system at each spot. Since most dry roofs contain hydrocarbons, they do not give zero readings.

FIG. 34—Surveying a roof with a nuclear meter.

FIG. 35—Surveying a roof with a capacitance meter.

When water is also present in the roof, nuclear readings increase because water is part hydrogen.

Capacitance meters create an alternating current electrical field in the roofing system below. When there is water in that area, the dielectric properties of the roof change and the reading on the capacitance meter increases.

An infrared scanner (Fig. 36) senses the temperature of the surface of the roof. Wet insulation changes the ability of the roofing system to store and conduct thermal energy, thereby causing changes in the temperature of the surface, which many infrared scanners can detect. Instead of a meter reading, the infrared results are presented as shades of brightness on a video monitor. This qualitative visual image provides information over every "square inch" of the roof (Fig. 37). This information is of a more subjective nature than are the numbers generated at grid points by nuclear or capacitance meters, but the images can often define the extent of wet materials very effectively.

Infrared surveys should be done at night. They are commonly conducted by walking with the infrared scanner on the roof. However, they can also be conducted from helicopters (Fig. 38) and fixed-wing aircraft. Generally airborne surveys become more economical than on-the-roof surveys when over about 23 000 m^2 (about 250 000 ft^2) of roofing is to be surveyed in one area [*86*]. Remotely controlled, dual-lens infrared scanners are available that allow wide-angle overviews for finding the target (Fig. 39*A*), followed by telephoto views as the aircraft closes in on the target (Fig. 39*B*), and final telephoto views that yield mapping quality images when the aircraft is directly over the target (Fig. 39*C*).

FIG. 36—Surveying a roof with an infrared scanner.

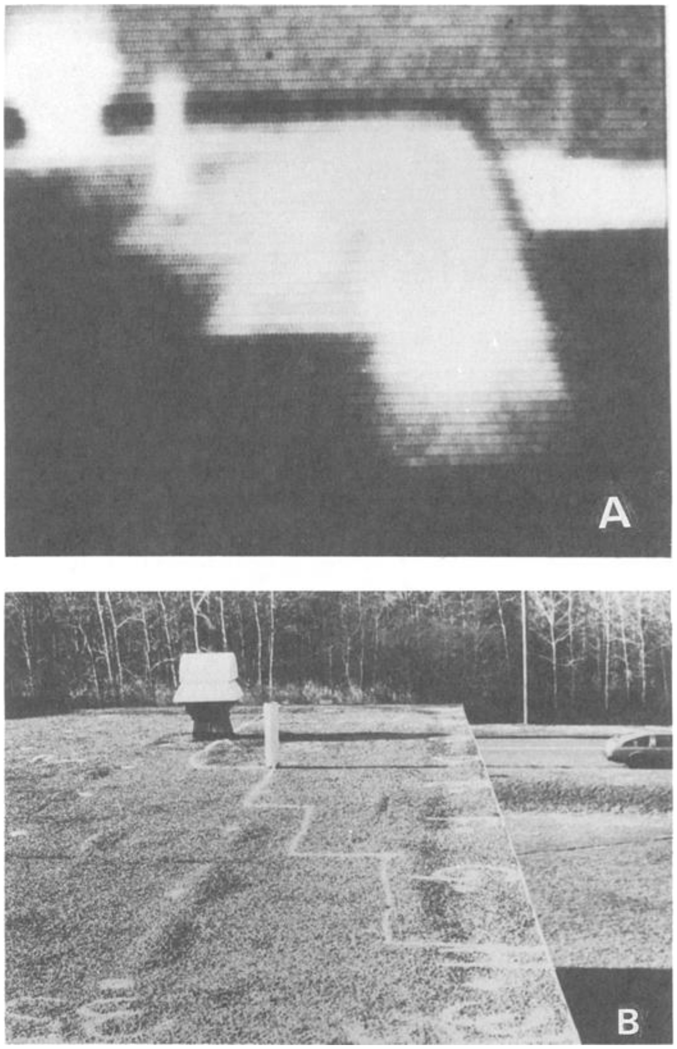


FIG. 37—Thermal image and conventional photograph of the corner of a roof with wet insulation boards: (A) Thermal image (thermogram) showing bright (wet) insulation boards; (B) Photograph of same area after wet insulation was outlined with spray paint.

All nondestructive roof moisture surveys need to be verified by taking a few core samples of the insulation in areas expected to be wet and others expected to be dry (Fig. 40). A low-cost unverified roof moisture survey is usually not recommended. A comprehensive visual inspection and core cuts are usually needed to define, with assurance, the location of wet insulation, to understand why it is wet, and to determine what should be done about it.

Roof moisture surveys are discussed in American Society for Testing and Materials (ASTM) Standard E 936-83, "Practice for Roof System Assemblies Employing Steel Deck, Preformed Roof Insulation and Bituminous Built-up Roofing."

FIG. 38—Conducting an airborne infrared roof moisture survey from a helicopter.

ASTM Standard C 1153-90, "Standard Practice for the Location of Wet Insulation in Roofing Systems Using Infrared Imaging," describes how to conduct on-the-roof and airborne infrared roof moisture surveys.

How Wet is Wet?

The moisture content of insulation samples can be determined by weighing them before and after they are dried in an oven. The moisture content determined in this way is compared to a maximum permissible value for that material.

When constructing *new* roofing systems, it is generally agreed that the moisture content of each material, as determined after each has reached thermal and moisture equilibrium at room temperature and at a relative humidity of about 45% (i.e., its equilibrium moisture content at these conditions), is an appropriate limit. These equilibrium moisture contents have been determined for many materials used in roofs [*15*].

For existing roofs it is reasonable to accept somewhat more moisture. One approach is to use the equilibrium moisture content at 90% RH [*15,87*]. Another approach is to determine the relationship between moisture content and insulating ability of insulations by subjecting them to steady-state wetting in the laboratory [*28–31*] and then establish a maximum acceptable loss in insulating ability.

The ratio of a material's wet thermal resistivity to its dry thermal resistivity, expressed as a percentage, is termed its thermal resistance ratio (TRR). Graphs of TRR versus moisture content for common roof insulations are presented in Figs. 41 through 46 [*31*]. Any insulation that contains enough moisture to reduce its insulating ability to 80% of its dry value (i.e., reduce its TRR to 80%) is considered wet and unacceptable [*31*]. Table 2 presents equilibrium moisture contents for roof insulations at 45 and 90% RH and compares these values to the moisture content at which their TRR is 80%. For most insulations the 80% TRR limit allows much more moisture than either of the equilibrium moisture content limits. Advocates of the equilibrium moisture content limits state that long before the 80% TRR limits are reached, roofs contain enough moisture to cause deterioration and delamination of components so that lower limits are needed. Advocates of the 80% TRR limits, of which I am one, indicate that lower limits result in condemning many existing roofs that, although not perfect, are giving good service.

Table 2 indicates that fibrous glass insulation with a moisture content of 42% (dry weight basis) has 80% of its insulating ability as determined by steady-state laboratory wetting tests. Other dynamic thermal tests and exposure studies [*88–90*] indicate that fibrous glass insulation can lose much of its insulating ability at much lower moisture contents. A loss of about 8% was observed at a moisture content of less than 2% (dry weight basis) [*90*], and a 50% loss was measured at a moisture content of about 12% (dry weight basis) [*89*].

This large decay in insulating ability appears to be unique to fibrous glass insulation. It is attributed to the high vapor permeance of that material, which permits rapid moisture movement within the insulation and significantly increased heat transfer under temperature cycles by condensation and evaporation [*88–90*].

Perhaps a series of moisture limit states are needed for roofing systems [*10*]. With knowledge of limits associated with rot, corrosion, delamination, thermal resistance, and such, appropriate condensation control measures can be specified to prevent moisture levels from exceeding acceptable values. For one roofing system, the corrosion limit might control; for another, the thermal resistance limit might control. Developing all these moisture limits for the myriad of roofing sys-

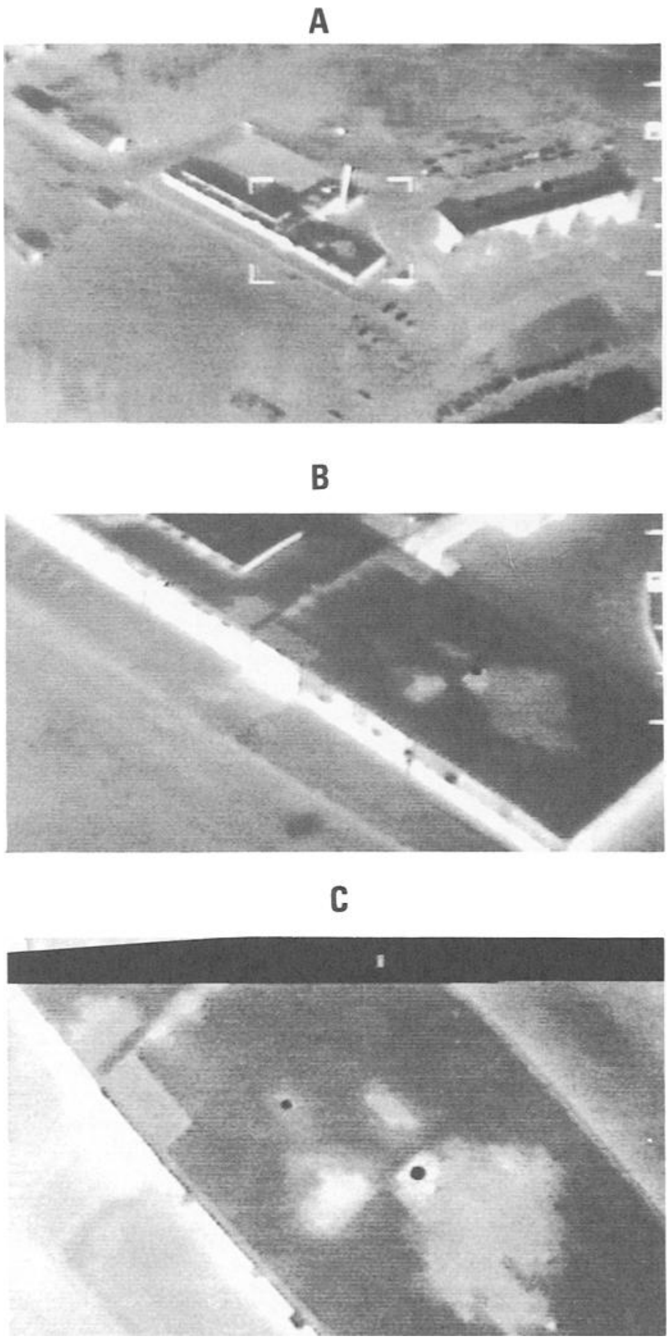


FIG. 39—Sequence of thermograms approaching a target roof in a helicopter: (A) Distant view with wide angle lens—target roof is within reticles; (B) Telephoto view approaching target roof; (C) Mapping-quality telephoto view of target roof.

tems on the market is a sizable task that has not yet been accomplished.

Drying Wet Insulation

Moisture is very difficult to remove from wet roof insulation in compact membrane roofing systems. Edge vents, breather vents (Fig. 15), and breathable membranes have been promoted to dry out wet insulation. Exposure studies in

FIG. 40—Obtaining cores to verify a roof moisture survey.

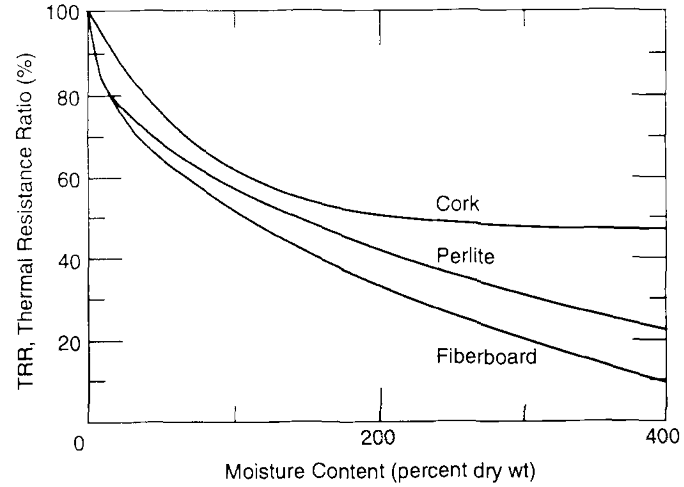


FIG. 41—TRR versus moisture content relationship for cork, fiberboard, and perlite.

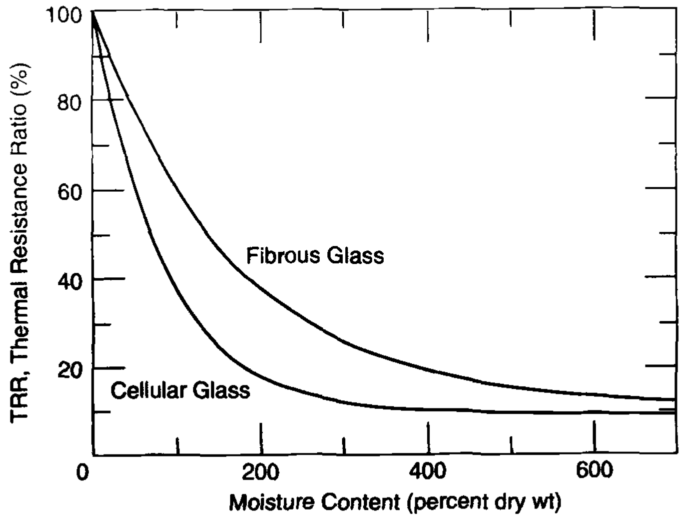


FIG. 42—TRR versus moisture content relationships for fibrous glass and cellular glass.

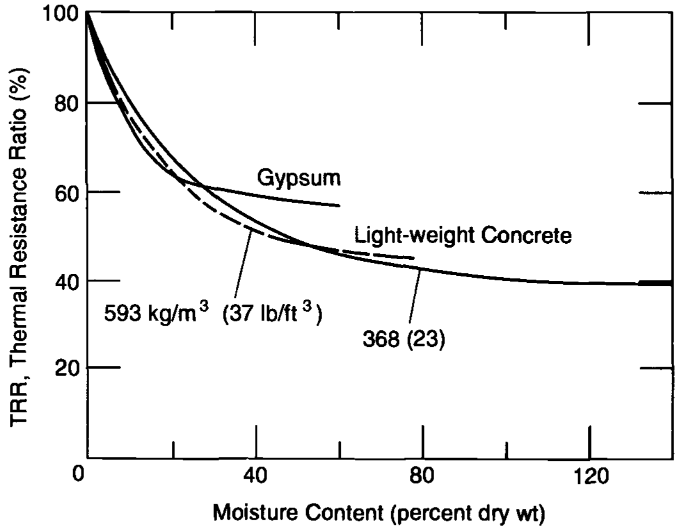


FIG. 43—TRR versus moisture content relationships for gypsum and lightweight concrete.

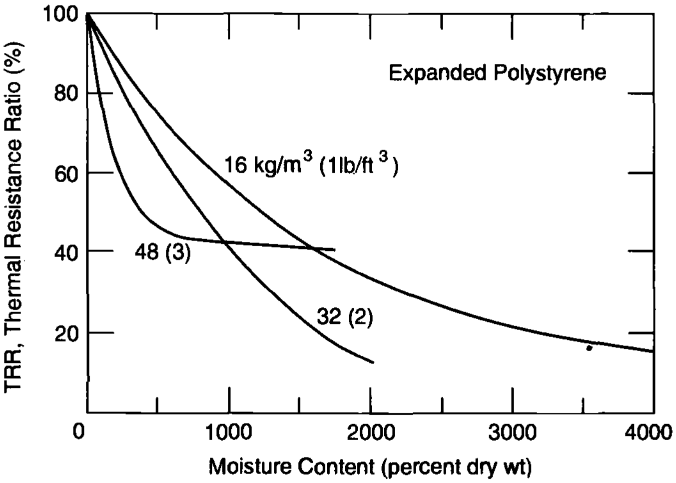


FIG. 44—TRR versus moisture content relationships for expanded polystyrene.

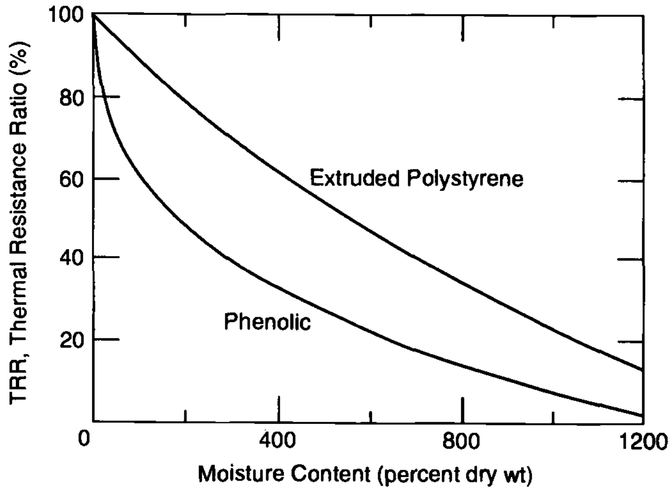


FIG. 45—TRR versus moisture content relationships for extruded polystyrene and phenolic.

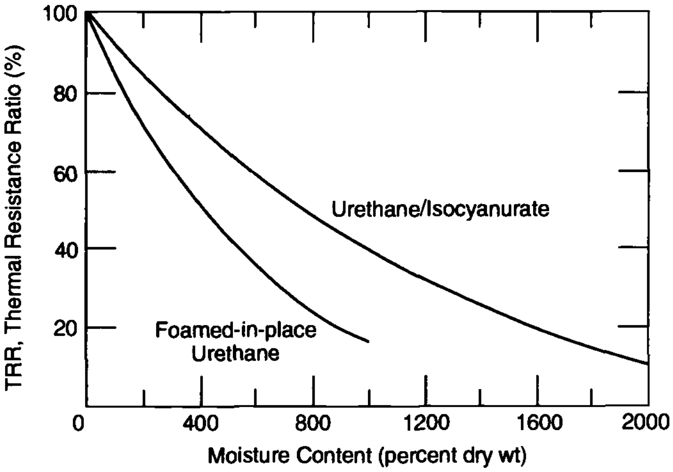


FIG. 46—TRR versus moisture content relationships for urethane/isocyanorate and foamed-in-place urethane.

Hanover, New Hampshire [*47*] and in Saskatoon, Saskatchewan [*44*] indicate that drying is a very localized and very slow process that takes many years or decades. Table 3 summarizes the time to dry wet perlite and fibrous glass insulation boards in roofs exposed to the New Hampshire climate: very slow.

The most promising use of breather vents is the use of several two-way vents to allow cross-ventilation of fibrous glass insulation. A specimen of such insulation, configured to allow cross-ventilation, dried much faster than did any of the other specimens tested. Even at its relatively fast drying rate, however, this specimen would take many years to dry.

Other considerations, such as the decreasing effectiveness of a breather vent as its area of coverage increases, suggest that even the rather slow drying rates determined from exposure studies [*44,47*] may not be achieved in practice.

Unfortunately, it does not appear possible to dry out wet insulation in compact roofing systems in a reasonable amount of time by venting.

Some success has been achieved in drying fibrous glass insulation in a roof by removing water with a vacuum cleaner [*47*]. In a series of tests lasting about five days, about 0.42 m^3 (110 gal) of water was removed from a 17-m^2 (180-ft^2) area of 38-mm- (1.5-in.-) thick insulation. Before the water was removed, the insulation had only 21% of its dry insulating ability; afterward it had 83%.

TABLE 2—Comparison of equilibrium moisture contents and those at 80% TRR for insulations without facers [*30*].

Insulation	Equilibrium Moisture Content, % of Dry Weight (from Ref *87*) At 45% RH	At 90% RH	Moisture Content, % of Dry Weight at 80% TRR
Cellular glass	0.1	0.2	23
Expanded polystyrene 16 kg/m^3 (1 lb/ft^3)	1.9	2.0	383
Extruded polystyrene	0.5	0.8	185
Fibrous glass	0.6	1.1	42
Isocyanurate	1.4	3.0	262
Perlite	1.7	5.0	17
Phenolic	6.4	23.4	25
Urethane	2.0	6.0	262

TABLE 3—Time to dry two kinds of insulation in a compact membrane roofing system in New Hampshire [*47*].

	Time to Remove 29 kg/m² (6 lb/ft²) of Water from:	
Venting Feature	Perlite Boards	Fibrous Glass Boards
One-way breather vent	no drying observed	no drying observed
Two-way breather vent	67 years	46 years
Two two-way breather vents	30 years	13 years
Solar-powered vent	33 years	120 years
Vented edge	75 years	60 years
"Breathable" EPDM membrane	86 years	86 years

In a laboratory study [*91*], a layer of polyester fabric, placed under wet fibrous glass insulation with a slope of 2%, was able to wick away most of the moisture in the insulation in a few days by way of an exposed flap at the low end of the polyester. The use of such wicks in compact membrane roofs with fibrous glass insulation would be complicated by the need to expose their low portions to facilitate drying. Because of this difficulty and the high cost of polyester fabric, such drying schemes have not been incorporated into roofs.

Tests have been conducted on a composite "hygrodiode" membrane that serves as an air barrier and vapor retarder but also has the ability to wick moisture out of a roof [*92*]. This membrane consists of a synthetic fabric with good wicking action between impermeable surfaces. Gaps in the impermeable surfaces alternate from side to side with overlaps, as shown in Fig. 47. The overlapping surfaces give the membrane a low permeance to vapor. The hygrodiode membrane could limit the growth of "cancers" of wet insulation caused by flaws in the waterproofing system. In roofs where moisture is expected to accumulate in the insulation during certain periods, it could be used to wick that moisture away at other times. Incorporating drying methods in the design is considered prudent by some, but others argue that most roofs should be designed to keep the insulation from getting so wet that wicks are needed to dry it.

Light-weight insulating concretes and other wet-applied insulations contain a lot of water when they are placed. Current practice is to place such materials on slotted steel decks so that they can dry out downward into the building after their top surface is covered by a waterproof membrane [*90*]. Unfortunately, in the past, many such systems were placed on solid steel decks that did not allow them to dry downward and numerous moisture-related problems developed. Some drying has been achieved by drilling holes down through these materials and the steel deck on 0.6-m (2-ft) centers before installing a new roofing system above [*93*].

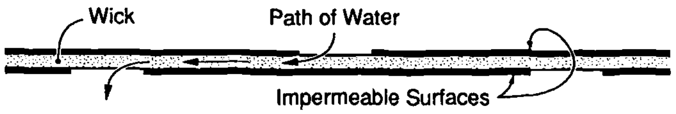


FIG. 47—"Hygrodiode" membrane. It stops air, retards vapor, and allows water to wick away.

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Moisture Control for New Residential Buildings*

by Joseph Lstiburek[1] *and John Carmody*[2]

MOISTURE ACCUMULATES WHEN THE RATE OF MOISTURE entry into an assembly exceeds the rate of moisture removal. When moisture accumulation exceeds the ability of the assembly materials to store the moisture without significantly degrading performance or long-term service life, moisture problems result.

Various strategies can be implemented to minimize the risk of moisture damage. The strategies fall into the following three groups:

- control of moisture entry
- control of moisture accumulation
- removal of moisture

Strategies in the three groupings can be utilized in combination and have been proven to be most effective in that manner. Strategies effective in the control of moisture entry, however, are often not effective if building assemblies start out wet and, in fact, can be detrimental. If a technique is effective at preventing moisture from entering an assembly, it is also likely to be effective at preventing moisture from leaving an assembly. Conversely, a technique effective at removing moisture may also allow moisture to enter. Balance between entry and removal is the key in many assemblies.

Of the mechanisms involved in the surface wetting and interstitial wetting of building assemblies, the most significant are liquid flow and capillary suction, where groundwater and rain are the moisture sources. Controlling groundwater entry below grade and rain entry above grade have traditionally been the preoccupation of generations of builders and designers. Air transport and vapor diffusion are not so obvious contributions to the wetting of building assemblies. Each mechanism is capable of leading to moisture-related building problems.

All moisture movement and therefore any moisture-related problem is a result of one of these mechanisms or some combination of these mechanisms.

Historically, successful approaches to moisture control have typically been based on the following strategy: (1) prevent building assemblies and surfaces from getting wet from the exterior, (2) prevent building assemblies and surfaces from getting wet from the interior, and (3) should building assemblies or surfaces get wet, or start out wet, allow them to dry to either the exterior or the interior.

Building assemblies in all climates can get wet from the exterior in similar manner by liquid flow (rain, dew, and groundwater as moisture sources) and capillary suction (rain, dew, and groundwater as moisture sources). Accordingly, techniques for the control of liquid flow and capillary suction are similar in all climates and are interchangeable.

However, building assemblies get wet by air movement and vapor diffusion in a different manner depending on climate and time of year. Accordingly, techniques for the control of air movement and vapor diffusion are different for each climate and are not interchangeable.

The "duality" that air movement and vapor diffusion possess with respect to their ability to move moisture from both the interior and exterior of a building enclosure into the building envelope is dependent on both climatic and interior conditions and is often overlooked by designers and builders. It is not unusual to find "cold" climate building envelope designs employed in "warm" climate regions. Even more confusing to the builder and designer are conditions where both heating and cooling occur for extended periods of time.

SURFACE MOLD AND OTHER BIOLOGICAL GROWTH

The following conditions are necessary and sufficient for mold and other biological growth to occur on surfaces:

- mold spores must be present
- a nutrient base must be available (most surfaces contain nutrients)
- temperature range between 40 (4.4°C) and 100°F (37.7°C)
- relative humidity adjacent to surface above 70% [*1*]

Of these conditions, relative humidity near surfaces is the most practical to control. Spores are always present in outdoor and indoor air. Almost all of the commonly used construction materials can support mold growth; therefore, control of available nutrients is limited and human comfort constraints limit the use of temperature control.

Where relative humidities near surfaces are maintained below 70%, mold and and other biological growth can be controlled. Since relative humidities are dependent on both tem-

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perature and vapor pressure, mold control is dependent on controlling both the temperature and vapor pressure near surfaces.

In heating climates, mold growth on interior surfaces occurs during the heating season because the interior surfaces of exterior walls are cool from heat loss and because moisture levels within the conditioned space are too high. Mold growth control is facilitated by preventing the interior surfaces of exterior wall and other building assemblies from becoming too cold and by limiting interior moisture levels. The key is to prevent relative humidities of adjacent surfaces from rising above 70%. The thermal resistance of the building envelope and the local climate determine the interior surface temperatures of exterior walls and other building assemblies. Controlled ventilation and source control limit the interior moisture levels.

Experience has shown that where interior moisture levels in heating climates during the heating season are limited to the 25 to 35% relative humidity range at 70°F (21.1°C), relative humidities adjacent to the interior surfaces of exterior walls (of typical thermal resistance) fall below 70% and mold growth is controlled. The colder the climate (for the thermal resistance of any given building envelope), the lower the interior relative humidity necessary to prevent 70% relative humidities from occurring adjacent to interior surfaces of exterior walls. Building enclosures of similar thermal resistance (building code minimums) located in Minneapolis, Minnesota and Cincinnati, Ohio should be limited to different interior moisture levels during the heating season. A 25% interior relative humidity at 70°F (21.1°C) would be appropriate for Minneapolis. Interior relative humidities up to 35% at 70°F (21.1°C) would be appropriate for Cincinnati. Correspondingly, the higher the desired interior relative humidity, the higher the thermal resistance necessary to control relative humidities adjacent to interior surfaces.

In mixed climates, during the heating season, interior moisture levels should be limited to the 35 to 45% relative humidity range at 70°F (21.1°C). This limits the relative humidity adjacent to the interior surface of exterior walls to below 70% for the typical thermal resistance found in most building assemblies in this climate zone.

In cooling climates, interior mold growth also occurs because interior surfaces are typically cold and subsequently accessed by moisture levels which are too high. The cold surfaces in cooling climates arise from the air conditioning of enclosures. When exterior hot air is cooled, its relative humidity increases. If the exterior hot air is also humid, cooling this air will typically raise its relative humidity above the point at which mold growth can occur (70%).

Where air-conditioned "cold" air is supplied to a room, and this air is "blown" against an interior surface due to poor diffuser design, diffuser location, or diffuser performance, cold spots can occur on the interior gypsum board surfaces. Although this cold air is typically dehumidified before it is supplied to the conditioned space, it can create a mold problem on room surfaces as a result of high levels of airborne moisture within the room contacting the cooled surface. This typically leads to a rise in relative humidity near the surface and a corresponding mold problem.

If exterior humid air comes in contact with the interstitial cavity side of cooled interior gypsum board, mold and other biological growth can occur. Cooling this exterior hot, humid air by air conditioning or contact with cool surfaces will raise its relative humidity above 70%. When nutrients are present, mold and other growth occurs. This is exacerbated with the use of impermeable wall coverings such as vinyl wallpaper, which can trap moisture between the interior finish and the gypsum board. When these interior finishes are coupled with cold spots (from poor diffuser placement and/or overcooling) and exterior moisture, mold and other growth can occur.

Accordingly, one of the most practical solutions in controlling mold and other biological growth in cooling climates is the prevention of hot, humid exterior air or other forms of moisture transport from contacting the interior cold (air-conditioned) gypsum board surfaces (controlling the vapor pressure at the surface). This is most commonly facilitated by maintaining the conditioned space at a positive air pressure to the exterior and the installation of an exterior vapor diffusion retarder. Pressurization of building assemblies is expedited by airtight construction.

Interior moisture levels within the conditioned space should also be limited to 60% relative humidity at 75°F (23.8°C) by dehumidification and source control to prevent mold growth on the interior surfaces within the conditioned space [*2*].

Experience has also shown that where conditons for mold growth are controlled, other biological growth such as dust mite infestations can also be controlled. Specifically, for dust mites to grow, 70% relative humidities are also necessary. Carpets located on cold surfaces, such as concrete slabs, are particularly sensitive to dust mite growth. Carpets on cold surfaces should be avoided, or these surface temperatures should be elevated by the use of appropriate thermal insulation [*3*].

MOISTURE CONTROL PRACTICES FOR HEATING CLIMATES

A heating climate has 4000 degree days heating or greater. Intermittent cooling (air conditioning) typically occurs. The climate zone specified is broad and general for simplicity. Specific microclimates should always be considered. Incident solar radiation, nearby water and wetlands, and vegetation and undergrowth all affect the microclimate of a building assembly. For any specific location, designers and builders should consult weather records and consider local experience.

Key Concerns and Control Strategies

In heating climates, the principal moisture concerns are rain penetration, groundwater, interstitial condensation (condensation within building assemblies), and interior mold and mildew linked to high interior levels of humidity.

Typically, in heating climates, wetting from the interior during the heating season by air movement is a major concern. In heating climates, building envelopes are constructed in an airtight manner to control air leakage openings, to expedite air pressure control (depressurization of the building envelope above grade during the heating season and pressurization below grade to control ingress of soil gas and other pollutants), and to facilitate controlled ventilation, which provides for the dilution of interior pollutants and interior moisture by controlled air change.

Vapor diffusion from the interior is also a concern in heating climates. Accordingly, vapor diffusion retarders in heating climates are located towards the interior, and walls and other building assemblies are designed and built to dry to the exterior, should they get wet or start out wet.

The presence of ground frost penetration concerns in this climate has led to the widespread use of basement foundations, with foundation footings located below ground frost penetration depth. Frost-protected crawl spaces are common in the more moderate regions of heating climates. Concrete and masonry foundations are common with limited use of wood foundations. Above-grade frame walls predominate.

Rain and Groundwater

Rain penetration and groundwater concerns are common to builders in all climates, and the methods of control in this climate are similar to those of other climates. Examples include: rain screens; building papers; appropriate placement of flashings, gutters, and downspouts which direct water away from foundations; and careful site grading and subgrade drainage.

Basement spaces are often conditioned and occupied. As such, concerns with groundwater penetration and infiltration of soil gas (including radon) are common.

Another source of external water, air-conditioning condensate drains, should be plumbed directly to the graywater system.

Condensation Within Building Assemblies

Conditioned spaces are heated by both electric and fuel-fired appliances. Traditional negative interior air pressures have been reduced as a result of the trend away from active chimneys toward high-efficiency combustion appliances and electric heat sources. When combined with the trend towards tighter enclosures, reduced airchange, and higher levels of interior moisture, this has led to concerns about the exfiltration of interior moisture-laden air leading to condensation within insulated assemblies. Reduced air change and resultant higher levels of interior moisture have led to elevated incidences of interior surface mold and mildew.

Air leakage from the interior into insulated attics during the heating months, coupled with insufficient attic ventilation, can lead to roof sheathing decay. Air leakage into insulated wall cavities during the heating months, coupled with an insufficient or limited drying ability, can lead to the decay of structural framing members.

Moisture movement by air leakage (the exfiltration of interior moisture-laden air) is controlled in several ways. Air leakage openings can be limited, the above-grade conditioned spaces can be depressurized, and the interior moisture levels can be controlled by ventilation (dilution by air change) combined with source control. Source control involves direct venting of clothes dryers, as well as the use of subgrade vapor retarders under concrete floor slabs and bath and kitchen exhaust systems.

Moisture movement by vapor diffusion from the interior is controlled by the use of vapor diffusion retarders in walls, roofs, and foundations.

Cladding systems which can absorb significant amounts of moisture when exposed to rain, such as brick, masonry, wood, and stucco, should only be incorporated in wall assemblies which are designed and built to deal with the inward migration of moisture. Solar radiation warms exterior wall surfaces, and this warming creates temperature gradients from the exterior to the interior. Along with the air conditioning of interior surfaces, this can cause problems if not taken into account. An example of this is the installation of gypsum board covered with vinyl wallpaper on the interior of a masonry block wall without provision for an appropriate vapor diffusion retarder and air retarder system. Without these, the gypsum board is not protected from this exterior moisture or from construction moisture which may be trapped in the masonry units [*4*].

Vinyl interior wall coverings are not exclusive to masonry or concrete wall systems and are also used with wood frame construction. Thus, wherever vinyl interior wall coverings are used in this climate zone, precautions must be taken to prevent the absorption of moisture by gypsum wall board from the exterior or from the moisture of construction.

Where wet masonry, wet lumber (greater than 19% moisture content by weight), or wet-applied insulation (wet spray cellulose or wet blown fiberglass) are installed in building assemblies, those assemblies must be designed and built in such a manner that they can dry to the exterior or interior or the materials must be allowed to dry prior to enclosure.

Ice Damming

Heat loss at the perimeter edges of roof and attic assemblies during the heating months can lead to ice damming. This is caused by a lack of thermal insulation where exterior walls intersect these assemblies as well as air leakage up and out of exterior walls, coupled with insufficient or discontinuous soffit ventilation.

High Interior Humidity Resulting in Mold and Surface Condensation

The absence of a controlled ventilation system can lead to elevated levels of moisture within the conditioned space during the heating months as a result of a low air change rate. These elevated levels of interior moisture can lead to condensation on window surfaces and give rise to surface mold and mildew, as well as concealed condensation within walls and roof spaces.

Cold interior surfaces during the heating months arising from thermal bridges or wind blowing through insulations create high interior surface relative humidities and often lead to mold and mildew at these locations. Most common locations are where exterior walls intersect insulated ceilings, exterior corners, and uninsulated (or poorly insulated) window lintels or headers.

Low air change during the heating season due to the construction of tight enclosures can lead to elevated interior levels of moisture. Cold air is not capable of holding as much moisture as warm air. Cold air is therefore typically dryer than warm air. During the heating season, cold, dry air from the exterior infiltrates through random leakage openings in building enclosures or is brought into the building by controlled ventilation. This cold, dry air is subsequently heated by the enclosure's heating system and becomes capable of holding appreciable amounts of moisture. Should moisture be available, it is picked up by this heated, dry air. This heated air, now containing moisture, exfiltrates to the exterior through other random leakage openings or is deliberately exhausted by controlled ventilation.

Air change (infiltration/exfiltration combined with controlled ventilation) removes interior moisture from within building enclosures during the heating season. The greater the air change rate, the greater the removal rate of interior moisture. However, typical construction practice results in building enclosures which have air change rates from random leakage that are inadequate to control interior moisture levels. As such, in heating climates it is desirable to ventilate enclosures in a controlled manner to limit interior moisture levels.

Relative humidity should be maintained at 35% or lower at 70°F (21.1°C) within the conditioned spaces during the heating months (the key is to prevent 70% relative humidities from occurring adjacent to surfaces in order to control mold, mildew, and other biological growth). Humidity control within conditioned spaces is accomplished by the dilution of interior moisture by air change, facilitated by controlled mechanical ventilation coupled with source control. In the more moderate heating regions with high exterior vapor pressures during the heating season, such as the Pacific Northwest, mechanical dehumidification is also practical.

Mechanical System Concerns

Ductwork for forced-air heating and cooling systems should be installed only within conditioned spaces. Ductwork should not be installed in attics or vented crawl spaces. Leaky return ducts located in attics draw significant amounts of cold air into conditioned spaces during the heating months, increasing heating loads and drawing significant amounts of warm, moisture-laden air into the conditioned space from the attic during cooling periods, increasing cooling loads. Leaky return ducts located in vented crawl spaces draw significant amounts of soil gas, moisture, possibly pesticides, radon, and other pollutants into the conditioned spaces, often creating moisture problems and increasing heating loads during the heating months and cooling loads during the cooling periods as well as risking occupant health and safety [*5*].

Leaky supply ducts located in attics or vented crawl spaces lead to the uncontrolled depressurization of the conditioned space, leading to excessive infiltration of cold air during heating periods, increasing heating loads and potentially supplying sufficient interior moisture to attic and roof assemblies to create roof sheathing moisture and decay problems. During cooling periods, the same mechanism can lead to the infiltration of exterior warm moisture laden air, increasing cooling loads.

Many building enclosures in heating climates are now built in an airtight manner. Where forced air systems with minimal returns (a single return is common) are installed in tight building enclosures, pressurization of bedrooms and depressurization of basement spaces can occur. This can lead to the spillage and backdrafting of combustion appliances, infiltration of soil gas, and the exfiltration of moisture-laden air into interstitial spaces. To prevent these air pressure extremes, multiple return air registers and/or air transfer grills are recommended. Additional returns in master bedroom suites coupled with transfer grills located in bedroom/hallway partition walls have proven successful [*6*].

Where duct work is located in dropped ceilings adjacent to attics and exterior walls, it is important that air barrier continuity is maintained above the dropped ceiling or at the exterior wall.

Should duct work be installed in attics and/or vented crawl spaces (or outside of the conditioned space), it is essential that it be installed in a leak-free, airtight manner. This typically necessitates the utilization of mastic sealants (duct tape has proven ineffective) and specialized training [*7*].

Combustion Appliances

Unvented combustion appliances such as gas stoves with standing pilot lights and room space heaters are significant sources of moisture as well as sources for other pollutants and should be avoided. Gas stoves and cook tops without standing pilot lights should be installed in conjunction with vented range hoods or some other vent provision.

Where combustion appliances are installed they should be uncoupled (not influenced by enclosure air pressures or supply air availability) from the conditioned space. In other words, sealed combustion, power-vented, induced draft, condensing, or pulse combustion devices should be used. Devices with traditional draft hoods should be avoided. Where fireplaces are installed, they should have their own supply of air from the exterior as well as tight-fitting glass doors. Wood stoves should also have their own supply of exterior air ducted directly to their firebox [*8*].

WHOLE BUILDING SYSTEMS

Three examples of desirable whole building systems for this climate zone are (Fig. 1):

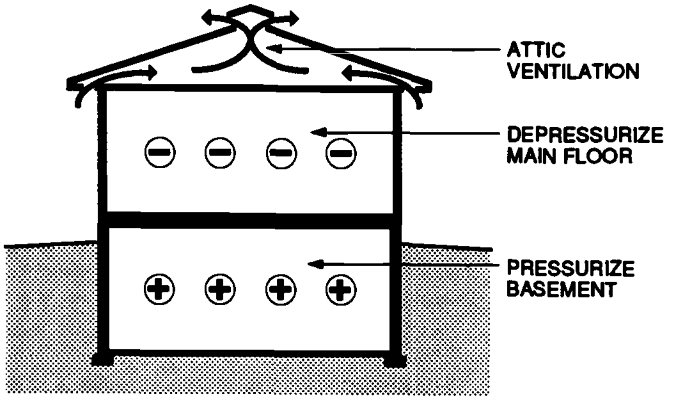
- buildings with basements and vented attics
- buildings with basements and vented cathedral ceilings
- buildings with basements and unvented cathedral ceilings

Common features of the three systems are basement spaces maintained at a positive air pressure to the exterior and above grade spaces maintained at a negative air pressure to the exterior.

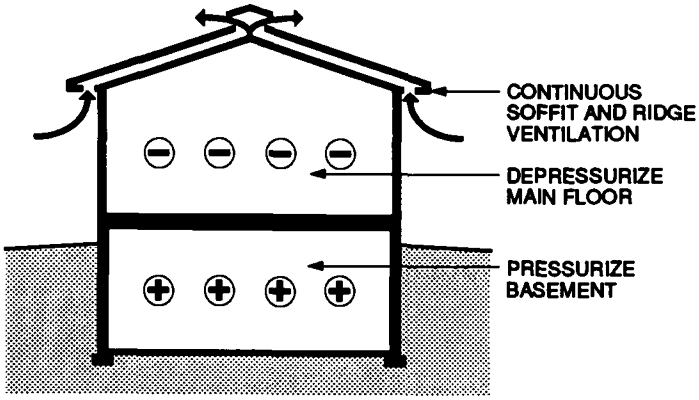
Positive pressurization of the basement (below grade) spaces eliminates the infiltration of soil gas, radon, and other pollutants. Depressurization of the above grade conditioned spaces eliminates the exfiltration of interior moisture-laden air.

Ventilation of roof assemblies removes moisture in all but heavily insulated assemblies in the harshest climates.

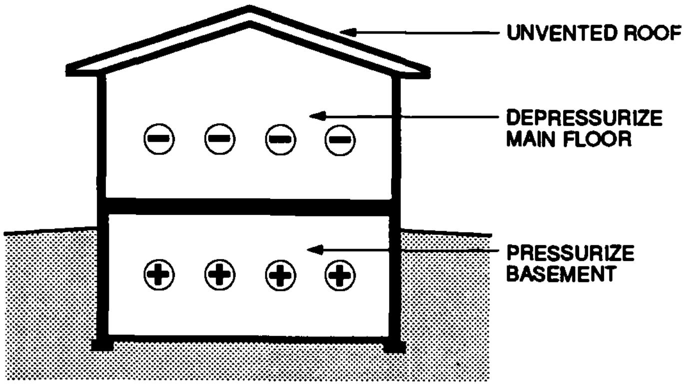
Wall design and construction in this climate typically locates vapor diffusion retarders and measures to control air leakage towards the interior. In this climate it is convenient to allow walls to dry to the exterior in the direction of typical vapor flow during the heating season. Drying to the interior



Building 1



Building 2



Building 3

FIG. 3—Whole house concepts for cooling climates.

is possible, but more difficult to facilitate and typically intermittent.

MOISTURE CONTROL PRACTICES FOR MIXED CLIMATES

A mixed climate has 4000 degree days heating or less combined with a significant number of cooling (air-conditioning) hours. In this climate zone, heating and cooling both occur for significant periods of time. The climate zone specified is broad and general for simplicity. Specific microclimates should always be considered. Incident solar radiation, nearby water and wetlands, and vegetation and undergrowth all affect the microclimate of a building assembly. For any specific locations, designers and builders should consult weather records and consider local experience.

Key Concerns and Control Strategies

In mixed climates where both heating and cooling occur for significant periods of time, the principal moisture concerns are rain penetration, groundwater, concealed condensation within wall and roof spaces, and interior mold and mildew linked to high interior levels of humidity during heating periods as well as to high exterior levels of humidity and cool interior surfaces due to the air conditioning of enclosures during cooling periods.

In mixed climates, wetting by air movement can occur from both the exterior and interior. In mixed climates, building envelopes are constructed in an airtight manner to control air leakage openings, to expedite air pressure control (depressurization of the building envelope above grade during the heating season, pressurization below grade to control ingress of soil gas and other pollutants, and pressurization of the building envelope during the cooling season) and to facilitate the dehumidification of indoor air during the cooling season, thereby limiting interior moisture levels. Controlled ventilation is also necessary to provide for the dilution of interior pollutants and for the dilution of interior moisture during the heating season by controlled air change.

In mixed climates, wetting by vapor diffusion can occur from both the exterior and the interior. Drying can also occur in both directions. Accordingly, vapor diffusion retarders in mixed climates can be located to either the interior or the exterior. Where vapor diffusion retarders are located to the interior, building assembly components located to the exterior can be vapor permeable to facilitate drying to the exterior. Where vapor diffusion retarders are located to the exterior, building assembly components located to the interior can be vapor permeable to facilitate drying to the interior.

If vapor diffusion retarders are located to the exterior in mixed climates (and are coupled with permeable interior sheathings and finishes), they should be maintained at a warm enough temperature during the heating season to control the amount of interior moisture which can accumulate on their interior surfaces (elevation of the condensing surface temperature). Impermeable insulating sheathings can be effectively utilized with this technique [9].

If vapor diffusion retarders are located to the interior in mixed climates (and are coupled with permeable exterior sheathings), they should allow for the intermittent wetting from the exterior during the cooling season of their exterior surface (surface facing the exterior of the building assembly) without damage. Low permeability interior paint or impermeable wall coverings located on interior gypsum board, although effective in preventing interior moisture from diffusing outward during the heating season, would be ineffective in protecting interior gypsum board from damage by moisture diffusing inward during the cooling season.

Due to shallow ground frost penetration, this climate is marked by a mix of basement foundations and frost-protected crawl spaces. Concrete and masonry foundations are common, with limited use of wood foundations and wood crawl spaces. Frame walls predominate.

Rain and Groundwater

Rain penetration and groundwater concerns are common to builders in all climates, and the methods of control in this climate are similar to those of other climates. These include: the rain screen; building papers; appropriate placement of flashings, gutters, and downspouts, which direct water away from foundations; and careful site grading and subgrade drainage.

Basement spaces are typically conditioned and occupied. Concerns with groundwater penetration and infiltration of soil gas and radon are common with this type of construction.

Another source of external water, air-conditioning condensate drains, should be plumbed directly to the graywater system.

Condensation Within Building Assemblies

Conditioned spaces are heated by both electric and fuel-fired appliances. Traditional negative interior air pressures have been reduced as a result of the trend away from active chimneys towards high-efficiency combustion appliances and electric heat sources. When coupled with the trend towards tighter enclosures, reduced air change, and higher levels of interior moisture, this has led to concerns about the exfiltration of interior moisture-laden air leading to condensation within insulated assemblies. Reduced air change as a result of tighter construction practices and resultant higher levels of interior moisture have also led to elevated incidences of interior surface mold and mildew during heating periods.

During cooling periods, mechanical cooling coupled with dehumidification for comfort reasons is widespread. This gives rise to moisture flow by air movement and vapor diffusion from the exterior to the interior cooled area as a result of a higher outdoor vapor pressure than indoor vapor pressure during the cooling periods. These outdoor-to-indoor vapor pressure differences during cooling periods in this climate can be greater than the indoor-to-outdoor vapor pressure differences during heating periods in this same climate.

High inward flow of moisture during cooling periods can result in elevated energy costs due to high cooling loads, building fabric deterioration from decay and corrosion, and health and safety concerns from mold and mildew growth.

Leakage of warm, interior moisture-laden air during heating periods into insulated attics from the interior coupled with insufficient attic ventilation can lead to roof sheathing decay. Leakage of this warm air during heating periods into insulated wall cavities coupled with an insufficient or limited drying ability can lead to decay of structural framing members.

Moisture movement by air leakage (the exfiltration of interior moisture-laden air during heating periods and the infiltration of exterior moisture-laden air during cooling periods) is controlled by limiting air leakage openings, depressurizing the above grade conditioned spaces during heating periods, pressurizing the above grade conditioned spaces during cooling periods, controlling the interior levels of moisture during heating periods by utilizing controlled ventilation (dilution by air change) combined with source control (direct venting of clothes dryers as well as the use of subgrade vapor retarders under concrete floor slabs and bath and kitchen exhaust systems), controlling the interior levels of moisture during cooling periods by utilizing the dehumidification capabilities of mechanical cooling systems, and limiting controlled ventilation to minimum values established by indoor air quality concerns.

Moisture movement by vapor diffusion from the interior and from the exterior is controlled by the use of vapor diffusion retarders in walls, roofs, and foundations.

Cladding systems which can absorb significant amounts of moisture when exposed to rain—such as brick, masonry, wood, and stucco—should only be incorporated in certain wall assemblies. Such assemblies are designed and built to deal with the inward migration of moisture driven by temperature gradients from the exterior to the interior. Solar radiation warming exterior wall surfaces creates those gradients, along with the air conditioning of interior surfaces. Problems often arise where this is not taken into account, such as the installation of vinyl wallpaper–covered gypsum board on the interior of a masonry block wall without provision for an appropriate vapor diffusion retarder and air retarder. The vapor diffusion retarder and air retarder system protect the gypsum board from this exterior moisture or from construction moisture which may be trapped in the masonry units.

Vinyl interior wall coverings are not exclusive to masonry or concrete wall systems and are also used with wood frame construction. Thus, wherever vinyl interior wall coverings are used in this climate zone, precautions must be taken to prevent the absorption of moisture by gypsum wall board from the exterior or from the moisture of construction.

Where wet masonry, wet lumber (greater than 19% moisture content by weight), or wet-applied insulations (wet spray cellulose or wet-blown fiberglass) are installed in building assemblies, those assemblies must be designed and built in such a manner that they can dry to the exterior or interior or the materials must be allowed to dry prior to enclosure.

Ice Damming

Heat loss at the perimeter edges of roof and attic assemblies during heating months can lead to ice damming. This is caused by a lack of thermal insulation where exterior walls intersect roof and attic assemblies as well as air leakage up and out of exterior walls, coupled with insufficient or discontinuous soffit ventilation.

High Interior Humidity Resulting in Mold and Surface Condensation

Without a controlled ventilation system, moisture levels within the conditioned space can be elevated during the heating months as a result of a low air change rate. These elevated levels of interior moisture can lead to condensation on window surfaces and give rise to surface mold and mildew and concealed condensation within walls and roof spaces.

If thermal bridges or wind blowing through insulations create cold interior surfaces during heating months, interior surfaces will have high adjacent relative humidities, and mold and mildew will often grow at these locations. Most common locations are where exterior walls intersect insulated ceilings, exterior corners, and uninsulated (or poorly insulated) window lintels or headers.

Low air change during heating periods due to the construction of tight enclosures can elevate interior moisture. Cold air is not capable of holding as much moisture as warm air, so cold air is typically drier. During heating periods, cold, dry air from the exterior infiltrates through random leakage openings in building enclosures or is brought into the building by controlled ventilation. This cold, dry air is subsequently heated by the enclosure's heating system and becomes capable of holding appreciable amounts of moisture. Should moisture be available, it is picked up by this heated, dry air. This moisture-containing, heated air now exfiltrates to the exterior through other random leakage openings or is deliberately exhausted by controlled ventilation.

Air change (infiltration/exfiltration combined with controlled ventilation) removes moisture from within building enclosures during heating periods. The greater the air change rate during heating periods, the greater the removal rate of interior moisture. Typical construction practice results in building enclosures which have air change rates inadequate to control interior moisture levels by random leakage alone. As such, in mixed climates during heating periods, it is desirable to ventilate enclosures in a controlled manner to limit interior moisture levels.

High air change during cooling periods due to infiltration/exfiltration, duct leakage, and excessive ventilation can lead to elevated interior levels of moisture. This is due to the high exterior humidity conditions which occur during the cooling season. The greater the amount of exterior air brought into an enclosure during cooling periods, the greater the amount of moisture brought in with it. As such, in mixed climates, it is desirable to build tight enclosures and ventilate these enclosures during cooling periods with outside air at a minimum, controlled rate. Minimum ventilation rates typically are established by indoor air quality issues and are stipulated by ASHRAE Standard 62, the strength of pollutant sources within enclosures and/or authorities having jurisdiction.

Relative humidity should be maintained at 45% or lower at 70°F (21.1°C) within the conditioned spaces during the heating months and be maintained at 60% or lower at 75°F (23.8°C) within the conditioned spaces during the cooling months (the key is to prevent 70% relative humidities from occurring adjacent to surfaces in order to control mold, mildew, and other biological growth). Humidity control within conditioned spaces is accomplished during heating periods by the dilution of interior moisture (air change) along with controlled mechanical ventilation and source control. During cooling periods, humidity is controlled by the dehumidification capabilities of air-conditioning systems and source control. Since latent cooling loads on air-conditioning systems can be higher than sensible cooling loads, proper sizing of air-conditioning systems with consideration of dehumidification capabilities is important. Oversizing of air-conditioning equipment can lead to high interior humidity problems due to a lack of dehumidification capability (oversized air-conditioning equipment will not operate as often and therefore will dehumidify less than properly sized equipment).

Mechanical System Concerns

Ductwork for forced-air heating and cooling systems should be installed within conditioned spaces where possible. Ductwork located in attics or vented crawl spaces must be air sealed with mastic (tapes are ineffective). During hot, humid cooling periods, leaky return ducts located in attics draw significant amounts of warm, moisture-laden air into the conditioned space from the attic, often creating moisture problems and increasing cooling loads. During heating periods these same, leaky return ducts draw cold air into the conditioned space, increasing heating loads. Leaky return ducts located in vented crawl spaces draw significant amounts of soil gas, moisture, possibly pesticides, radon, and other pollutants into the conditioned spaces, often creating moisture problems and increasing cooling loads during cooling periods and heating loads during heating periods as well as risking occupant health and safety.

Leaky supply ducts located in attics or vented crawl spaces during cooling periods lead to the depressurization of the conditioned space, leading to the infiltration of exterior warm moisture-laden air often creating moisture problems and increasing cooling loads. During heating periods the same mechanism can deposit sufficient interior moisture into attic assemblies, leading to roof sheathing moisture and decay problems as well as uncontrolled depressurization of the conditioned space, leading to infiltration and thereby increasing heating loads.

Most air-conditioned enclosures in mixed climates have a preponderence of supply leaks (leaky supply ductwork located in attics). This coupled with a minimal return air system (a single return is common) leads to significant depressurization of most of the common areas of the house and corresponding moisture problems due to the infiltration of hot, humid air. Bedrooms, especially the master bedroom suite, are typically pressurized when bedroom doors are closed as they typically have only supply air registers located within them. The pressurization of the bedrooms leads to the depressurization of the other areas of the enclosure. To prevent these air pressure extremes, multiple return air registers and/or air transfer grills are recommended. Additional returns in master bedroom suites coupled with transfer grills located in bedroom/hallway partition walls have proven successful.

Where duct work is located in dropped ceilings adjacent to attics and exterior walls, it is important that air barrier continuity is maintained above the dropped ceiling or at the exterior wall.

Air-conditioning supply air registers should be located such that cold air is not blown directly across wall and ceiling surfaces, potentially chilling the surfaces below dew point temperatures and leading to condensation or to high-surface relative humidities and potential mold and mildew growth.

Air-conditioning supply ductwork should be insulated and protected with an exterior vapor diffusion retarder to control condensation on cold duct surfaces.

Cold water piping may need to be insulated if exposed to warm, humid air during the cooling season.

Combustion Appliances

Unvented combustion appliances such as gas stoves with standing pilot lights and room space heaters are significant sources of moisture as well as sources for other pollutants and should be avoided. Gas stoves and cook tops without standing pilot lights should be installed in conjunction with vented range hoods or some other vent provision.

Where vented combustion appliances are installed, they should be uncoupled (not influenced by enclosure air pressures or supply air availability) from the conditioned space. In other words, sealed combustion, power-vented, induced draft, condensing, or pulse combustion devices should be used. Devices with traditional draft hoods should be avoided. Where fireplaces are installed, they should have their own supply of air from the exterior as well as tight-fitting glass doors. Wood stoves should also have their own supply of exterior air ducted directly to their firebox.

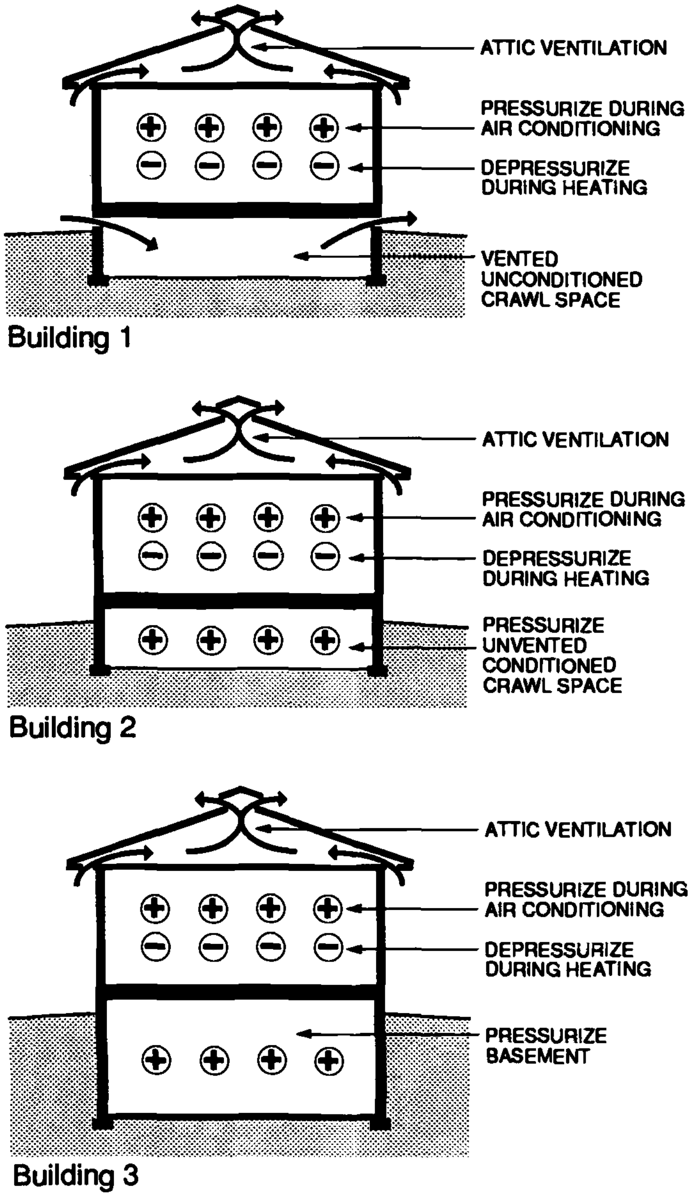


FIG. 2—Whole house concepts for mixed climates.

Whole Building Systems

Three examples of desirable whole building systems for this climate zone are (Fig. 2):

- buildings built with vented, unconditioned crawl spaces and vented attics (ductwork located in attic spaces air sealed with mastic; air handlers located within conditioned spaces)
- buildings with unvented, conditioned crawl spaces and vented attics (ductwork located within the conditioned crawl space)
- buildings with basements and vented attics (ductwork located completely within conditioned space)

Common features of the three systems are basement spaces and crawl spaces maintained at a positive air pressure to the exterior. Above-grade spaces are maintained at a negative air pressure to the exterior during heating periods and at a positive air pressure to the exterior during cooling periods. Vented roofs are also common to the three systems.

Positive pressurization of the basement spaces and crawl spaces eliminates the infiltration of soil gas, radon, and other pollutants. Depressurization of the above-grade conditioned spaces during heating periods eliminates the exfiltration of interior moisture-laden air, and pressurization of the above-grade conditioned spaces during cooling periods eliminates the infiltration of exterior moisture-laden air.

Ventilation of roof assemblies removes moisture continuously during heating months and intermittently during cooling months.

Wall design and construction in this climate locates vapor diffusion retarders and measures to control air leakage towards both the exterior and interior. In this climate it is convenient to allow walls to dry to either the interior or to the exterior.

MOISTURE CONTROL PRACTICES FOR COOLING CLIMATES

A cooling climate is a warm, humid climate with a significant number of cooling (air-conditioning) hours. It generally follows the ASHRAE definition [*10*] of a humid climate where one or both of the following conditions occur:

1. A 67°F (19.4°C) or higher wet-bulb temperature for 3000 or more hours during the warmest six consecutive months of the year.
2. A 73°F (22.8°C) or higher wet-bulb temperature for 1500 or more hours during the warmest six consecutive months of the year.

The climate zone specified is broad and general for simplicity. Specific microclimates should always be considered. Incident solar radiation, nearby water and wetlands, and vegetation and undergrowth all affect the microclimate of a building assembly. For any specific location, designers and builders should consult weather records. Fringe areas of the ASHRAE humid-climate definition are also included based on local experience with moisture problems.

Key Concerns and Control Strategies

In cooling climates, the principal moisture concerns are rain penetration, groundwater, and mold and mildew. High exterior levels of humidity encourage mold and mildew growth, as do cool interior surfaces due to the air conditioning of enclosures.

In cooling climates, wetting from the exterior during the cooling season by air movement is a major concern. In cooling climates, building envelopes are constructed in an airtight manner to control air leakage openings, to expedite air pressure control (pressurization of the building envelope during the cooling season), and to facilitate the dehumidification of indoor air, thereby limiting interior moisture levels. Controlled ventilation is also necessary to provide for the dilution of interior pollutants by controlled air change.

Vapor diffusion from the exterior is also a concern in cooling climates. Accordingly, vapor diffusion retarders in cooling climates are located towards the exterior and walls, and other building assemblies are designed and built to dry to the interior.

The absence of ground frost penetration concerns in this climate zone has led to a preponderance of crawl space and ground slab construction. Basement foundations are rare, if not completely nonexistent. Both frame walls and masonry walls are common.

Rain and Groundwater

Rain penetration and groundwater concerns are common to builders in all climates, and the methods of control are similar in this climate to those of other climates, notably the use of the rain screen, building papers, appropriate placement of flashings, gutters, and downspouts which direct water away from foundations, and careful site grading and subgrade drainage.

Another source of external water, air-conditioning condensate drains, should be plumbed directly to the graywater system.

Moisture Within Building Assemblies

Cladding systems which can absorb significant amounts of moisture when exposed to rain—such as brick, masonry, wood and stucco—should only be incorporated in certain wall assemblies. Such assemblies are designed and built to deal with the inward migration of moisture driven by temperature gradients from the exterior to the interior. Solar radiation warming exterior wall surfaces creates these gradients, along with the air conditioning of interior surfaces. Problems often arise where this is not taken into account, such as the installation of vinyl wallpaper–covered gypsum wall board on the interior of a masonry block wall without provision for an appropriate vapor diffusion retarder and air retarder system located to the interior of the wall assembly. The vapor diffusion retarder and air retarder system protect the gypsum wall board from this exterior moisture or from construction moisture which may be trapped in the masonry units.

Vinyl interior wall coverings are not exclusive to masonry or concrete wall systems and are also used with wood frame construction. Thus, wherever vinyl interior wall coverings are used in this climate zone, precautions must be taken to prevent the absorption of moisture by gypsum wall board from the exterior or from the moisture of construction.

Where wet masonry, wet lumber (greater than 19% moisture content by weight), or wet-applied insulations (wet spray cellulose or wet-blown fiberglass) are installed in building assemblies, those assemblies must be designed and built in such a manner that they can dry to either the interior or exterior or the materials must be allowed to dry prior to enclosure.

High Interior Humidity Resulting in Mold and Surface Condensation

The practice of mechanical cooling coupled with some dehumidification for comfort reasons is widespread. This gives rise to continuous moisture flow by air leakage and vapor diffusion from the exterior to the interior-cooled area as a result of a higher outdoor vapor pressure than indoor vapor pressure. The outdoor-to-indoor vapor pressure differences in humid climates are typically much greater than the vapor pressure differences in cold climates.

The impacts of this high inward flow of moisture are manifested as elevated energy costs due to high cooling loads, building fabric deterioration from decay and corrosion, and health and safety concerns from mold and mildew growth.

Moisture movement by air leakage (the infiltration of exterior moisture laden air) is controlled by limiting air leakage openings, maintaining a positive air pressure within conditioned spaces relative to the exterior (pressurization), and by locating forced-air ductwork within conditioned spaces where possible coupled with duct air sealing, transfer grills, and multiple returns to limit the effects of duct leakage and depressurization.

Moisture movement by vapor diffusion from the exterior is controlled by the use of vapor diffusion retarders in walls, roofs, and crawl spaces.

High air change due to infiltration/exfiltration, duct leakage, and excessive ventilation can lead to elevated interior levels of moisture. This is contrary to heating climates, where the same mechanisms lead to low levels of interior moisture. This is due to the high exterior humidity conditions which occur for most of the year in warm, humid climates. The greater the amount of exterior air brought into an enclosure, the greater the amount of moisture brought in with it. As such, in warm, humid climates it is desirable to build tight enclosures and to ventilate these enclosures with outside air at a minimum, controlled rate. Minimum ventilation rates typically are established by indoor air quality issues and are stipulated by ASHRAE Standard 62, the strength of pollutant sources within enclosures and/or authorities having jurisdiction.

Relative humidity should be maintained at 60% or lower at 75°F (23.8°C) within the conditioned spaces during cooling periods (the key is to prevent 70% relative humidities from occurring adjacent to surfaces in order to control mold, mildew, and other biological growth). Humidity control within conditioned spaces is accomplished by the dehumidification capabilities of air-conditioning systems and source control.

Latent cooling loads on air-conditioning systems can be higher than sensible cooling loads in these climates. As such, proper sizing of air-conditioning systems with consideration of dehumidification capabilities is important. Oversizing of air-conditioning equipment can lead to high interior humidity problems due to a lack of dehumidification capability (oversized air-conditioning equipment will not operate as often and therefore will dehumidify less than properly sized equipment). Source control typically involves direct venting of clothes dryers, bath, and kitchen exhaust systems as well as the use of crawl space ground covers and subslab vapor diffusion retarders.

Mechanical System Concerns

Ductwork for forced-air heating and cooling systems should be installed within conditioned spaces where possible. Ductwork located in attics or vented crawl spaces must be air sealed with mastic (tapes are ineffective). Leaky return ducts located in attics draw significant amounts of warm, moisture-laden air into the conditioned space from the attic, often creating moisture problems and increasing cooling loads. Leaky return ducts located in vented crawl spaces draw significant amounts of soil gas, moisture, possibly pesticides, radon, and other pollutants into the conditioned spaces, often creating moisture problems, increasing cooling loads, and risking occupant health and safety. Leaky supply ducts located in attics or vented crawl spaces lead to the depressurization of the conditioned space, which leads to the infiltration of exterior warm, moisture-laden air that often creates moisture problems and increases cooling loads.

Most enclosures in cooling climates have a preponderance of supply leaks (leaky supply ductwork located in attics). This coupled with a minimal return air system (a single return is common) leads to significant depressurization of most of the common areas of the house and corresponding moisture problems due to the infiltration of hot, humid air. Bedrooms, especially the master bedroom suite, are typically pressurized when bedroom doors are closed, as they typically have only supply air registers located within them. The pressurization of the bedrooms leads to the depressurization of the other areas of the enclosure. To prevent these air pressure extremes, multiple return air registers and/or air transfer grills are recommended. Additional returns in master bedroom suites coupled with transfer grills located in bedroom/hallway partition walls have proven successful.

Where duct work is located in dropped ceilings adjacent to attics and exterior walls, it is important that air barrier continuity is maintained above the dropped ceiling or at the exterior wall.

Air-conditioning supply air registers should be located such that cold air is not blown directly across wall and ceiling surfaces, potentially chilling the surfaces below dew point temperatures, leading to condensation or to high-surface relative humidities and potential mold and mildew growth.

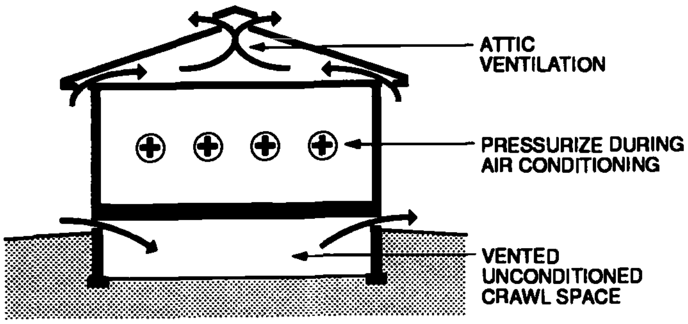
Air-conditioning supply ductwork should be insulated and protected with an exterior vapor diffusion retarder to control condensation on cold duct surfaces.

Cold water piping may need to be insulated if exposed to warm, humid ambient or nonconditioned air.

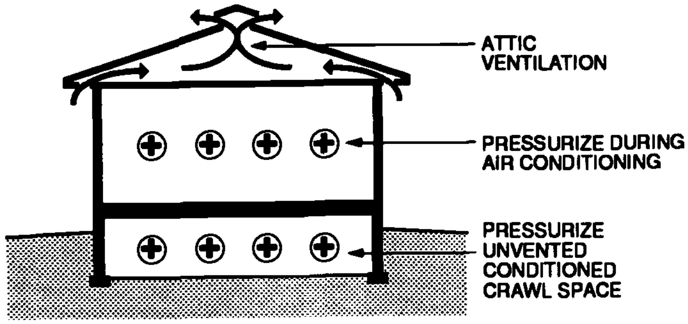
Combustion Appliances

Unvented combustion appliances such as gas stoves with standing pilot lights and room space heaters are significant sources of moisture as well as sources for other pollutants and should be avoided. Gas stoves and cook tops without standing pilot lights should be installed in conjunction with vented range hoods or some other vent provision.

Where vented combustion appliances are installed, they should be uncoupled (not influenced by enclosure air pressures or supply air availability) from the conditioned space. In other words, sealed combustion, power-vented, induced draft, condensing, or pulse combustion devices should be used. Devices with traditional draft hoods should be avoided. Where fireplaces are installed, they should have their own supply of air from the exterior as well as tight-fitting glass doors. Wood stoves should also have their own supply of exterior air ducted directly to their firebox.



Building 1



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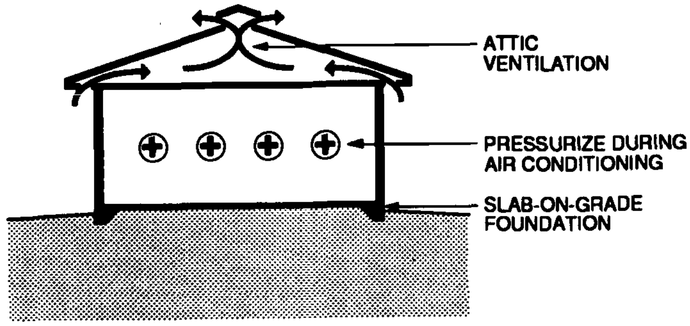

Building 3

FIG. 3—Whole house concepts for cooling climates.

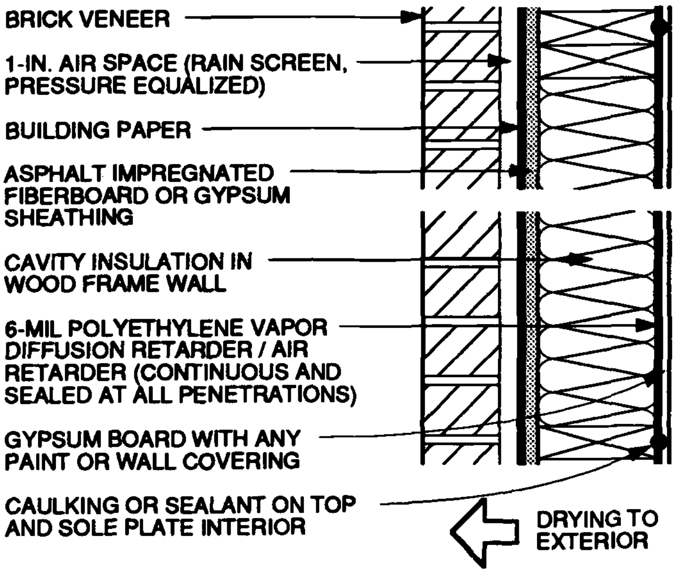

FIG. 4—Heating climate wall construction—brick veneer with permeable sheathing.

Whole Building Systems

Three typical whole building systems for this climate zone, listed in the order of most successful moisture performance, are (Fig. 3):

- buildings with vented, unconditioned crawl spaces and vented attics (ductwork located in attic spaces air sealed with mastic; air handlers located within conditioned spaces)
- buildings with unvented, conditioned crawl spaces and vented attics (ductwork located within the conditioned crawl space)
- buildings built on ground slabs with vented attics (ductwork located in attic spaces air sealed with mastic; air handlers located within conditioned spaces)

Common features of the three systems are vented roofs and conditioned spaces maintained at a positive air pressure to the exterior.

Ductwork in slabs should be avoided to minimize potential problems with soil gas entry (radon, moisture, pesticides, herbicides, and other ground-based pollutants). Ductwork in vented, unconditioned crawl spaces should be avoided for similar reasons.

Buildings with unvented, conditioned crawl spaces treat the crawl space as if the crawl space were part of the living area, connecting (coupling) the crawl space to the living area.

Positive air pressurization of the conditioned spaces eliminates the infiltration of exterior moisture-laden air. Positive pressurization of conditioned crawl spaces eliminates the infiltration of soil gas, radon, and other pollutants.

Ventilation of roof assemblies reduces cooling loads.

Wall design and construction in this climate typically locates vapor diffusion retarders and measures to control air leakage towards the exterior. In this climate it is convenient to allow walls to dry to the interior in the direction of typical vapor flow. Drying to the exterior is possible, but more difficult to facilitate and usually intermittent.

HEATING CLIMATE WALL CONSTRUCTION, BRICK VENEER, PERMEABLE SHEATHING (FIG. 4)

Rain

Rain penetration in this wall assembly is controlled by the application of the rain screen principle [*11*]. This is accomplished in this example by installing a brick veneer over a minimum 1-in. (2.54-cm) airspace. This air space must be clear of mortar droppings and should be open at the top of the brick veneer wall as well as vented at its base. Such brick veneer walls should be vented at their base by leaving every other vertical mortar joint in the first course of brick open. These vertical, open joints serve two functions: first, to allow inward air movement to facilitate pressure equalization and, second, to provide a weep or drainage function. For pressure equalization in the cavity to occur, the sheathing must be significantly "tighter" than the cladding. This is accomplished by installing the asphalt impregnated fiberboard or gypsum sheathing in an airtight manner (vertically, with all joints falling on framing members, with the option of utilizing a sealant or adhesive at sheathing joints/edges) and by deliberately making the brick veneer "leaky" by installing it over an air space which is open at the bottom by the use of open vertical masonry joints and open at the top by the use of similar openings or by venting the air space into a soffit assembly. Further tightening of the sheathing relative to the brick veneer is sometimes accomplished by the installation of a building paper in a continuous manner. Appropriate installation of flashings over window and door openings are critical in rain screen assemblies and must extend to the back of the air space, ideally "tucking" in behind sheathings or building papers. Flashings at the base of brick veneer walls are also critical so that cavity moisture can be directed to the exterior through the weep holes under the influence of gravity. These base flashings must also extend to the back of the rain screen cavity.

Rain Absorption/Capillary Suction

Rain absorption by the brick veneer and brick veneer capillarity effects are controlled by the provision of an air space behind the brick veneer which acts as a receptor for both brick veneer capillary moisture and brick veneer–absorbed moisture driven inward by incident solar radiation. A building paper is installed in some assemblies to limit absorption of rain by the asphalt-impregnated fiberboard or gypsum sheathing. In such cases a vapor-permeable, nonabsorptive building paper is desirable.

Air Movement

Air-transported moisture from the interior (exfiltration of warm, moisture-laden interior air during the heating season) is controlled by providing an air seal (air retarder) at either the interior or exterior of the wall. This is facilitated in this wall assembly by either sealing the interior gypsum wall board or polyethylene vapor diffusion retarder to the wall framing or by sealing the exterior sheathing to the wall framing. This air sealing can be accomplished with adhesive, caulk, or some other sealant. An exterior air seal at the asphalt-impregnated fiberboard sheathing in this example also facilitates pressure equalization of the exterior cladding. Exterior air seals are typically accomplished in this example by installing a continuous exterior building paper (vapor permeable and nonabsorptive is desirable).

Vapor Diffusion

Vapor diffusion from the interior during heating periods is controlled by installing a vapor diffusion retarder at the interior of the wall. In this example, a continuous polyethylene sheet is installed between the interior gypsum board and the wall framing and acts as the vapor diffusion retarder.

Vapor diffusion from the exterior in this wall assembly during cooling periods (and under the action of incident solar radiation) is controlled by installing a vapor diffusion retarder at the interior of the wall assembly between the wall framing and the interior gypsum board. Although installing a vapor diffusion retarder at this location in this climate does not prevent moisture movement by vapor diffusion from entering the wall, the vapor diffusion retarder effectively protects the interior gypsum board and any interior finishes from moisture damage. This interior vapor diffusion retarder can get wet on the cavity side during the day as a result of exterior-absorbed moisture in the brick veneer driven inward by incident solar radiation and the air-conditioned interior. This moisture then typically migrates outward in the evening when the temperature gradient reverses. This wall assembly in this climate can get intermittently wet from the exterior as well as dry intermittently to the exterior. Since intermittent wetting of the vapor diffusion retarder may occur in this assembly, this interior vapor diffusion retarder should be continuous to provide satisfactory performance. Foil-backed interior gypsum board may not be effective due to discontinuities at joints. Foil-backed cavity insulation also may not be effective for the same reason. A continuous polyethylene vapor diffusion retarder has proven to be effective in this type of assembly.

Comments

Wall drying towards the exterior in this wall assembly is facilitated by installing a vapor-permeable sheathing on the exterior of the wall framing along with an air space between the cladding (brick veneer), the sheathing to act as a receptor for interior cavity moisture. Should the wall assembly become wet during service or be built initially wet through the use of wet framing materials or the use of wet-applied cavity insulations (wet spray cellulose or blown fiberglass), it can dry to the exterior into the air space behind the brick veneer during the heating season or during evenings.

Either vapor-permeable or vapor-impermeable surface finishes may be used in conjunction with this wall assembly.

HEATING CLIMATE WALL CONSTRUCTION, VINYL/ALUMINUM SIDING, IMPERMEABLE SHEATHING (FIG. 5)

Rain

Rain penetration in this wall assembly is controlled by the application of the rain screen principle.

Rain Absorption/Capillary Suction

Rain absorption by the vinyl or aluminum siding and siding capillarity effects are not a concern in this wall assembly as a result of the inherent material properties of the vinyl and aluminum. A building paper, installed only to protect the impermeable rigid insulation from water absorption, is not required in this assembly for the same reason.

Air Movement

Air-transported moisture from the interior (exfiltration of warm moisture-laden interior air during the heating season) is controlled by providing an air seal (air retarder) at either the interior or exterior of the wall.

Vapor Diffusion

Vapor diffusion from the interior during heating periods is controlled by installing a vapor diffusion retarder at the interior of the wall.

Accumulation of moisture within the wall assembly transported by vapor diffusion from the interior during heating periods is also controlled by elevating the temperature of the first condensing surface within the wall assembly, namely the cavity side of the exterior sheathing. This is accomplished in this example by installing an insulating sheathing which limits periods of potential condensation.

Comments

In this wall assembly, drying towards either the interior or exterior is limited by virtue of the installation of a vapor-

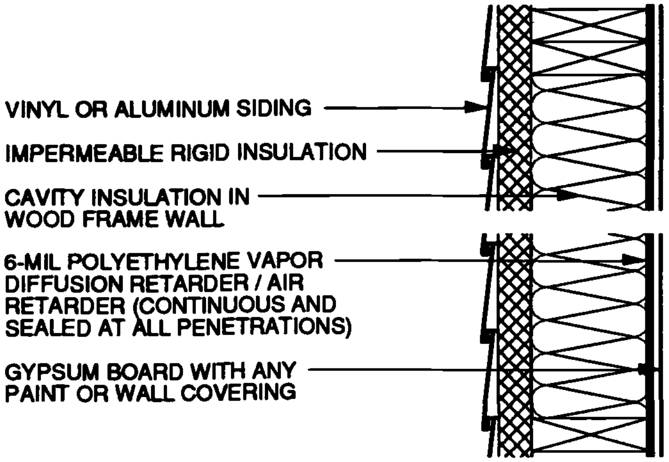

FIG. 5—Heating climate wall construction—vinyl/aluminum siding with impermeable sheathing.

impermeable exterior sheathing and an interior vapor diffusion retarder.

If the wall assembly is built initially wet through the use of wet framing materials or the use of wet-applied cavity insulations (wet spray cellulose or blown fiberglass), it may not dry. Accordingly, dry framing materials (wood at a moisture content of 19% by weight or lower) and dry-applied insulations are recommended; alternatively, wall assemblies must be allowed to dry prior to enclosure.

Interior moisture levels should be limited to 35% relative humidity at 70°F (21.1°C) during heating periods to further facilitate the control of air-transported moisture and vapor diffusion with this wall assembly since only limited drying of the assembly occurs.

Either vapor-permeable or vapor-impermeable surface finishes may be used in conjunction with this wall assembly.

MIXED CLIMATE WALL CONSTRUCTION, VINYL/ALUMINUM SIDING, PERMEABLE SHEATHING (FIG. 6)

Rain

Rain penetration in this wall assembly is controlled by the application of the rain screen principle.

Rain Absorption/Capillary Suction

Rain absorption by the exterior asphalt-impregnated fiberboard or gypsum sheathing and capillarity effects are controlled by the installation of a building paper. In this assembly, a vapor-permeable, nonabsorptive building paper is desirable.

Air Movement

Air-transported moisture from either the exterior (infiltration of warm, humid air during the cooling season) or from the interior (exfiltration of warm, moisture-laden interior air during the heating season) is controlled by providing an air seal (air retarder) at either the interior or exterior of the wall.

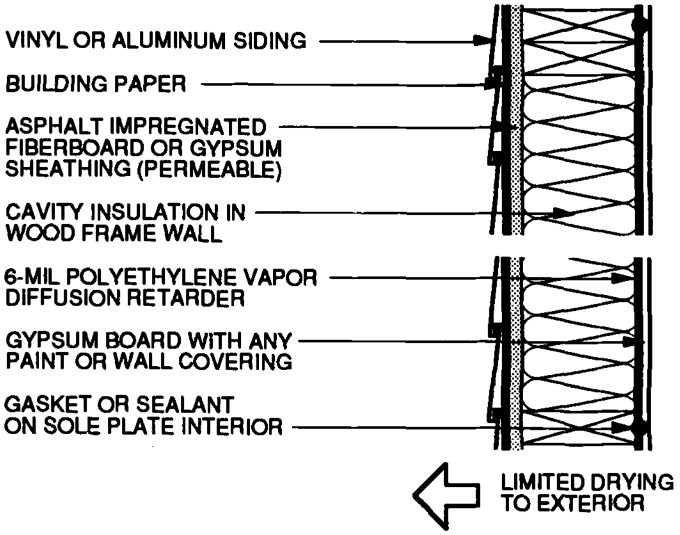

FIG. 6—Mixed climate wall construction—vinyl/aluminum siding with permeable sheathing.

Vapor Diffusion

Vapor diffusion from the exterior in this wall assembly during cooling periods is controlled by installing a vapor diffusion retarder at the interior of the wall assembly between the wall framing and the interior gypsum board. Although installing a vapor diffusion retarder at this location in this climate does not prevent moisture movement by vapor diffusion from entering the wall from the exterior, the vapor diffusion retarder effectively protects the interior gypsum board and any interior finishes from moisture damage as well as reducing the latent cooling load of the structure. This interior vapor diffusion retarder can get wet on the cavity side during the day as a result of exterior-absorbed moisture in the fiberboard or gypsum sheathing drive inward by incident solar radiation. This moisture then typically migrates outward in the evening when the temperature gradient reverses. This wall assembly in this climate can get intermittently wet from the exterior as well as dry intermittently to the exterior. Since intermittent wetting of the vapor diffusion retarder may occur in this assembly, this interior vapor diffusion retarder should be continuous to provide satisfactory performance. Foil-backed interior gypsum board may not be sufficiently effective due to discontinuities at joints. Foil-back insulation batts may not be effective for the same reason. A continuous polyethylene vapor diffusion retarder has proven to be effective in this type of assembly.

Vapor diffusion from the interior during heating periods is controlled by installing a vapor diffusion retarder at the interior of the wall. In this example, a continuous polyethylene sheet is installed between the interior gypsum board and the wall framing and acts as the vapor diffusion retarder.

Comments

In this wall assembly, drying towards the exterior through the vapor-permeable exterior sheathing (asphalt-impregnated fiberboard or gypsum board) occurs but is limited somewhat by the installation of a vapor-impermeable exterior cladding (vinyl or aluminum siding). Drying towards the interior is limited by virtue of the installation of an interior vapor diffusion retarder. Should the wall assembly become wet during service or be built initially wet through the use of wet framing materials or the use of wet-applied cavity insulations (wet spray cellulose or blown fiberglass), the wall assembly will dry to the exterior. However, the rate of drying may not be sufficient to prevent the occurrence of problems. Local experience may provide guidance. In the absence of prior experience or local historical experience, it may be desirable to use dry framing materials (wood at a moisture content of 19% by weight or lower) and dry-applied insulations. Alternatively, wall assemblies could be allowed to dry prior to enclosure.

Either vapor-permeable or vapor-impermeable surface finishes may be used in conjunction with this wall assembly.

MIXED CLIMATE WALL CONSTRUCTION, VINYL/ALUMINUM SIDING, IMPERMEABLE SHEATHING (FIG. 7)

Rain

Rain penetration in this wall assembly is controlled by the application of the rain screen principle.

Rain Absorption/Capillary Suction

Rain absorption by the vinyl or aluminum siding and siding capillarity effects are not a concern in this wall assembly as a result of the inherent material properties of the vinyl and aluminum. A building paper, installed only to protect the impermeable rigid insulation from water absorption, is not required in this assembly for the same reason.

Air Movement

Air-transported moisture from either the exterior (infiltration of warm humid air during the cooling season) or from the interior (exfiltration of warm moisture laden interior air during the heating season) is controlled by providing an air seal (air retarder) at either the interior or exterior of the wall.

Vapor Diffusion

Vapor diffusion from the exterior during cooling periods is controlled by installing a vapor diffusion retarder on the exterior of the wall. In this example, an impermeable rigid insulation is installed as the exterior wall sheathing and acts as the exterior vapor diffusion retarder.

Accumulation of moisture within the wall assembly transported by vapor diffusion from the interior during heating periods is controlled by elevating the temperature of the first condensing surface within the wall assembly, namely the cavity side of the exterior sheathing. This is accomplished in this example by installing an insulating sheathing of sufficient thermal resistance to limit periods of potential condensation to acceptable levels. An acceptable period of potential condensation would be a period sufficiently brief that does not allow wood decay to commence or interior surface water stain marks or mold or mildew to appear. The period of potential condensation of a wall assembly is determined by the temperature of the first condensing surface and the interior moisture level. The temperature of the first condensing surface during the heating period in this wall assembly is determined by the ratio of the amount of thermal insulation installed to the exterior of the condensing surface compared to the amount of thermal insulation installed to the interior of the condensing surface. For this wall assembly in this climate zone, the thermal resistance of insulating sheathings should be R-7 or greater, and the thermal resistance of cavity insulation should be R-11 or less, where an interior vapor diffusion retarder is not utilized. Furthermore, interior moisture levels during heating periods should be limited to 45% relative humidity at 70°F (21.1°C) [*12*].

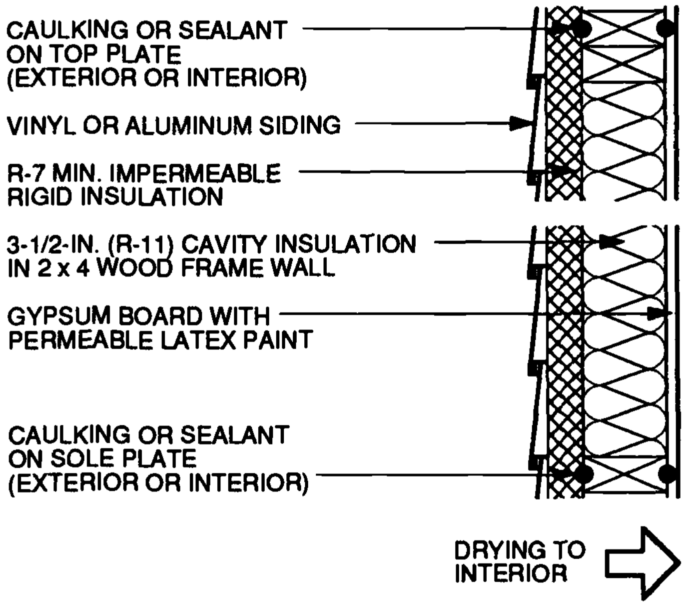

FIG. 7—Mixed climate wall construction—vinyl/aluminum siding with impermeable sheathing.

Comments

Wall drying towards the interior in this wall assembly is facilitated by installing a vapor-permeable paint finish on the interior gypsum wall board. Should the wall assembly become wet during service or be built initially wet through the use of wet framing materials or the use of wet-applied cavity insulations (wet spray cellulose or blown fiberglass), it can dry to the interior due to an inward temperature and vapor pressure gradient present as a result of air conditioning the enclosure during the cooling season and ambient climatic conditions during the spring and fall.

Interior moisture levels should be limited to 45% relative humidity at 70°F (21.1°C) during heating periods to further facilitate the control of air-transported moisture and vapor diffusion with this wall assembly since limited drying of the assembly can only occur to the interior.

The facing material on faced cavity insulations installed with the facing towards the interior of the wall in this climate can serve to retard drying to the interior. Faced cavity insulations can be installed where drying to the interior is not required, or, alternatively, the cavity insulation can be installed with the facing material towards the outside of the cavity.

The facing material on faced cavity insulations installed with the facing towards the interior of the wall in this wall assembly can also act as an interior vapor diffusion retarder, depending on the permeance of the facing material. An interior vapor diffusion retarder would significantly reduce the potential for condensation on the cavity side of the exterior insulating sheathing during the heating season and therefore reduce the amount of thermal resistance of the insulating sheathing needed for limiting wetting potentials. However, this same interior vapor diffusion retarder would also significantly reduce drying to the interior should it be required.

In cases where impermeable surface treatments are utilized, such as wall coverings and impermeable paints, or where interior vapor diffusion retarders are installed (faced cavity insulations or sheet polyethylene), dry framing materials (wood at a moisture content of 19% by weight or lower) and dry-applied insulations are recommended, or, alternatively, wall assemblies must be allowed to dry prior to enclosure.

Where wall assemblies with permeable interior surface treatments have been performing satisfactorily in service and are subsequently covered with impermeable interior surface treatments (repainting with impermeable paints or wall coverings by new or subsequent owners or tenants), mold and mildew problems may appear at the gypsum board/surface treatment interface if the previously mentioned moisture control strategies have not been effectively utilized.

COOLING CLIMATE WALL CONSTRUCTION, WOOD-BASED SIDING, IMPERMEABLE SHEATHING (FIG. 8)

Rain

Rain penetration in this wall assembly is controlled by the application of the rain screen principle where vinyl or aluminum siding is used and the barrier approach where wood-based siding is used. The rain screen principle requires a pressure-equalized cavity behind the cladding to perform satisfactorily. This is accomplished in this example by installing vinyl or aluminum siding over a "tight" sheathing. Cavities are created behind the vinyl or aluminum siding as a result of the siding cross sections themselves (cross sections which are filled with insulation material or support material are not recommended). For pressure equalization in these cavities to occur, the exterior sheathing must be significantly "tighter" than the cladding. This is accomplished by installing the impermeable rigid insulation (the exterior sheathing in this example) in an airtight manner (vertically, with all joints falling on framing members, with the option of utilizing a sealant or adhesive at sheathing joints/edges). Alternatively, a building paper installed in a "tight" manner (lapped or taped joints) may be utilized to facilitate pressure equalization. Appropriate installation of flashings over window and door openings are critical in rain screen assemblies, ideally "tucking" in behind exterior sheathings or building papers. Where wood-based siding is used, tight sheathing and/or building paper provides the rain control.

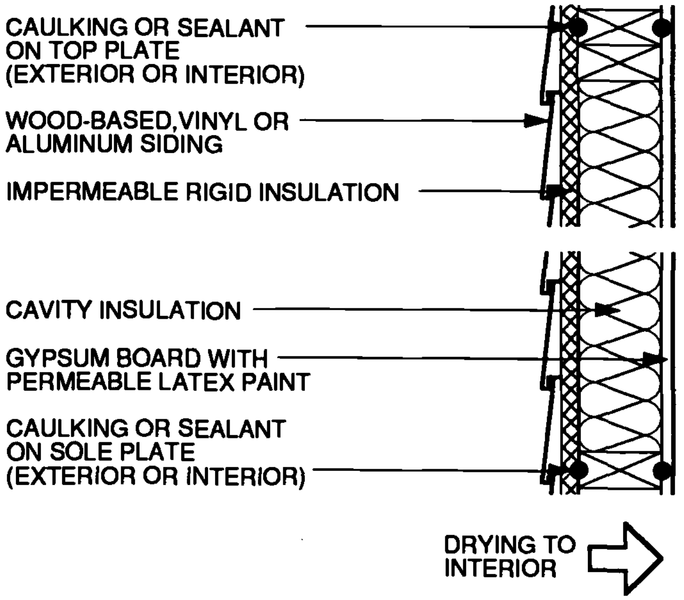

FIG. 8—Cooling climate wall construction—wood-based siding with impermeable sheathing.

Rain Absorption/Capillary Suction

Rain absorption by the vinyl or aluminum siding and siding capillarity effects are not a concern in this wall assembly as a result of the inherent material properties of the vinyl and aluminum. A building paper, installed only to protect the impermeable rigid insulation from water absorption, is not required in this assembly for the same reason.

Rain absorption by wood-based siding and siding capillarity effects are a potential concern if wood-based siding is used. Wood-based siding should be back primed with bottom edges carefully painted. Opening of the siding laps [⅜ in. (0.95 cm)] with spacers, wedges, clips, etc. should also be considered [*13*].

Air Movement

Airborne moisture from the exterior (infiltration of warm humid air during the cooling season) is controlled by providing an air seal (air retarder) at either the interior or exterior of the wall. In this example, this is facilitated by sealing either the exterior impermeable rigid insulation to the wall framing or by sealing the interior gypsum wall board to the wall framing. This air sealing can be accomplished with adhesive, caulk, or some other sealant. An exterior air seal at the exterior rigid insulation in this example also facilitates pressure equalization of vinyl or aluminum siding itself.

Vapor Diffusion

Vapor diffusion from the exterior is controlled by installing a vapor diffusion retarder on the exterior of the wall. In this example, an impermeable rigid insulation is installed as the exterior wall sheathing and acts as the vapor diffusion retarder.

Comments

Wall drying towards the interior in this wall assembly is facilitated by installing a vapor-permeable paint finish on the interior gypsum wall board. Should the wall assembly become wet during service or be built initially wet through the use of wet framing materials or the use of wet-applied cavity insulations (wet spray cellulose or blown fiberglass), it can dry to the interior due to an inward temperature and vapor pressure gradient present as a result of air conditioning the enclosure and ambient climatic conditions.

The facing material on faced cavity insulations installed with the facing towards the interior of the wall in this climate can serve to retard drying to the interior. Faced cavity insulations can be installed where drying to the interior is not required, or, alternatively, the cavity insulation can be installed with the facing material towards the outside of the cavity.

In cases where impermeable surface treatments are utilized, such as wall coverings and impermeable paints, dry framing materials (wood at a moisture content of 19% by weight or lower) and dry-applied insulations are recommended, or, alternatively, wall assemblies must be allowed to dry prior to enclosure.

Where wall assemblies with permeable interior surface treatments have been performing satisfactorily in service and are subsequently covered with impermeable interior surface treatments (repainting with impermeable paints or wall coverings by new or subsequent owners or tenants), mold and mildew problems may appear at the gypsum board/surface treatment interface if the previously mentioned moisture control strategies have not been effectively utilized.

COOLING CLIMATE WALL CONSTRUCTION, STUCCO CLADDING, INTERIOR IMPERMEABLE RIGID INSULATION (FIG. 9)

Rain

Rain penetration in this wall assembly is controlled by the application of the barrier approach or face-sealing. This approach requires the elimination of all exterior openings.

Rain Absorption/Capillary Suction

Rain absorption by the stucco cladding and stucco capillarity effects are controlled to a limited extent by the formulation and material properties of the stucco cladding itself.

Rain absorption by the stucco cladding and stucco capillarity effects can also be controlled by the application of exterior paint films and hydrophobic coatings. However, caution and judgment need to be exercised in the application of this control strategy since, although these coatings reduce rain absorption and capillarity, these same coatings also often retard the drying of the wall assembly to the exterior if it is getting wet through other mechanisms.

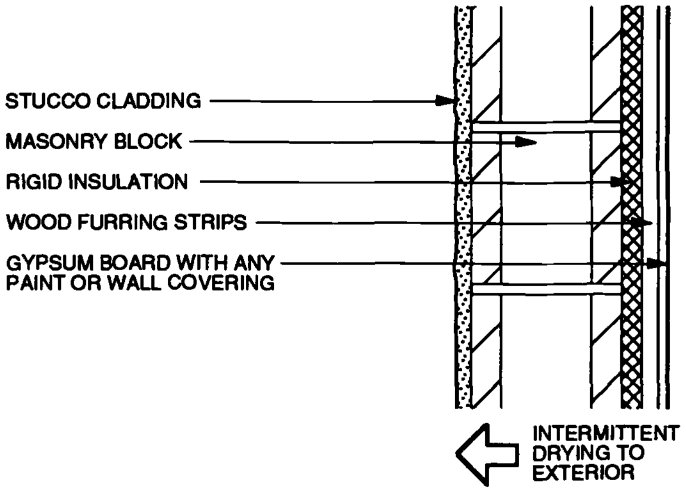

FIG. 9—Cooling climate wall construction—stucco cladding with impermeable rigid insulation on the interior.

Air Movement

Airborne moisture from the exterior (infiltration of warm, humid air during the cooling season) in this wall assembly can be controlled by the airtightness characteristics of the stucco cladding on the outside of the masonry block wall coupled with filling the upper course of masonry blocks with mortar and by sealing the rigid wall insulation and the ceiling gypsum board to this masonry block wall. Alternatively, the airtightness provisions of the wall assembly (air retarder system) may be located towards the interior of the assembly and consist of the rigid wall insulation installed in a continuous, taped manner and sealed to the ceiling vapor diffusion retarder.

Vapor Diffusion

Vapor diffusion from the exterior in this wall assembly is controlled by installing the rigid insulation, which acts as a vapor diffusion retarder at the interior surface of the masonry block wall. Although installing a vapor diffusion retarder at this location in this climate does not prevent moisture movement by vapor diffusion from entering the wall, the vapor diffusion retarder effectively protects the interior gypsum board and any interior finishes from moisture damage as well as reducing the latent cooling load of the structure.

Comments

In instances where the rigid insulation has been installed in a discontinuous manner or where it has been punctured (at electrical wall outlets), hot, humid exterior air has been shown to infiltrate down the masonry cavities and through the openings, leading to mold and mildew on the interior gypsum wall board. This mechanism of failure can be dramatically enhanced when the masonry wall is also saturated from rain penetration or construction moisture combined with an enclosure which is air conditioned (possibly under a slight negative air pressure due to poorly designed or installed HVAC systems) with incident solar radiation which serves to drive moisture inward. To reduce the migration of air down the masonry cavities, the upper course of blocks should be filled with mortar.

Intermittent wall drying towards the exterior in this wall assembly is facilitated by installing only vapor-permeable surface finishes on the stucco cladding. Should the wall assembly become wet during service or be built initially wet through the use of wet masonry blocks, it can dry intermittently to the exterior during cool weather or during evenings.

Wall drying towards the interior in this wall assembly from within the assembly is facilitated by installing a vapor-permeable paint finish on the interior gypsum wall board.

Where wall assemblies with permeable interior surface treatments have been performing satisfactorily in service and are subsequently covered with impermeable interior surface treatments (repainting with impermeable paints or wall coverings by new or subsequent owners or tenants), mold and mildew problems may appear at the gypsum board/surface treatment interface if the previously mentioned moisture control strategies have not been effectively utilized.

BASEMENT CONSTRUCTION (FIG. 10)

Rain and Groundwater

Rain and surface water should be prevented from entering basements by the use of gutters and downspouts along with careful site grading which direct water away from basement perimeters.

Surface water penetration into the ground immediately adjacent to basements is limited by using a "cap" of impermeable backfill material.

Groundwater entry into basements is controlled by a subgrade drainage system, namely a drain pipe located at the perimeter of the concrete footings coupled with "free-draining" backfill material. The drain pipe and the "free-draining" backfill material act together to provide a "drain screen." The drain pipe is connected to a sump, storm sewer, or to daylight. Perforations in the perimeter drain pipe should be installed "holes down" to allow groundwater to rise up into the drain pipe and be carried away. Coarse gravel should surround the perimeter drain pipe and in turn be surrounded by a filter fabric. Filter fabric should be located both below and above the perimeter drain pipe, as drain pipe perforations face down and often clog from underneath.

Capillary Suction

Moisture movement by capillarity into the concrete foundation wall is controlled by installing a dampproof coating on the exterior of the concrete foundation wall as well as installing a capillary break (dampproofing or polyethylene) over the top of the concrete footing. Alternatively, the footings can be constructed on a granular pad.

Moisture movement by capillarity into the concrete floor slab and into the underslab insulation is controlled by installing a granular capillary break under the slab [4 to 6-in.- (15.5 and 38.7-cm) thick layer of ¾-in. (1.90-cm) gravel with fines removed].

Moisture movement by capillarity from the moisture of construction contained in the perimeter concrete foundation wall into the sill/rim joist/floor assembly is controlled by installing a capillary break at the top of the perimeter concrete foundation wall.

Air Movement

In basement assemblies it is important to eliminate airflow between the surrounding soil and the basement space. Air-transported moisture infiltrating into the basement space is controlled by pressurizing the basement space relative to the surrounding soil and by limiting air leakage openings (tight construction).

Where perimeter concrete foundation walls are insulated on the interior, it is also important to prevent warm, interior, moisture-laden air from the basement space from coming in contact with cold, concrete surfaces during both heating and cooling periods.

Air leakage openings in this basement construction which deal with both exterior and interior moisture-laden air are limited by sealing the floor slab polyethylene vapor diffusion retarder to the foundation wall perimeter polyethylene vapor diffusion retarder. In addition, air leakage openings at the rim joist/floor assembly are controlled by sealing the joints of the elements which comprise the sill/rim joist/floor assembly. Tight-fitting faced batt insulation is installed at the interior of the rim joist assembly between floor joists. Gaps at this location in the batt insulation need to be minimized to control potential convective moisture transfer from the interior basement space to the interior surface of the rim joist. Pipe penetrations and electrical conduits through concrete floor slabs and perimeter concrete walls, floor drains, and sump openings are also sealed or closed with "tight" covers.

Vapor Diffusion

Moisture movement by vapor diffusion from the surrounding soil into the concrete foundation wall is controlled by installing a vapor diffusion retarder on the exterior of the concrete foundation wall. The dampproofing on the exterior of the concrete foundation wall acts as a vapor diffusion retarder.

Moisture movement by vapor diffusion from the surrounding soil into the concrete floor slab is controlled by installing a polyethylene vapor diffusion retarder under the concrete floor slab.

Moisture movement by vapor diffusion from the moisture of construction contained in the perimeter concrete foundation wall into the perimeter foundation frame wall cavity is controlled by installing dampproofing on the interior of the perimeter concrete foundation wall.

Moisture movement by vapor diffusion from the interior basement space into the perimeter foundation wall framing is controlled by installing a polyethylene vapor diffusion retarder on the interior of the perimeter foundation wall framing.

Moisture movement by vapor diffusion from the interior basement space into the perimeter rim joist assembly during the heating season is controlled by the facing on the batt insulation, which acts as a vapor diffusion retarder. Moisture accumulation from vapor diffusion migrating from within the interior basement space at the rim joist assembly is limited by installing insulating sheathing at the exterior of the rim joist, which serves to elevate the temperature of the first condensing surface at this location (the interior surface of the rim joist).

COMMENTS

In this perimeter foundation frame wall assembly, drying towards either the interior or exterior is limited by virtue of the impermeability of the perimeter foundation wall concrete and the interior polyethylene vapor diffusion retarder. Should the wall assembly become wet during service or be built initially wet through the use of wet framing materials or the use of wet-applied cavity insulations (wet spray cellulose or blown fiberglass), it may not dry. Accordingly, dry framing materials (wood at a moisture content of 19% by weight or lower) and dry-applied insulations are recommended, or, alternatively, wall assemblies must be allowed to dry prior to enclosure.

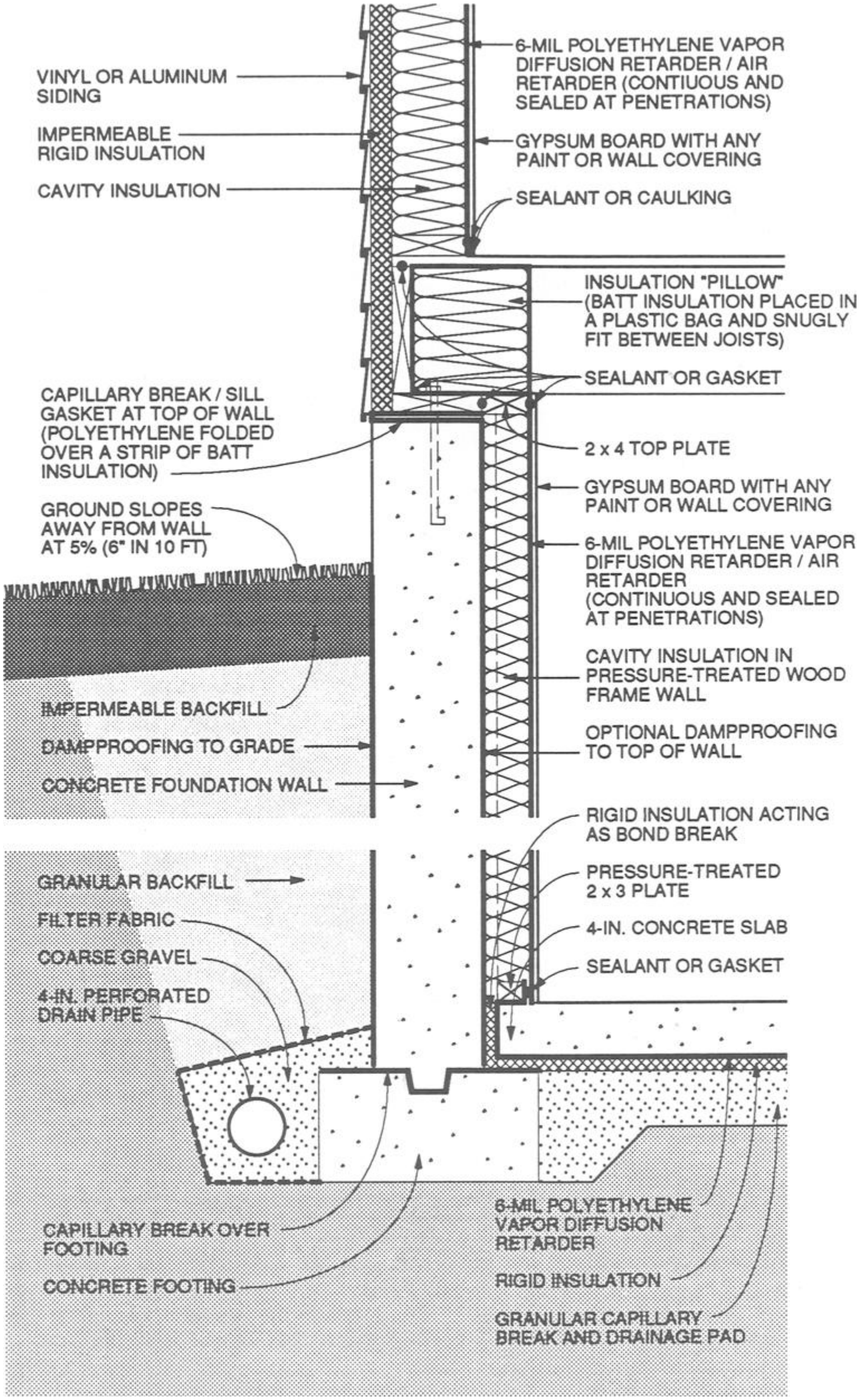

FIG. 10—Basement construction.

Interior basement space moisture levels should be limited to 35% relative humidity at 70°F (21.1°C) during heating periods to further facilitate the control of air-transported moisture and vapor diffusion with this wall assembly since only limited drying of the assembly occurs.

Either vapor-permeable or vapor-impermeable interior surface finishes may be used in conjunction with this foundation wall assembly.

The concrete floor slab contains significant quantities of moisture when initially placed. Covering this surface with an impermeable surface finish or floor covering may lead to deterioration of these surfaces if the moisture of construction is not allowed to dry. Initial drying of the moisture of construction contained in concrete may also lead to elevated interior moisture levels during the first few months of occupancy.

Installing carpets on cold, damp, concrete floor slabs can lead to serious allergenic reactions in sensitive individuals and other health-related consequences. It is not recommended that carpets be installed on concrete slabs unless the carpets can be kept dry and warm (that is, carpet relative humidities should be kept below 70%). In practice, this is typically not possible unless floor slab assemblies are insulated and basements areas are conditioned [*14*].

The granular drainage pad located under the basement concrete floor slab can be integrated into a subslab ventilation system to control radon migration by the addition of a vent pipe connected to the surface and an exhaust fan [*15*].

CRAWL SPACE CONSTRUCTION, VENTED/ UNCONDITIONED (FIG. 11)

Rain and Groundwater

Rain and surface water should be prevented from entering crawl spaces by the use of gutters and downspouts along with careful site grading which direct water away from crawl space perimeters.

Groundwater entry into the crawl space is controlled by subgrade drainage located at the perimeter of the concrete footing. The perimeter drain pipe is connected to a sump, storm sewer, or to daylight. Perforations in the perimeter drain pipe should be installed "holes down" to allow groundwater to rise up into the drain pipe and be carried away. Coarse gravel should surround the perimeter drain pipe and in turn be surrounded by a filter fabric. Filter fabric should be located both below and above the perimeter drain pipe, as drain pipe perforations face down and often clog from underneath.

A continuous vapor diffusion retarder, 6-mil or greater polyethylene, as a ground cover is essential to reduce moisture migration by evaporation from the soil into the crawl space.

Ventilation

Crawl space ventilation in vented crawl spaces is provided to remove moisture from crawl spaces and should be provided, at a minimum, according to the 1/500 ratio, where 1 ft^2 (0.9 m^2) of vent area is provided for every 500 ft^2 (46.45 m^2) of subfloor area. In addition, vents should be distributed over the crawl space perimeter to prevent zones of dead or stagnation air and should not be blocked by shrubs, plants, or other obstructions.

It should be noted that during hot, humid periods ventilation air into the crawl space will often bring moisture into the crawl space rather than remove it. However, during cooler periods, this moisture is subsequently removed by the same ventilation air. Under severe ambient hot/humid conditions, moisture accumulation in the crawl space from ventilation air can exceed moisture removal by the same ventilation air on a seasonal basis. When this is combined with a heavily air-conditioned enclosure, it is necessary to protect the floor system from this moisture or to consider an alternative strategy.

Air Movement

In vented crawl space assemblies it is important to eliminate airflow between the crawl space and the conditioned spaces. The crawl space needs to be uncoupled from the conditioned space so that conditions within the crawl space influence the building enclosure to a minimum. This is best accomplished by not installing any forced-air ductwork, furnaces, or air conditioners in the crawl space. Experience has shown that is difficult to seal such units or ductwork to prevent leakage. In addition, penetrations for plumbing, wiring, bathtubs, etc. must be sealed, making the crawl space subfloor assembly airtight.

Where vented crawl spaces experience extreme humid conditions during heavy air conditioning, the installation of impermeable rigid insulation [1½ in. (3.8 cm) thick] on the underside of the floor joists can protect the entire floor system from moisture brought into the crawl space by ventilation air. This rigid insulation acts as both a vapor diffusion retarder and air retarder system and as such needs to be installed in an airtight manner and should completely enclose any supporting beam structures. The rigid insulation installed as wall sheathing is extended down to cover the rim joist and should be sealed to the sil plate. Cavity insulation within the floor joists (if installed) should be installed in contact with the rigid insulation.

Airborne moisture infiltrating from the crawl space into the enclosure can also be controlled in cooling climates by pressurizing the enclosure relative to the crawl space and the exterior.

Vapor Diffusion

Moisture movement by diffusion from the crawl space into the enclosure is retarded by the impermeability of the subfloor sheathing. In other words, the subfloor sheathing acts as a vapor diffusion retarder. However, moisture can accumulate on the underside of subfloor sheathing in humid, cooling climates or during hot, humid weather conditions.

Backed or unbacked insulation can be installed between floor joists. Vapor diffusion retarder-backed insulation is recommended to prevent the accumulation of moisture in the

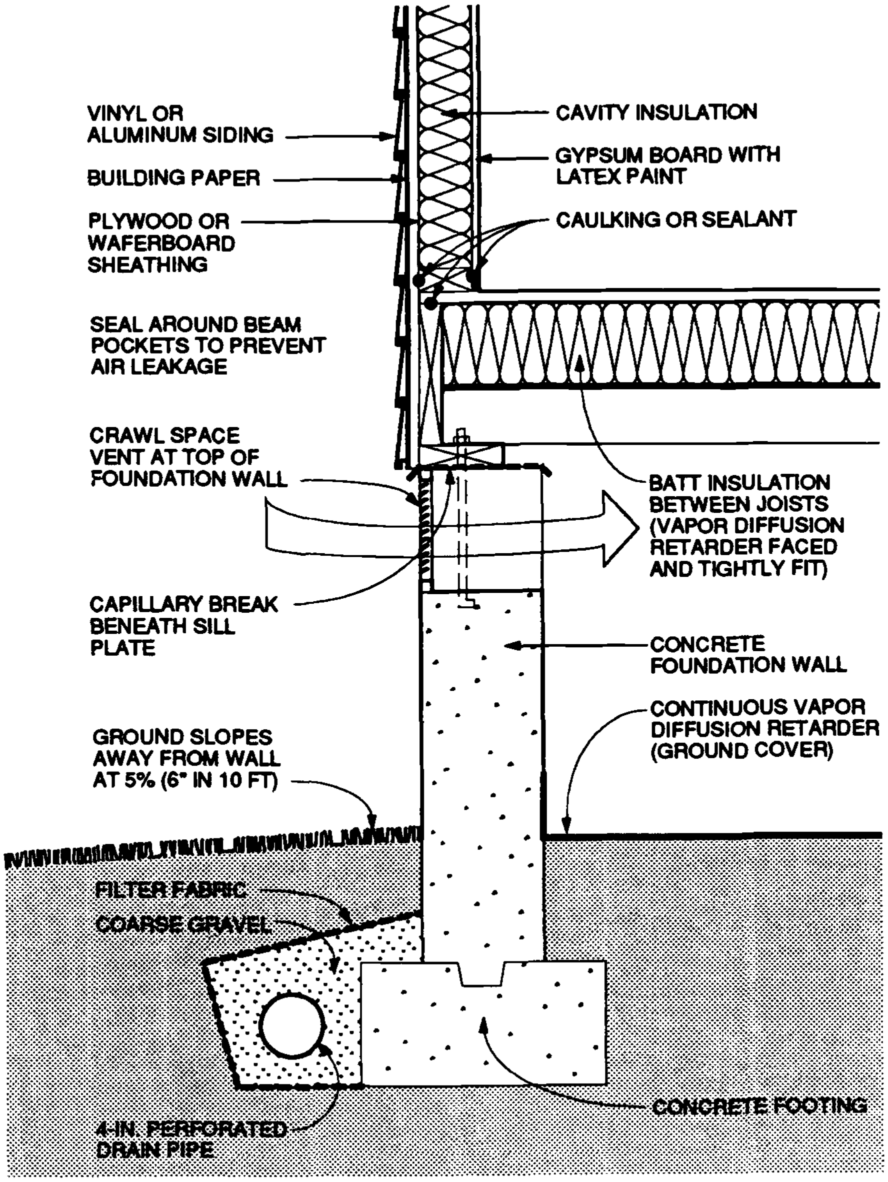

FIG. 11—Crawl space construction—vented and unconditioned.

insulation by vapor diffusion (backed side facing down) in humid, cooling climates. Unbacked insulation can be installed to promote drying should such moisture accumulate at the underside of the subfloor. A choice between the two can be determined by local experience. Unbacked insulation has traditionally been installed in heating climates and climates which experience less extreme humid conditions.

Capillary Suction

Moisture movement by capillarity into the perimeter framing assembly from the concrete foundation wall is controlled by the placement of a capillary break (polyethylene, or a sheet metal also doubling as termite protection) at the top of the foundation wall.

CRAWL SPACE CONSTRUCTION, UNVENTED/CONDITIONED (FIG. 12)

Rain and Groundwater

Rain and surface water should be prevented from entering crawl spaces by the use of gutters and downspouts along with careful site grading which direct water away from crawl space perimeters.

Groundwater entry into the crawl space is controlled by subgrade drainage located at the perimeter of the concrete footing.

Capillary Suction

Moisture movement by capillarity into the masonry block foundation wall is controlled by installing a dampproof coat-

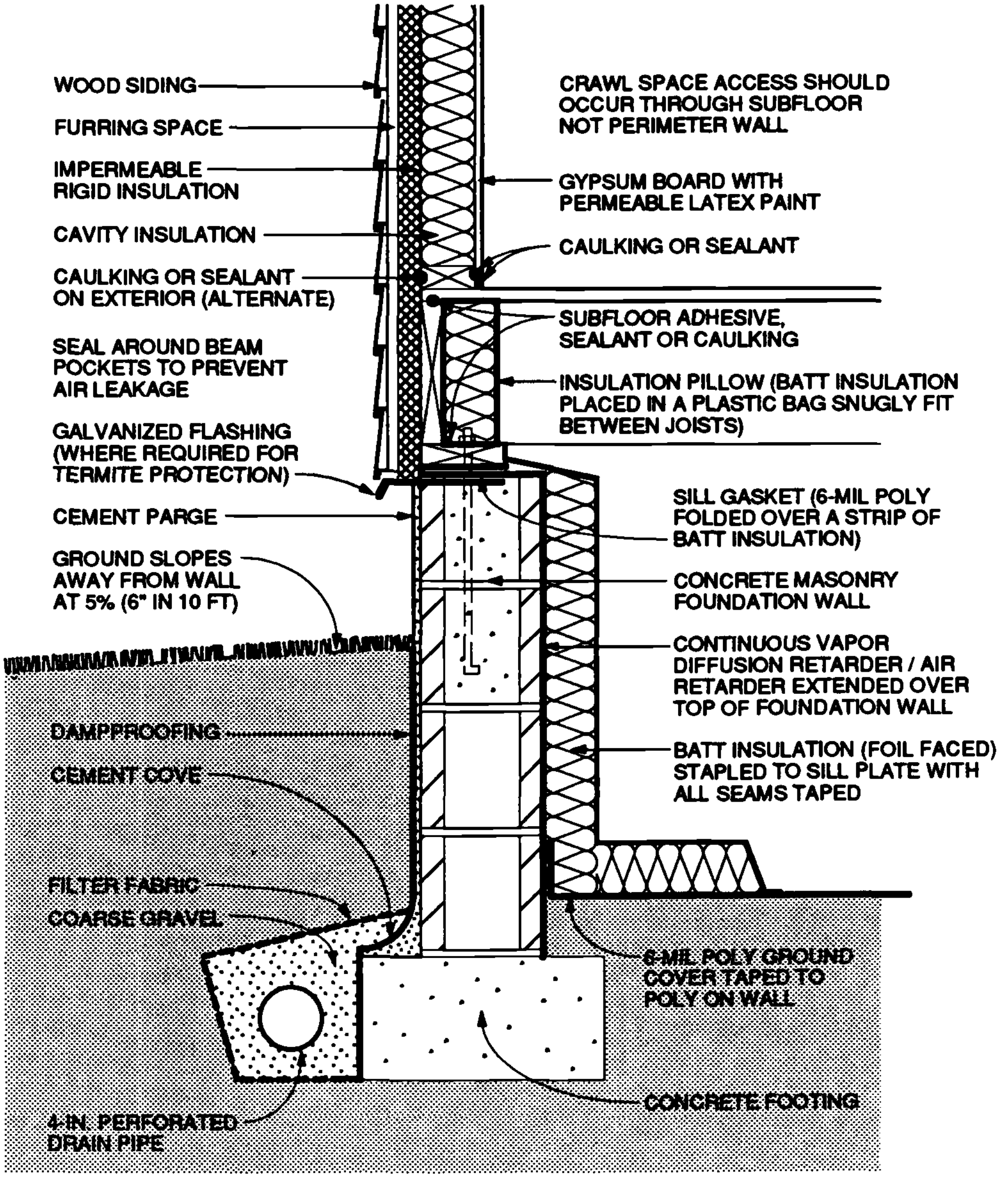

FIG. 12—Crawl space construction—unvented and conditioned.

ing (bitumen over a cement parge coat) on the exterior of the concrete foundation wall.

Moisture movement by capillarity from the moisture of construction contained in the masonry block foundation wall into the sill/rim joist/floor assembly is controlled by installing a capillary break at the top of the perimeter concrete foundation wall by extending the crawl space ground cover over the top of the masonry block foundation wall.

Air Movement

In unvented crawl space assemblies, it is important to eliminate airflow between the surrounding soil and the crawl space. Air-transported moisture infiltrating into the crawl space is controlled by pressurizing the crawl space relative to the surrounding soil and by limiting air leakage openings (tight construction).

Pressurization of the crawl space can be accomplished in enclosures with forced air systems by providing a supply air register in the crawl space, with no corresponding return air register. In enclosures without forced air systems, a separate fan for this purpose can be installed, taking air from the other conditioned spaces. The tighter the construction of the crawl space, the less air that has to be introduced to pressurize the crawl space. As such, it is desirable to build as tight a crawl space as is practical. This is accomplished by extending the ground cover/vapor diffusion retarder up over the top of the perimeter masonry block foundation wall and sealing all joints. In addition, the rim joist assembly is also sealed against air leakage with the application of adhesive, caulking, gaskets, or other air seals. Exterior wall sheathing is also extended down over the rim joist assembly to further reduce air leakage at this location. This exterior wall sheathing can be utilized as the principal air seal at this location and hence eliminate seals at the top and bottom of the rim joist if the exterior wall sheathing is sealed directly to the exterior of the sill plate, the sill/rim, and joist/floor assembly. In addition, pipe penetrations and electrical conduits through concrete floor slabs and perimeter concrete walls, floor drains, and sump openings are sealed or closed with "tight" covers.

Pressurization of crawl spaces should not be accomplished at the expense of depressurization of the rest of the building enclosure during cooling periods. In other words, the entire building should be pressurized relative to the exterior, including the crawl space during cooling periods. As such, air which is taken from the building in order to pressurize the crawl space needs to be replaced by outside air introduced in a controlled manner, typically to the air-conditioning duct system.

Vapor Diffusion

Moisture movement by vapor diffusion from the surrounding soil into the masonry block foundation wall is controlled by installing a vapor diffusion retarder on the exterior of the concrete foundation wall. In this example, the dampproofing on the exterior of the masonry block foundation wall also acts as a vapor diffusion retarder.

Moisture movement by vapor diffusion into the crawl space from the soil is controlled by installing a continuous polyethylene vapor diffusion retarder as a ground cover.

Moisture movement by vapor diffusion from within the crawl space into the perimeter batt insulation is controlled by installing a perimeter batt insulation with an impermeable facing that can act as an interior vapor diffusion retarder.

Accumulation of moisture in the perimeter foundation wall rim joist framing, transported by vapor diffusion from the interior of the crawl space during heating periods, is controlled by elevating the temperature of the first condensing surface within the rim joist assembly, namely the cavity side of the rim joist. This is accomplished in this example by installing rigid insulation on the exterior of the rim joist, which limits periods of potential condensation.

Comments

Insulation is installed on the interior of the perimeter concrete foundation wall to reduce heating and cooling loads. This insulation can act as a conduit for insects to enter the rim joist assembly, and as such appropriate flashings or other protection may be necessary.

In unvented, conditioned crawl spaces, it is convenient to install ductwork, plumbing, and other mechanical components because the effects of duct leakage and freezing pipes are eliminated or reduced.

SLAB CONSTRUCTION (FIG. 13)

Rain and Groundwater

Rain and surface water should be prevented from entering beneath slabs located at grade by the use of gutters and downspouts directed away from the building along with careful site grading which directs water away from slab perimeters.

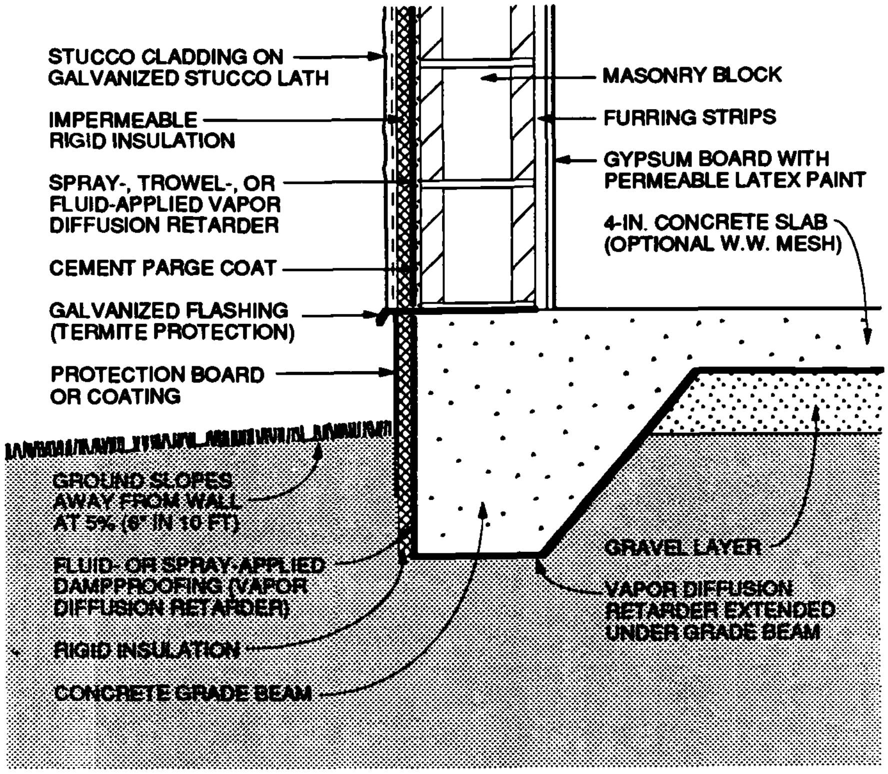

FIG. 13—Slab-on-grade construction.

Air Movement and Vapor Diffusion

In slab assemblies it is important to eliminate the moisture flow from the exterior into the enclosure by airflow and vapor diffusion. This is accomplished by the use of a vapor diffusion retarder installed under the slab along with pressurization of the building enclosure relative to the exterior. Ductwork should be avoided in slabs as groundwater seepage into ducts and diffusion and capillarity into concrete slabs from surrounding soil transferred to the ducts often becomes a significant source of moisture to the enclosure.

Capillary Suction

Moisture movement by capillarity into the slab from the ground is controlled by the placement of a capillary break, in this case the granular layer under the slab. Where slab construction is utilized with a perimeter concrete grade beam, the slab vapor diffusion retarder is extended under the concrete grade beam to act as a capillary break at this location. Furthermore, dampproofing is installed on the exterior of the perimeter of the grade beam also to act as a capillary break. This dampproofing, if it is fluid or spray applied, must be chemically compatible with any rigid insulation installed over it.

Comments

Rigid insulation is installed on the exterior of the perimeter foundation assembly to reduce cooling loads and is protected on its exterior from mechanical damage. This rigid insulation can act as a conduit for insects to enter the enclosure, and as such appropriate flashings or other protection may be necessary.

The wall assembly shown does not have a vapor diffusion retarder located on the interior. Accordingly, this wall will dry towards the interior in cooling climates. This wall assembly has a vapor diffusion retarder located on its exterior to control vapor diffusion migrating from the exterior. Moisture of construction may be present in the masonry wall and may lead to moisture problems in the gypsum board interior finish as the wall dries to the interior. As such, it is not recommended that impermeable wall coverings or impermeable paint finishes be installed unless the assembly has completely dried prior to enclosure or unless an additional vapor diffusion retarder (polyethylene film) is installed between the masonry and the gypsum board to protect this interior gypsum finish from the moisture of construction. Foil-backed gypsum board may not be sufficient protection in this application as a result of discontinuity at gypsum board joints.

The concrete floor slab contains significant quantities of moisture when initially placed. Covering this surface with an impermeable surface finish or floor covering may lead to deterioration of these surfaces if the moisture of construction is not allowed to dry. Initial drying of the moisture of construction contained in concrete may also lead to elevated interior moisture levels during the first few months of occupancy.

Installing carpets on cold, damp, concrete floor slabs can lead to serious allergenic reactions in sensitive individuals and other health-related consequences. It is not recommended that carpets be installed on concrete slabs unless the carpets can be kept dry and warm (that is, carpet relative humidities should be kept below 70%). In practice, this is typically not possible unless floor assemblies are insulated and floor areas are conditioned.

The granular drainage pad located under the concrete floor slab can also be integrated into a subslab ventilation system to control radon migration by the addition of a vent pipe connected to the surface and an exhaust fan.

VENTED ATTIC CONSTRUCTION (FIG. 14)

Ventilation

Ventilation in roof assemblies is provided to remove moisture from attic spaces and to reduce cooling loads by reducing solar heat gain through the assembly. Ventilation should be provided, at a minimum, according to the $^1/_{300}$ ratio, where 1 ft^2 (0.9 m^2) of vent area is provided for every 300 ft^2 (27.8 m^2) of insulated ceiling area. In addition, vents should be distributed between the soffit and ridge to prevent zones of dead or stagnation air and should not be blocked by roof assembly insulation or other obstructions.

Air Movement

In vented roof assemblies it is important to eliminate airflow between conditioned spaces and the attic. The attic needs to be uncoupled from the conditioned space so that conditions within the building enclosure influence the attic space to a minimum. This is best accomplished by not installing any forced-air ductwork, furnaces, or air conditioners in attics. Experience has shown that is is not possible to seal such units or ductwork sufficiently to prevent leakage. In addition, penetrations for plumbing, wiring, dropped ceilings, and kitchen cabinet bulkheads should be sealed.

Air-transported moisture exfiltrating during the heating season from the enclosure into the attic is controlled by depressurizing the enclosure relative to the attic and the exterior and by limiting air leakage openings (tight ceiling construction).

Vapor Diffusion

Moisture movement by diffusion during the heating season from the enclosure into the attic is retarded by the installation of a continuous ceiling vapor diffusion retarder sealed to the perimeter wall vapor diffusion retarder.

Comments

A wind baffle should be installed at the perimeter of the roof area where the insulated ceiling intersects the exterior wall to prevent thermal short circuiting of the insulation by wind ("wind-washing"). In this climate, wind-washing by cold air during the heating season can lead to the cooling of the perimeter wall top plate and ceiling gypsum board surfaces and subsequent interior mold and mildew growth.

The combination of a "narrow" soffit vent opening up to a relatively "large" volume soffit assembly and then being

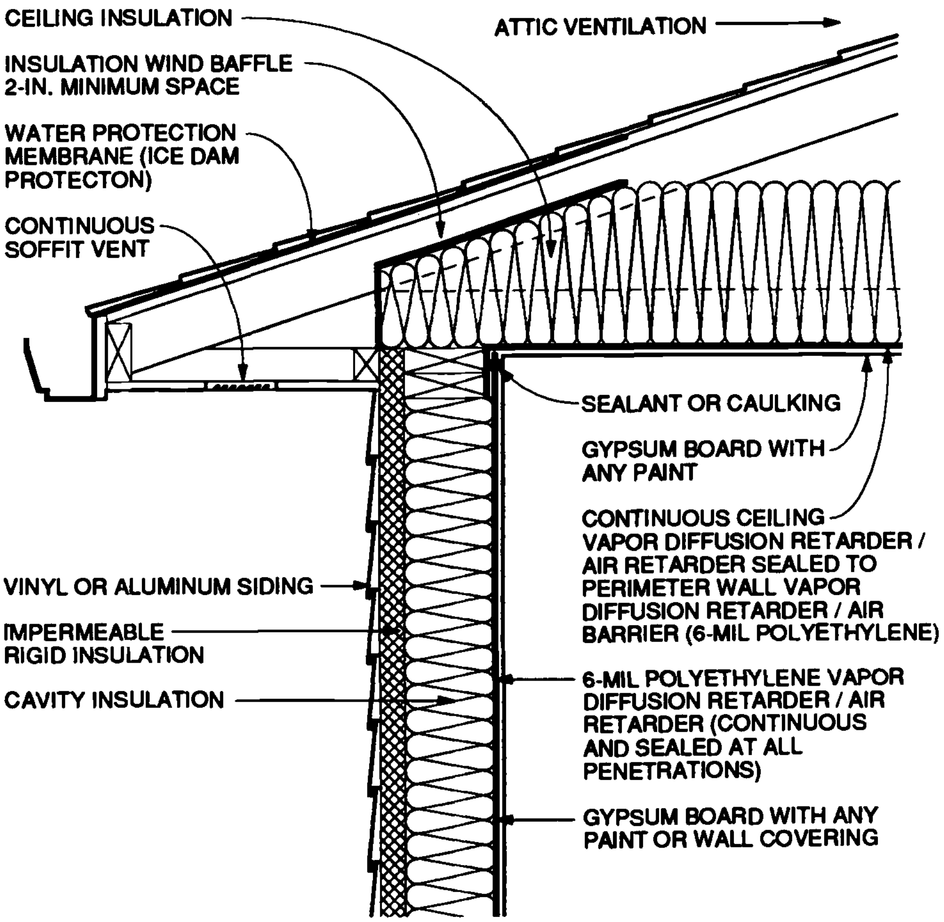

FIG. 14—Vented attic construction.

"squeezed" into a "narrow" space between the underside of the roof sheathing and the wind baffle causes exterior ventilation air entering soffit assemblies to experience a pressure drop as the soffit assembly acts as an "expansion" space. This pressure drop results in the ventilation air depositing airborne rain droplets and snow in the soffit assembly rather than transporting them farther into the roof assembly.

Ice damming in mixed and heating climates is controlled by installing a water-protection membrane at the eave and by providing sufficient thermal insulation at the intersection of the perimeter wall and ceiling to reduce heat loss, which can lead to snow melt. In addition, ventilation at the soffit assembly is provided to "flush" heat from the roof sheathing to maintain a "cold deck."

VENTED CATHEDRAL CEILING CONSTRUCTION (FIG. 15)

Ventilation

Ventilation in cathedral ceiling assemblies is provided to remove moisture from ceiling spaces and to reduce cooling loads by reducing solar heat gain through the assembly. Ventilation in cathedral ceiling assemblies should be provided at a minimum, according to the $1/150$ ratio, where 1 ft^2 (0.9 m^2) of vent area is provided for every 150 ft^2 (13.9 m^2) of insulated ceiling area. Continuous soffit and ridge vents should be installed with a minimum of a 2-in. (5.08-cm) space between the top of the insulation and the underside of the roof sheathing [*16*]. In addition, vents should be distributed between the soffit and ridge and should not be blocked by roof assembly insulation or other obstructions.

Air Movement

Air-transported moisture exfiltrating during the heating season from the enclosure into the cathedral ceiling space is controlled by depressurizing the enclosure relative to the cathedral ceiling and the exterior and by limiting air leakage openings (tight ceiling construction).

Vapor Diffusion

Moisture movement by diffusion during the heating season from the enclosure into the cathedral ceiling space is retarded by the installation of a continuous ceiling vapor diffusion retarder sealed to the perimeter wall vapor diffusion retarder.

Comments

The continuous ceiling vapor diffusion retarder is installed "shingle" fashion and extended over the top of the exterior

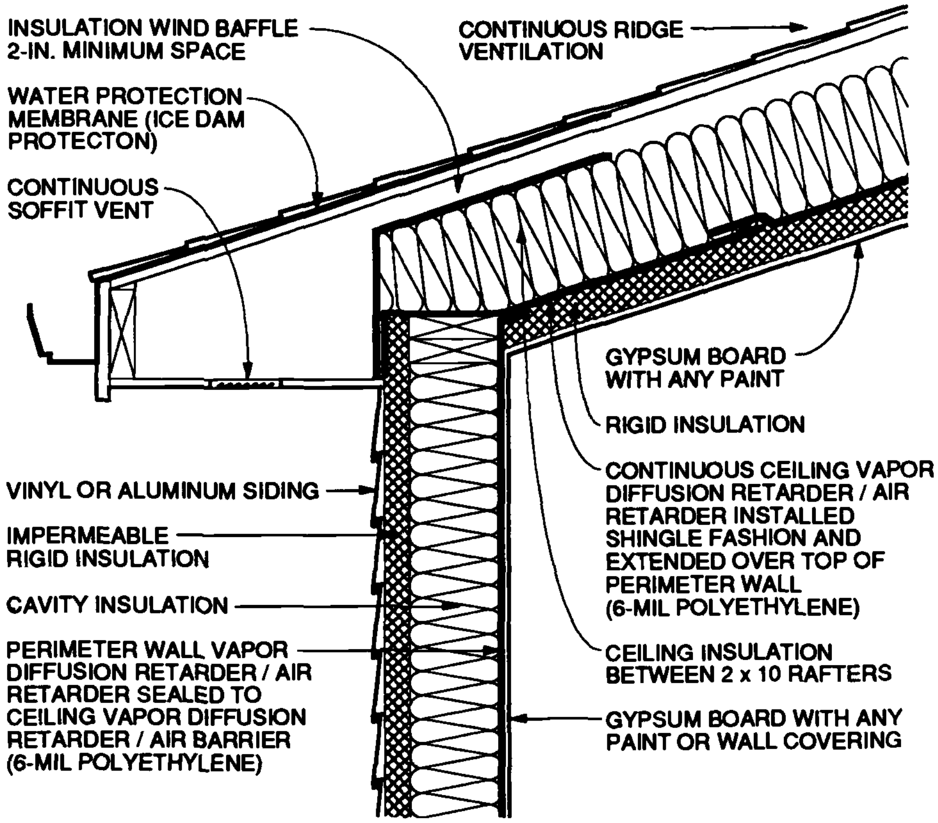

FIG. 15—Vented cathedral ceiling construction.

perimeter wall to allow for drainage of any condensed moisture and to provide secondary protection for roof rain water leakage.

Additional thermal resistance is provided in this vented cathedral ceiling assembly by installing rigid insulation on the interior side of the roof rafters beneath the sheet polyethylene vapor diffusion retarder. Alternatively, the sheet polyethylene ceiling vapor diffusion retarder is replaced by the rigid insulation alone in cases where the rigid insulation is impermeable and is installed in a continuous fashion (edges sealed) and sealed to the perimeter wall vapor diffusion retarder or air retarder.

In cases where attachment of the interior-applied rigid insulation and ceiling gypsum board is a concern, the rigid insulation can be held in place by furring (installed to the interior of the rigid insulation) and the gypsum board subsequently fastened to the furring.

A wind baffle should be installed at the perimeter of the cathedral ceiling area where the insulated cathedral ceiling intersects the exterior wall to prevent thermal short circuiting of the insulation by wind ("wind washing"). In this climate, wind washing by cold air during the heating season can lead to the cooling of the perimeter wall top plate and ceiling gypsum board surfaces and subsequent interior mold and mildew growth.

The combination of a "narrow" soffit vent opening up to a relatively "large" volume soffit assembly and then being "squeezed" into a "narrow" space between the underside of the roof sheathing and the wind baffle causes exterior ventilation air entering soffit assemblies to experience a pressure drop as the soffit assembly acts as an "expansion" space. This pressure drop results in the ventilation air depositing airborne rain droplets and snow in the soffit assembly rather than transporting them farther into the roof assembly.

Ice damming in mixed and heating climates is controlled by installing a water protection membrane at the eave and by providing sufficient thermal insulation at the intersection of the perimeter wall and ceiling to reduce heat loss which can lead to snow melt. In addition, ventilation at the soffit assembly is provided to "flush" heat from the roof sheathing to maintain a "cold deck."

UNVENTED CATHEDRAL CEILING CONSTRUCTION (FIG. 16)

Ventilation

Ventilation in cathedral ceiling assemblies is typically provided to remove moisture from ceiling spaces and to reduce cooling loads by reducing solar heat gain through the assembly. In unvented cathedral ceiling assemblies, as in most wall assemblies, the emphasis is on the prevention of moisture movement into the assembly rather than the removal of moisture once it has entered the assembly.

Air Movement

Air-transported moisture exfiltrating during the heating season from the enclosure into the cathedral ceiling space is

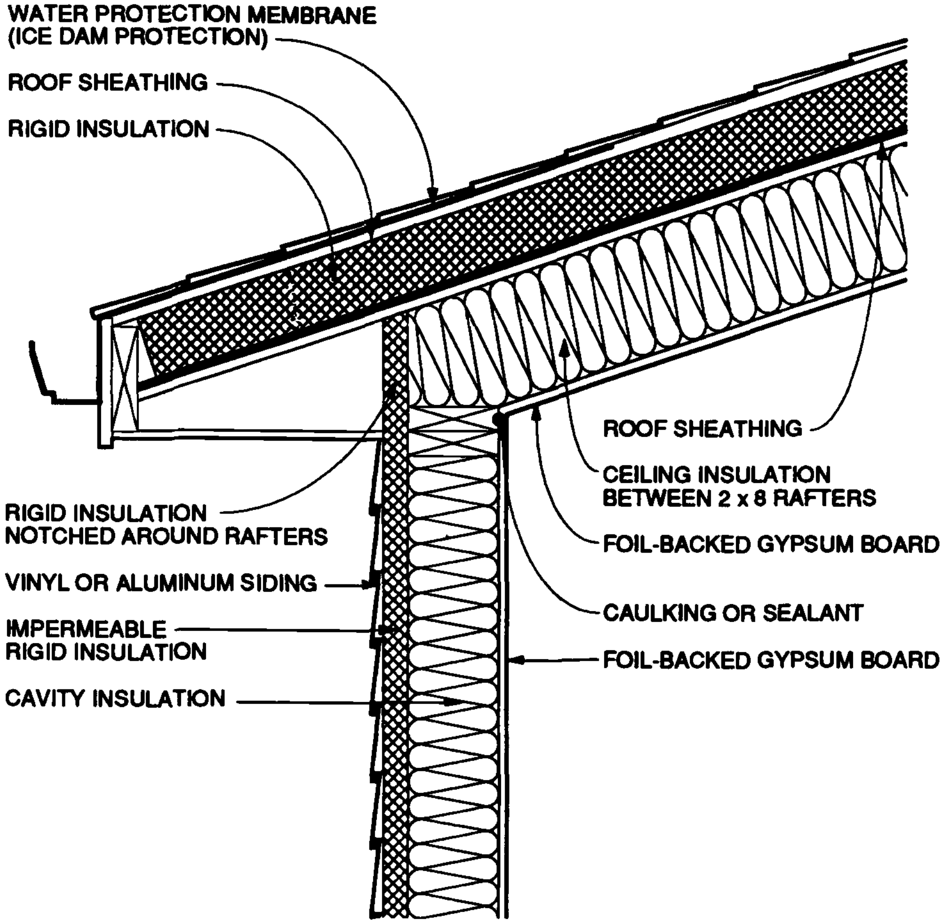

FIG. 16—Unvented cathedral ceiling construction.

controlled by depressurizing the enclosure relative to the cathedral ceiling and the exterior and by limiting air leakage openings (tight ceiling construction).

Air-transported moisture from the interior (exfiltration of warm, moisture-laden interior air during the heating season) in this cathedral ceiling assembly is controlled by sealing both the interior gypsum wall board to the roof joists framing and the exterior rigid insulation to the roof joists. This air sealing can be accomplished with adhesive, caulk, or some other sealant. Experience has shown that some exterior rigid insulations are thermally unstable and may not be compatible with sealing techniques which provide little allowance for movement. Accordingly, polyethylene or building paper is installed under the rigid insulation, and the joints in the roof sheathing installed over the rigid insulation are staggered over the joints in the rigid insulation to enhance airtightness.

Vapor Diffusion

Vapor diffusion from the interior during heating periods is controlled by installing a vapor diffusion retarder at the interior of the cathedral ceiling assembly. The foil backing on the ceiling gypsum board acts as the vapor diffusion retarder.

Accumulation of moisture within the wall assembly transported by vapor diffusion from the interior during heating periods is also controlled by elevating the temperature of the first condensing surface within the cathedral ceiling assembly, namely the cavity side of the roof sheathing. Rigid insulation elevates the temperature of the first condensing surface and limits periods of potential condensation.

Comments

In this cathedral ceiling assembly, drying towards either the interior or exterior is limited by virtue of the installation of the vapor-impermeable rigid insulation and an interior vapor diffusion retarder.

Should the cathedral ceiling assembly be built initially wet through the use of wet framing materials or the use of wet-applied cavity insulations (wet spray cellulose or blown fiberglass), it may not dry. Accordingly, dry framing materials (wood at a moisture content of 19% by weight or lower) and dry-applied insulations are recommended, or, alternatively, cathedral ceiling assemblies should be allowed to dry prior to enclosure.

Interior moisture levels should be limited to 35% relative humidity at 70°F (21.1°C) during heating periods to further facilitate the control of air-transported moisture and vapor diffusion with this cathedral ceiling assembly since only limited drying of the assembly occurs.

A wind baffle should be installed at the perimeter of the cathedral ceiling area where the insulated cathedral ceiling intersects the exterior wall to prevent thermal short circuiting of the insulation by wind ("wind washing"). Extending the exterior rigid insulation on the perimeter wall up so that it intersects the underside of the rigid insulation installed on top of the roof joists will effectively control wind washing.

Ice damming in mixed and heating climates is controlled by installing a water protection membrane at the eaves and by providing sufficient thermal insulation at the intersection of the perimeter wall and ceiling to reduce heat loss, which can lead to snow melt.

Some unvented roof assemblies have led to an elevation of shingle/shake/sheathing temperatures and subsequently to premature degradation of shingles/shakes/sheathings and a reduced service life. Accordingly, light-colored shakes/shingles should be utilized. In addition, it may be desirable to install roofing papers to provide additional protection against rain water entry should shakes/shingles deteriorate prematurely [17].

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18

New High-Rise Commercial and Residential Buildings

by Gustav Handegord[1]

THE MOISTURE PERFORMANCE OF ANY BUILDING is dependent on the outdoor environment to which it is exposed, the indoor environment within the building, and the materials and methods used in its construction. The outdoor environment is characteristically variable, while the indoor environment is under some degree of control and is relatively constant. The moisture performance of the materials involved relate to their physical and chemical properties with respect to the variations in temperature, air, and moisture conditions to which they are exposed, further influenced by the condensation and evaporation of water vapor and the freezing, melting, and flow of liquid water.

Although day-by-day changes in the weather cannot be predicted for a given locality, the climate for a region can, and the characteristic variations between indoor and outdoor conditions may be typified on a representative daily, monthly, seasonal, or annual basis. Indices of the probable range of conditions or of extremes to be expected have been developed for various design disciplines and can be used both qualitatively and quantitatively for the analysis and solution of problems.

Moisture problems in buildings arise primarily from the exposure of materials to high relative humidities or liquid water from condensation, rain, or meltwater. Inorganic building materials such as masonry and concrete suffer deterioration when wetted and exposed to below freezing conditions, while organic materials such as wood and cellulose are attacked by microorganisms when wetted and exposed to temperatures above freezing. Both biological and chemical activity increase with increasing temperature and duration of exposure.

In cold climates, condensation and freezing are experienced in winter, and conditions conducive to mold, mildew, decay, and corrosion can be experienced within the exterior envelope as well as indoors throughout the year. In general, the potential for drying will be greater the colder the climate, and longer periods of dormancy or inactivity will generally be the rule. In hot and humid climates, condensation may be experienced in any season both indoors and out, and conditions conducive to mold, mildew, decay, and corrosion can be maintained for long periods. In regions of intermediate climate, condensation will not be as prevalent, and moisture problems will more often be the result of rain except in the case of specialty occupancies where very high indoor humidities are experienced. Each situation and each building will be different, however, and should be considered in as much detail as possible. Even small differences between materials and construction methods or minor fluctuations in the indoor or outdoor environment can sometimes result in problems.

MOISTURE PROBLEMS IN HIGH-RISE BUILDINGS

The types of problems attributed to moisture experienced in high-rise buildings include:

- condensation on windows
- wetting and staining of interior and exterior finishes
- mildew and mold on interior and exterior finishes
- wetting of walls beneath windows
- water entry or wetness at the junction of wall and floor slab
- mildew and mold on gypsum sheathing or interior cladding
- deterioration or delamination of gypsum sheathing
- efflorescence (white deposits) on exterior masonry
- spalling of exterior masonry
- corrosion of masonry ties and shelf angles
- corrosion of precast panel anchors
- dislocation and bulging of masonry components
- deterioration of mortar joints
- discoloration and corrosion of exterior metal cladding
- corrosion of sheathing fasteners
- corrosion of metal roof decks and fasteners
- corrosion of steel structural members
- corrosion of metal studs
- deterioration or delamination of exterior and interior coatings

DIFFERENCES BETWEEN HIGH-RISE AND LOW-RISE BUILDINGS

The major differences between low-rise residential buildings and high-rise buildings with respect to the effects of moisture relate to the materials used and the methods of construction. Most low-rise buildings involve some form of wood-frame construction or load-bearing masonry and wood framing, while high-rise buildings involve steel or reinforced concrete framing with noncombustible materials such as concrete, brick masonry, metal, and glass in the exterior envelope.

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The desirable indoor temperature and humidity conditions to be maintained in most high-rise buildings designed for human occupancy will be in the same human comfort range as low-rise residential buildings, but lower winter humidities may be experienced in some high-rise buildings in colder climates because of higher ventilation rates. Most new high-rise buildings are mechanically cooled in summer, with unitary equipment or fan-coil systems utilized in apartments and hotels and central air-conditioning systems in offices and commercial spaces.

Specialty occupancies such as swimming pools, saunas, physical fitness centers, and commercial laundries and kitchens have special requirements with HVAC systems designed accordingly. The higher indoor humidities experienced may give rise to surface condensation problems, but air-conditioning systems usually offer means to control supply air conditions, air distribution, and pressure differences across the envelope to minimize or alleviate problems due to condensation.

The effect of wind and wind-driven rain can be more severe with high-rise buildings because of their greater height, and in some cases air pressure differences across the building envelope due to stack effect may be greater. In cold climates, stack effect has more impact on the performance of central air-handling systems used in high-rise buildings. Stack effect may be reversed in air-conditioned buildings in the summer, but the air temperature difference between indoors and outdoors and the resultant pressure differences and air leakage rates will be much lower, even in hot climates.

THE OUTDOOR CLIMATE

In colder climates there has been a tendency to blame most moisture problems on condensation due to air leakage with less consideration given to the contributing effects of vapor diffusion or wetting from rain or meltwater. This may stem from the anticipated increased stack effect promoting greater rates of moist air exfiltration in cold weather. Unfortunately, conventional rules tend to be formulated on the theoretical prevention of condensation under extreme, steady-state (design) conditions rather than on a consideration of the potential for absorption, storage, and removal of moisture under the more realistic action of cyclical weather conditions and solar radiation.

Condensation on interior surfaces can occur in winter even with moderate indoor humidities because of low thermal resistance of the wall or window or because the insulating effect of internal blinds, drapes, or closely spaced furniture can lower the surface temperature. Condensation occurs because the temperature of a surface falls below the dew-point temperature of the air in contact with it. Condensation can also occur on outside surfaces in cold weather when surfaces are cooled below the dew-point temperature of the outside air by radiation to the night sky. Only a slight lowering of temperature is required since the relative humidity is high and the dew-point temperature is close to the air temperature. The air is cold and close to the temperature of the ice and snow on the ground.

In hot, humid climates the dew-point temperature of the air is close to the outside air temperature most of the time, and condensation on exterior surfaces cooled by radiation to a clear night sky is even more likely. Comfort cooling of the indoor air may well lower the temperature of building materials below the outdoor dew point, and certainly the refrigerant and chilled water lines will be at temperatures well below the dew point of both the indoor and outdoor air.

Cold climates and hot humid climates thus represent similar situations with respect to condensation conditions but offer extremes in regard to the moisture performance of materials. When exposed to low temperatures, wetted inorganic materials can deteriorate due to freezing, but wetted organic materials will not be attacked by microorganisms in cold weather. In hot, humid climates, wetted inorganic materials will not be subjected to freezing, but organic materials will remain wet and be susceptible to microbiological attack for longer periods. Condensation wetting conditions in more moderate climates will fall in between these extremes, and design rules related to such extremes will be less applicable. In all climates, consideration has to be given to the diurnal and seasonal variations in climate, the materials involved, and the specific conditions to which they are exposed.

The rain-wetting characteristics of buildings and building materials will generally be similar in all climates. Problems such as rain leakage through windows or curtain walls may often appear to be simply explained, but designing to avoid rain entry may not always be straightforward. When moisture-absorbent materials are involved, explanations are not as simple, and the prediction of performance is even more difficult. Once moisture is absorbed, the rate and direction of transfer can be influenced by any number of changing factors, such as temperature, humidity, evaporation, or freezing. It is therefore important to consider these factors in specific rather than general rules and for different climates and materials.

THE INDOOR CLIMATE

Offices and Commercial Occupancies

The temperature and humidity of the indoor air in offices and commercial buildings will normally be in the human comfort range as defined in standards and codes of practice. A central air-handling system will normally be installed that is capable of air cooling or heating with humidification or dehumidification on a year-round basis. The heating of spaces having exterior walls and windows will usually be accomplished with a perimeter system using electricity or circulating hot water. In some instances, perimeter spaces may be conditioned with fan-coil or induction units providing both heating and cooling.

Interior spaces will usually require cooling throughout the year because of the heat from internal lighting and people. East-, south-, and west-facing perimeter spaces with windows may also require cooling in winter even in cold climates because of the heat gain from the sun. In cold climates, central humidification is usually provided during winter to maintain the indoor humidity in all spaces at minimum acceptable levels. Special occupancies such as computer rooms will usually require relative humidities on the order of 50% to be maintained. Such conditions may also be required in locations where typing, word processing, and accounting procedures involve the machine handling of paper.

Most new high-rise office buildings are designed on an open-plan basis to provide flexibility in the arrangement of partitions and work stations. Partitioned or separated executive offices may occupy some of the space at the perimeter. A central core incorporating the required stair shafts, elevator shafts, and service shafts is the usual arrangement, with elevator access on each floor through a lobby or vestibule. Commercial spaces tend to involve open central areas having access to elevators and escalators with self-closing doors leading to the required exit stairwells.

Residential Occupancies

The indoor temperature and humidity conditions maintained in new high-rise residential buildings are under the control of the individual occupants rather than a central control system as is usually the case in offices and commercial buildings. Indoor humidities will tend to be higher because of the greater number of moisture sources with bathing, showering, and cooking operations, similar to those in low-rise housing. There is also a greater likelihood that more hygroscopic material in the form of clothing, furniture, carpeting, and draperies will be available to absorb water vapor during the higher humidities experienced in summer and will subsequently give up this moisture during fall and winter to add further to the internal moisture load [*1*].

Ventilation with outside air is usually achieved only through openable windows supplemented by the intermittent operation of individual exhaust fans or a central exhaust system. The individual apartments are separated from the central hallways, other apartments, and stair and elevator shafts by closed entrance doors. No central air recirculation system as in high-rise offices is involved, although a system employing a roof-top fan is usually installed to provide hallway pressurization. The effectiveness of such systems in supplying outdoor air to the apartments through leakage past the entrance doors is questionable, particularly in cold climates where the stack effect pressure in the hallways can exceed the fan supply pressure.

Fan-coil or unitary systems are employed to provide both heating and cooling in most new high-rise residential buildings. Fan-coil systems will normally be supplied seasonally with chilled water for cooling and hot water from a central source or integral electric elements for heating. In hot and humid climates, such systems have limited capacity to dehumidify the indoor air and are not as effective as central air systems or unitary systems in lowering the indoor dew-point temperature [*2*].

Unitary systems utilize direct expansion cooling with electric heaters or heat pumps. Both systems will have integral fans to recirculate the air in the space and may include outdoor air inlets for ventilation purposes. In colder climates, supplementary electric baseboard heaters are sometimes provided to handle the cooling/heating changeover periods. In lower-cost rental housing, only electric or hot water perimeter heating may be supplied, with cooling achieved by the occupant through the opening of windows or operation of window air conditioners.

WINDOWS AND CURTAIN WALLS

Offices and Commercial Buildings

Fixed, sealed multiple-glazed windows are almost always employed in high-rise office buildings. The fixed windows permit closer control of indoor air conditions, and double glazing allows reflective coatings to be used to reduce solar heat gain and to increase the thermal resistance of the central portion of the window. Window condensation over the central portion of the window such as might obscure vision can successfully be avoided in cold climates, but condensation around the perimeter of the glass or on the surrounding metal frame may pose problems.

Metal spacers are commonly used in sealed multiple-glazed windows, although less conductive spacers have recently been introduced. This high-conductivity path, often augmented by that of the metal frame, lowers the indoor surface temperature at the perimeter of the glass. The cold air flowing down the indoor surface of the window by natural convection, coupled with the convective circulation in the air space in the window itself, further lowers the temperature near the sill level.

Both of these cooling effects are aggravated by the common practice of installing the window frame as far to the outside of the wall as possible for exterior styling or to increase the chargeable rental area. The deeper sill and the contact of the window perimeter with the colder outer portion of the wall leads to further lowering of the temperature of the window perimeter.

Drapes or venetian blinds can act to further lower window surface temperatures by inhibiting room air circulation over the room-side surface of the window. The drapes or blinds should be installed or adjusted to allow a space at the top and bottom in order that room air can freely circulate over the window surface by natural convection. However, directing the warm air from fan-coil or heating convectors onto the window surface can lead to sealed unit breakage in cold weather [*3*].

Moisture condensing on the inside surface of sealed glazing is not likely to limit view but may collect at the lower edge and gain entry into the clearance space beneath the sealed glazing unit. If moisture is allowed to accumulate in this "rabbet" space, it can lead to deterioration of the seal, and water or water vapor may be drawn into the sealed unit by the suction resulting from a drop in ambient temperature or a rise in barometric pressure.

A similar problem can develop in warmer climates because of rain entry to the rabbet space from outside. It is difficult to ensure a perfect seal at the outer face, and even a minute accumulation of moisture in the rabbet space can cause premature failure of the sealed window and saturation of the dessicant within the spacer. It is important to drain and vent the rabbet space to outside with a protected opening. Such vent openings not only provide for drainage but permit equalization of pressure of the rabbet space with outside to inhibit water entry [*4,5*].

Water entry from outside is much more likely when sloped curtain wall glazing is used to form a "roof" for an atrium. Horizontal mullions in curtain walls are seldom designed to slope or to have conventional drips on their underside to make rain or meltwater fall free of the building façade. When employed without change as a "sloped roof," each horizontal mullion acts as a trough to collect rain or meltwater, holding it ready to be sucked into the glazing rabbet and promoting early glazing failure.

In some cold climates, excessive snow accumulation on sloped glazing at the top of high-rise buildings also leads to the problem of ice damming and "avalanching." Snow buildup insulates the underlying glass, inducing melting and promoting icicle formation at the edge of the atrium. This water buildup not only serves as a source for entry into the rabbet space or the building, but can cause the accumulation to slide, endangering people and objects below.

Residential Buildings

The windows employed in residential high-rise buildings are usually of lower cost and quality than those used in offices or prime commercial spaces. They are metal-framed units incorporating openable sash, usually of the horizontal sliding, awning, or jalousie types. Access to balconies is usually through sliding patio doors, with the balcony formed simply by an extension of the reinforced concrete floor slab.

In contrast to office buildings, drapes and blinds are the rule in apartments. Floor-to-ceiling drapes for decor, with sheer curtains or venetian blinds for control of light and privacy, are common. Dropped ceilings are not used, the ceiling of an apartment being the underside of the concrete floor slab of the apartment unit above. Windows are often carried to the underside of the floor slab with no lintel provided on which to fasten the drapery track. The drapes and blinds can thus effectively insulate the window and wall surfaces which they cover from the indoor environment, and, in cold climates, condensation on windows and mildew formation on wall finishes are not uncommon.

Metal window frames used in colder regions incorporate a "thermal break," provided by a plastic insert that joins the inner and outer sections. This thermal break is located between the inner and outer sash of the operating units and at or near the fixed, sealed double-glazed unit. The window frame is usually secured to the interior wythe of a masonry cavity wall or to the interior steel stud, back-up wall. Insulation installed in the cavity or on the exterior of the steel studs tends to keep the perimeter of the window frame warmer than when insulation is installed only in the stud space or on the room side of the interior wythe [6,7]. This exterior insulation tends to compensate for the thermal bridge effect caused by a metal spacer in sealed window units and reduces the possibility of thermal breakage.

At the sill level, this effect is usually overshadowed by the cold air flowing downward over the window surface and the resulting vertical air temperature gradient. This cooling effect is further emphasized when drapes are drawn or the venetian blinds lowered or closed. To make matters worse, lowering of the room air temperature at night or during the occupants' absence in the interest of energy conservation cools the window surface further while doing nothing to prevent the movement of water vapor from the room air to the cold window surface.

When the drapes are opened or outdoor temperatures rise, the condensate flows to the sill and may find its way to the wall below or adjacent to the sill and result in deterioration of the wall finish or gypsum board beneath. With sealed double-glazed window units, the condensate may penetrate past the gasket at the inner stop, enter the rabbet, and if not drained to the outside can accelerate deterioration of the perimeter seal of the fixed unit. In any event, excessive accumulation of condensate on the sill is a nuisance to the occupant, and buildup of ice on the frame in very cold weather persuades the occupant that the window is faulty or the construction is of poor quality.

The provision of a lintel above windows or installation of a dropped valance can allow some clearance to be provided above and below draperies to allow for room air circulation. Horizontal venetian blinds or roller blinds present a problem, but some improvement can result if they are not lowered completely to the sill.

Under-window perimeter heating behind or below draperies is effective in warming the window and promoting room air circulation, particularly with hot water systems since they are continuously warm. Electrical baseboard units with proportional control can be similarly effective, but simple on-off operation may not prove satisfactory, particularly if the baseboard units are not the prime source of space heating.

Draperies that extend up to the ceiling or laterally to partition walls can lower wall surface temperatures sufficiently to cause condensation or to maintain relative humidities high enough to foster mildew formation and growth. Wallpaper, wallpaper paste, or the paper coating on gypsum board may provide food sources for such organisms. Oil-based paints and enamels which provide more moisture resistance than water-based coatings may inhibit mildew formation, but promoting room air circulation over the wall surfaces is probably the most effective measure that can be taken.

A common builder reaction to owners' complaints is to suggest that the occupants increase the ventilation rate by opening windows or operating the exhaust fans more frequently. Even if the occupant is persuaded to do this, it is usually ineffective for a number of reasons.

The humidity level in an apartment at any time is primarily influenced by the moisture stored in the furnishings it contains and in the building materials used in its construction. The moisture initially in the building materials may have an influence for a period after construction, but the furniture, rugs, clothing, drapes, and other materials within the unit can continue to absorb and give off large quantities of moisture on a repetitive, seasonal basis.

These materials absorb moisture from the air when relative humidities are high and give off moisture to the air when relative humidities tend to drop. During the summer, relative humidities can be high, especially in cooled, air-conditioned spaces, and consequently the contents of the apartment increase in moisture content. Over the summer period this can involve very substantial amounts of moisture being stored in the materials within the apartment.

The outdoor air brought in for ventilation in cold and moderate climates has a minimal drying effect until midwinter, and the moisture given off by the interior furnishings is capable of maintaining the indoor humidity at near-summer levels until the colder weather arrives. Even then, only *continuous* ventilation with drier outdoor air is usually able to lower the indoor air humidity appreciably. Intermittent operation of exhaust fans or periodic opening of windows will only lower the humidity temporarily and is frequently resisted by the occupants because of discomfort.

MASONRY WALLS

Light-weight walls are almost a requirement in new high-rise building construction with the trend in masonry walls moving from brick veneer and block backup to brick veneer and steel stud backup. Traditionally, the brick cladding is supported on the edge of the floor slab, leaving the slab edge exposed as an architectural feature. The resulting "thermal bridge" can result in cold floors where no continuous perimeter heating is employed, condensation and resultant mildew in carpeting, or swelling and buckling of moisture-sensitive flooring materials. In cold climates, therefore, the single wythe brick cladding is best supported on ledger angles at each floor to allow some thermal insulation to be installed to cover the slab edge. This insulation is often provided as an extension of rigid board insulation installed on the outer face of the block back-up wall or of the gypsum sheathing on the steel stud framing.

In hot and humid climates, concrete floor slab projections can provide cold bridges from indoors and result in condensation, mold, and mildew growth on the building exterior, particularly where solar shading screens the wall surface from the warming effect of the sun [*2*]. Placement of insulation on the exterior of the slab edge or outside surface of a masonry or concrete wall should avoid this condition, but may increase the potential for condensation to occur because of more rapid cooling of the outside surface by radiation to a clear night sky.

With steel stud back-up walls, the space between the studs offers an opportunity to install mineral-fiber batt insulation for energy conservation. Since the stud space can also be used for electrical wiring or concealed services, penetrations through the interior cladding to the indoor environment often occur, providing paths for air leakage. In milder climates, filling the core spaces of the block back-up wall with insulation can provide some thermal improvement. In addition, or alternatively, batt insulation can be installed on the inside face of the block between furring strips or rigid board insulation adhered to the room side of the wall and covered with an inside finish of plaster or gypsum board.

Condensation in Masonry Walls

In winter, the temperature of the components of the wall that are outward of the thermal insulation may fall below the indoor air dew-point temperature and result in condensation of moisture from vapor diffusion or outward air leakage. For a given wall construction, the rate of outward diffusion of vapor will depend on the difference between the indoor air vapor pressure (dew-point temperature) and the saturation vapor pressure corresponding to the temperature of a condensation plane within the wall. This vapor pressure difference will be the same as for low-rise buildings with the same indoor conditions. However, the stack effect air pressure difference promoting moisture vapor transfer by outward air leakage can be much greater due to the greater height. Both of these pressure differences are a function of indoor-outdoor temperature difference.

In office buildings with open-plan floor areas, the outward-acting stack effect pressure will tend to be close to that in the vertical shafts since the exterior walls and windows tend to be more airtight than the walls and doors into the central vestibules and vertical shafts. Higher outward-acting stack pressures thus occur toward the upper floors of such buildings in winter, leading to an increased exfiltration of moist indoor air. The junction of the exterior wall with the roof is often a critical location—it is at the top of the building and is difficult to make airtight.

The usual sequence of construction and division of trades frequently results in openings at this location, even when parapets are constructed. Dropped ceiling construction is also commonly used in offices and commercial buildings, affording a space in which to conceal ductwork, piping, and electrical services. Interior finishing of the exterior walls above the dropped ceiling level is frequently omitted, "out of sight" being "out of mind," and the airtightness of the interior wall is reduced. A crack is also likely to develop between the underside of the floor slab and block infill walls due to shrinkage of the block, and although this may occur at all floors, outward airflow will be greatest at the top of the building where the outward acting stack effect pressure is greatest. Such cracks are not as likely to be experienced with steel stud walls since the upper plates are "nested" to allow floor slabs to deflect without loads bearing on the interior cladding. In some instances, however, interior gypsum board is not carried to the top of the steel stud walls above the dropped ceiling and the stud space is left open.

The potential for openings through the interior cladding at the wall roof junction is greater when fluted steel decking is employed and when structural steel framing is concealed within the exterior wall. It is difficult, if not impossible, to seal around structural steel members in walls or to close the flutes in steel roof decks at the roof perimeter. Foamed-in-place insulation appears to offer a solution provided the fire resistance requirements can be met.

Because of the greater outward-acting stack effect pressures and potentially greater suction pressures due to increased wind velocity with height, it is important to improve the airtightness of all exterior walls. The gypsum board interior finish offers adequate airtightness, provided the joints between the gypsum board, columns, windows, and walls are bridged with sealants, membranes, or other suitable components. Electrical outlets are easily gasketed, but it is the wiring and plumbing openings into the exterior wall at partition wall intersections that are frequently overlooked. Plumbing and service shafts at exterior should also be avoided since they can afford a vertical chimney throughout the building with little or no deliberate separation from the interior spaces of the exterior wall. Even if they area sealed at floor level, they may still afford many paths for air leakage from the occupied space on one floor into the exterior wall.

Some condensation is likely to occur within walls in cold climates in spite of efforts to avoid it. With masonry construction, a considerable amount of concealed condensation can be tolerated before the moisture content of the masonry materials reaches critical values. Even when saturated, masonry materials are not likely to deteriorate unless frozen at the same time and this is only likely to occur at the exterior face, not within the wall. Methods can be used to estimate the amount of moisture likely to accumulate from vapor diffusion or air leakage in a particular wall construction in a specific climate [*8*], but judgment as to the likelihood of moisture problems occurring should recognize the influence of moisture from other sources such as wind-driven rain and the potentials for moisture removal by such mechanisms as evaporation and particularly drainage [*9*].

Although some masonry units are more absorptive than others, masonry cladding is susceptible to moisture entry by virtue of the many joints between the units and the mortar between them. Some rain leakage through masonry cladding is recognized in the provision of a drained cavity behind the façade. In modern construction, weep holes are specified at the base of the cavity to allow drainage at the ledger angle, with some form of metal or plastic flashing extending across the cavity to the block or steel stud back-up wall. The cavity is intended to prevent rain from penetrating to the interior finish or into the building and to redirect any water that passes through the cladding to the outside.

These same features also provide a means to handle excess moisture resulting from condensation. Condensed moisture that is not absorbed into the back of the cladding can drain to the base of the cavity and through the weep holes to outside, and absorbed moisture can evaporate to effect drying when conditions are suitable. Some specifiers suggest that vent holes also be provided at the top of the cavity to promote moisture removal by ventilation.

Good masonry practice avoids mortar droppings building up at the bottom of the space or on ties as well as mortar joint extrusions into the cavity. Investigation of actual walls under intentional wetting have demonstrated that up to 80% of the water applied to the exterior surface can migrate into or through the brick cladding without any assistance from wind pressure. Moisture migration across the cavity to the inner wythe was observed to occur in a variety of ways, involving mortar droppings, inward sloping ties, extruded mortar, and in insulated cavities at horizontal joints between insulation boards [*10*].

Reversed Vapor Flow

An inward migration of moisture across the cavity can also occur by water vapor diffusion when wet masonry cladding is heated by solar radiation [*11*]. Solar heating can raise the temperature of the cladding well above the indoor air temperature even in cold climates and thus raise the vapor pressure of the moisture within the cladding to values above the indoor vapor pressure. The dew-point temperature of the air at the inner surface of the cladding can thus be higher than the temperature of the inner masonry wythe or of the gypsum sheathing in steel stud walls, resulting in condensation on the outer surface of the masonry or the gypsum sheathing. The amount of moisture involved may not be sufficient to raise the moisture content of masonry significantly, but could raise the moisture content of the paper covering of gypsum sheathing to the point where mildew could occur or corrosion of fasteners promoted. Diffusion of vapor further inward can even result in condensation on the outer face of the interior finish, leading to mildew, deterioration, or corrosion of fasteners.

A similar inward migration of water vapor can occur with air-conditioned buildings in hot and humid climates. Dehumidification of the indoor air can result in a lower water vapor pressure indoors, and cooling of the indoor air may lower the temperature of some components in the wall below the outdoor dew point. Thus water vapor moving inward under a vapor pressure or air pressure gradient could condense within the wall.

The traditional use of sheathing paper on the exterior of steel stud back-up walls, intended as a second line of defence against rain entry, provides a measure of protection from such condensation. Similarly, a vapor retarder such as plastic film or foil backing at the outer face of the interior gypsum board provides further protection. Without these components, vapor retardant interior finishes such as paint or wallpaper may serve to aggravate the situation.

It should be recognized that, in all cases, the temperature of the air supplied for cooling indoor spaces will be much lower than the resultant space temperature. The temperature of ductwork carrying conditioned air may well be below the outdoor and indoor air dew point and so will the surfaces of materials that the cooler supply air impinges on. Depending on conditions, condensation could occur in a variety of locations, both visible and concealed. Cases have occurred where a section of interior gypsum board ceiling cooled by the intermittent impingement of conditioned air has become wet enough to collapse of its own weight.

When building materials are exposed to humid air, mildew and mold growth are likely. Corrosion of metals can also occur at humidities above 85 or 90% and can best be controlled by providing corrosion-resistant coatings and means to remove moisture through evaporation and drainage. Very small quantities of moisture are required, and temperatures need only be above freezing. It is most important to avoid high humidities when organic materials are involved since such materials constitute a source of food for microorganisms. Mildew looks as bad whether it is dormant or flourishing and may constitute only an appearance problem as far as the building is concerned. The spores produced by the microorganisms may offer some health risks, however, and odors emanating from the microorganisms or other substances they generate may be offensive.

Rain and Meltwater

The absorption of water by masonry walls depends on the type of brick or block, but the penetration of water depends perhaps even more on the effectiveness of the bond achieved between the mortar and the masonry unit. This is greatly influenced by the moisture absorption properties of the bricks used as well as by the skill and judgment of the mason. With modern brick veneer construction, incorporating drained cavities, waterproof membranes, or coatings on the inner wythe, sheathing paper, gypsum board sheathing, and plastic film vapor retarders, the possibility of rain penetration into the occupied space is most unlikely. It is most likely to occur with slab to slab construction when interior wall flashings are omitted or poorly and improperly applied.

Mortar extrusions, mortar droppings on metal ties, or improperly installed ties can allow water to bridge the cavity space. With steel stud backup, such moisture is unlikely to penetrate the sheathing paper or sheathing, and if it does it will not likely bridge the stud space whether it is insulated or not. Masonry back-up walls on which exterior parging, air or vapor-retardant membranes, or coatings have been applied will be similarly resistant, and any moisture that does migrate through the block may have to bridge a furring space or gap between the block and the interior drywall and perhaps a vapor retarder before it appears at the inner face of the wall.

Rain that penetrates into the cavity may not be drained to the exterior if mortar droppings fill the bottom of the space or flashings are not installed correctly. Flexible plastic flashing that is not fixed to the face of the interior wythe has been known to flop to the outer wythe, become fixed by mortar droppings, and direct water to the interior at the base of the wall. When flashings are omitted or discontinuous in exposed slab-edge construction, water draining to the bottom of the space has every chance of flowing inward rather than outward.

Efflorescence and Staining

Efflorescence is the most common form of staining experienced with masonry cladding [*12*]. These white deposits result from dissolved salts brought to the exterior surface through moisture migration and left as a result of evaporation. These salts usually originate from cement mortar, although they may also come from the soil near ground level when no damp-proof course or through-the-wall flashing exists, or from de-icing chemicals used on walkways or terraces. Efflorescence is most commonly observed near the top corners of masonry-clad buildings and in some cases beneath window sills.

The top edge and corners of tall buildings are the first to become wetted by wind-driven rain and offer the initial source of water flowing down the face of the building once the rate of deposition exceeds the rate of surface absorption [*13*]. When drying conditions occur, the moisture is brought to the surface by capillary action where the moisture evaporates, leaving the salts on the surface. In heated buildings this outward migration of moisture can be aided by the resultant temperature gradient, with some possibility that moisture from condensation on the back face of the masonry may also contribute.

Rain or meltwater from snow accumulation on window sills or on or behind parapets can also be a contributor, through entry above flashings, at joints in discontinuous sills or capping stones, or by surface flow down the face of the masonry below because of inadequate drips or flashing. Efflorescence concentrated at the sides of window sills serves to indicate a flow off the sides of the sill due to the lack of gutters or flashing to guide water to fall free of the façade. Water from condensation in the joints between the window frame and wall due to outward air leakage or as a result of excessive condensation on the window itself finding its way through the joints in the window frame can sometimes be a contributor.

Since efflorescence occurs on masonry in all climates, wind-driven rain or drainage from roofs and terraces can be considered as the principal sources of moisture. Reducing the cement content of mortars will reduce a possible source of salts, but the use of lime mortars is not in keeping with the speed of erection and "strength" concerns prevalent in modern building design and practice.

The use of water-repellant "sealers" such as silicones can provide a means to inhibit efflorescence by deterring rain entry from the face and promoting evaporation at the depth of sealant penetration beneath the exterior surface [*14*]. The rate of evaporation will be reduced because of the reduced surface area, and this will result in a reduced drying potential from masonry that is wetted from other sources such as roof and terrace runoff or condensation. Suggestions have also been made that the concentration of salts behind the surface as a result of this subsurface evaporation can lead to expansive forces that cause spalling. It would seem that a substantial source of salt-laden water would have to exist for this to happen, such as might occur from moisture rising from the soil or from the use of additives such as calcium chloride in the mortar. It is not likely that salts are likely to come from the distilled moisture condensed from the air of the indoor environment.

Dirt deposition and dirt washing create patterns on building façades that are the result of patterns of rainwater flowing down the surface under the influence of gravity, wind, and most particularly, the exterior surface features and geometry [*13*]. Staining can occur on all surfaces including "stainless" steel, with patterns being most noticeable on modern buildings incorporating large plain surfaces following the Bauhaus style. Staining most commonly occurs where downward water flow concentrates: at exterior corners, panel edges, below window mullions, and at all such vertically oriented features. Nonuniform drainage from sills and horizontal ledges creates tell-tale patterns on sill facings and spandrel panels below where inadequate drips are provided. Several observers have noted that on the older classical styles, with ornate cornices and sculptured columns, dirt marking served to enhance rather than detract from the building's appearance.

Deterioration of Masonry through Freezing

The exfiltration of indoor air due to stack effect and the characteristics of wind-driven rain both tend to wet the cladding at the upper portions of buildings. These also tend to be the locations where spalling of bricks and deterioration of mortar joints frequently occur in colder climates. Similar deterioration is also noticed below window sills. As a result, there is often a difference of opinion as to whether air leakage or rain wetting is the primary source of moisture.

It is generally agreed that such deterioration is the result of the material being frozen when it is at or near saturation. While authorities differ on whether repeated cycling above and below freezing or whether only a few cycles or a single rapid freezing can cause failure, it is agreed that the material has to be wet. The porosity of the materials involved is regarded as a prime determinant, and simple water absorption tests of bricks have been used as a means for rating their frost susceptibility. Experience with the effectiveness of air entrainment of concrete as a means for improving performance and the use of freeze-thaw cycling tests as a means for assessment has also influenced practices.

The problems of spalling and mortar deterioration are not experienced as often in regions having very cold winters, particularly where outside temperatures remain consistently below freezing. Moisture migrating from indoors by air leakage or vapor diffusion will usually accumulate as frost on the inner face of exterior cladding, melting only occasionally during solar heating and milder weather. Under such conditions, absorption is less likely, and the excess water can form into icicles as it emerges from the exterior drainage openings. It could be considered that the temperature gradient maintained by the internally heated building will tend to induce the absorbed water to migrate to the outer face, but the migration is bound to be slower if temperatures are below freezing and is likely to be reversed whenever the sun is shining. It thus seems unlikely that the outer face of porous cladding materials will become saturated solely by condensation from indoors in such cold climates.

Milder, less sunny climates are more likely to experience wet rainy days or greater snowfalls and melting conditions prior to temperatures falling below freezing at nightfall. This moisture will be absorbed at the outer surface of cladding, creating conditions more conducive to rapid freezing of saturated materials. In regions having less frequent, below-freezing temperatures, the outer face of the cladding may be wetted, but less severe drops in outdoor temperature will be experienced and deterioration due to freezing will be uncommon.

Based on observations in Canada, it has been suggested that masonry deterioration due to frost action is not likely to occur in localities having a winter design temperature above −7°C [*3*]. In the coldest populated regions such as those in the prairies, where winter design temperatures range below −30°C, masonry deterioration at the tops of buildings is not common, whereas icicle formation at such locations under sunny conditions or following mild spells sometimes occurs.

Another problem in walls that can be attributed to condensation in cold climates is that of the outward displacement of masonry at shelf angles. Masonry has been observed to have moved outward by up to 2 cm at a shelf angle at the operating room floor of a hospital building where no weep holes were provided. It was suggested that condensation on the inner face of the brick cladding due to outward air leakage and diffusion of moisture from the high humidity air in the operating room suite melted to drain and accumulate on the shelf angle during mild weather or solar heating. The subsequent freezing, melting, and freezing of the accumulated moisture incrementally pushed the lower course of brick outward until it reached observable proportions. Ice lensing in mortar accumulated at the base of a cavity could act in the same way.

In suggesting that drainage of moisture from wall cavities is important, it should be recognized that icicle formation may occur if nothing is done to reduce the amount of moisture condensation in such cases. The importance of achieving airtightness of the inner wall components must be stressed. It may not be effective in reducing spalling and mortar deterioration caused by rain wetting, but is a necessary requirement for avoiding other problems in building envelopes.

PRECAST CONCRETE WALLS

Precast concrete cladding offers many of the advantages of masonry while allowing for faster erection and consequent savings in total cost. Panels may have an exterior finish involving sculptured concrete, exposed aggregate, decorative stone, or brick veneer. In colder climates, sandwich panels incorporating air spaces and thermal insulation are sometimes used, but the more common construction involves thinner precast panels hung on the building frame at column or spandrel locations with a back-up wall of masonry or steel stud framing. With steel stud framing, gypsum sheathing is often omitted, and in cold climates it is replaced with mineral fiber or foamed plastic insulation.

As with modern masonry construction, there is an opportunity to protect the floor slab edge with some form of rigid insulation. Normal concrete construction tolerances may not be precise enough in higher buildings, and the space allowed for insulation may be usurped to maintain precast panels' vertical alignment. As a consequence, the desirable thickness of insulation may not be maintained. In any event, the precast concrete panel anchors offer a highly conductive thermal bridge wherever they are located. In many instances this is at a column location, and little room may exist for access to insulate or to effect air sealing. When the exterior precast is erected before the in-fill walls are built, provision can sometimes be made to treat the anchor locations.

Since the precast anchors form a high conductivity path, they offer likely locations for condensation to occur. Consideration should therefore be given to corrosion protection or through increasing the thickness to provide extended service life for the anchor supports.

Condensation accumulating on the back face of the precast concrete panel may manifest itself in the formation of icicles at horizontal joints in cold weather following a warm spell or because of solar heating. Cases of icicle formation have been reported for some buildings in cold regions. In most cases the problem has been traced to excessive air exfiltration through major openings in the back-up wall, often at precast anchor locations. In some instances it was discovered that these openings had been made by the precast erection contractor after installation of a reasonable airtight back-up wall [*15*].

Since precast panels are made in reusable forms under controlled conditions in a central plant, the quality of the concrete and adherence to specified tolerances are generally assured. Air entrainment, adequate cover for reinforcing steel, and other precautions can be undertaken to ensure freeze-thaw resistance. The concrete panels themselves can thus be considered relatively impermeable to water penetration, particularly when compared to masonry, and rain leakage problems are usually confined to the joints. The traditional practice of requiring an air space for drainage behind the panel persists, however, and although this requirement offers a practical way to allow for construction tolerances in the erection of cladding panels, it can greatly complicate the design and fabrication of precast, insulated sandwich panels [*16*].

Rain penetration at joints between panels and between panel openings and windows is best avoided by utilizing the two-stage weather-tightening system as in well-designed curtain walls. This involves providing a seal inward of the face of the panel that is tighter than the opening at the outside face. If the outer joint is left open, this is fairly easy to achieve even with a poor inner seal since the pressure differences across each seal vary inversely with the square of the leakage opening area [*3*]. It is this principle that led to the name "open rain screen" as a design concept [*4*].

The primary objective of the "open rain screen" or "two-stage weather tightening" principle is to avoid the openings in the primary seal becoming bridged with water, the primary seal being the seal subjected to the greatest air pressure difference. This approach to joint design was first advocated by the Norwegians and subsequently promoted by Canadians in North America during the 1970s. It represents a prime example of the practical application of science to building design as well as one which has become a byword for some modern practices that are not entirely consistent with the principles.

In many instances designers and builders have regressed to face sealing of joints, apparently to achieve a more desirable appearance. This has been carried to an extreme in the case of horizontal joints where the seal forms an effective dam against drainage from the cavity. This may be due to the incorrect assumption that no moisture will be present or ever enter the cavity or that the provision of some token "drainage" tubes at widespread intervals will serve as effective "pressure equalization" or drainage openings. Simultaneous, uninterrupted face sealing of vertical joints is also common, with reliance being placed on the ability of the sealant and of the applicator to achieve perfection under the vagaries of weather and the variety of materials and application conditions encountered.

A sort of "token" two-stage approach is attempted by specifying a bead of sealant inward of the face as well as a face seal. If this inner seal is not applied from the interior before the back-up wall is constructed, it must be installed by the sealant applicator from the exterior. The width of the joint or length of the nozzle required may be prohibitive, and in any event the adequacy of the seal provided can be questioned. More importantly, the variation in joint width normally experienced on-site requires the applicator to carry a wide variety of sizes of backing rope to cope with the range widths involved.

The effectiveness of this "inner seal" is directly related to the effectiveness of the outer seal. The more complete the face seal is, the greater the pressure difference is across it, and the more likely water will penetrate through any imperfections, and, being exposed to the weather, the more likely will imperfections tend to develop in the face seal. The situation represents a vicious circle that should be considered seriously by all designers.

In wall construction incorporating an air space behind the cladding, intermittent water entry may not be a problem providing drainage is not inhibited by such practices as sealing horizontal joints. Horizontal joints may well be left open at the face, with the lower panel surface sloped or flashing installed to direct water to the outside. Vertical joints could also be left open, with the inner seal effected with a backing rope and sealant where joint widths are suitable or with less airtight seals such as compressible, open-cell plastic foams treated to permit delayed re-expansion. If the outer face of the joint is left open, very limited airtightness is required of the inner seal, and the danger of its openings being bridged with water is very small.

The design of precast panels in the 1970s often incorporated lapped joints or splines to act as a deterrent to direct rain entry. The edges of vertical joints were also profiled to intercept water flowing laterally over the façade and to keep the bulk of it away from the open joint [*4*]. In one case, the use of a backer rope alone as an unprotected inner seal was shown to be more effective than face sealing in preventing water entry [*17*].

In the case of modern designs incorporating an effective seal or "air barrier" in the masonry or steel stud back-up wall and waterproof or water-shedding membranes or coatings on the exterior of the block or steel stud walls, there seems to be little reason why joints in precast concrete cladding cannot be left open provided that appropriate flashings or other means are provided for drainage [*4,16*]. In order to avoid excessive lateral airflow in the wall cavity, strategically placed barriers may be desirable at locations such as corners, where large pressure differences are created by wind [*4*].

PREFABRICATED METAL CLADDING

Many of the principles and practices involved in designing, detailing, and erecting precast concrete cladding and curtain walls apply in the case of prefabricated metal cladding panels. Metal and glass are impermeable to moisture, and precast concrete is essentially impermeable as compared to masonry. In terms of rain penetration, the joints between components are the only locations where penetration is likely to occur, and application of the principles of two-stage weather tightening will be the most effective preventive measure. Recognition that some moisture may enter the wall—from rain, water vapor from outdoors or indoors, or initially be present in the materials themselves—requires that some means be provided to ensure that it can escape. Drainage is particularly important in the design of metal cladding panels, and where inadequate provision for bottom drainage has been made corrosion has occurred, necessitating the complete removal of the cladding for both safety and aesthetic reasons. A parallel can be drawn between the corrosion of rocker panels in automobiles and the performance of some metal cladding panels. In both cases, inadequate drainage is the root cause. The automobile analogy can go one step further—the principle involved in preventing rain penetration at automobile door and trunk openings is identical to that of the two-stage weather tightening of joints in buildings.

EXTERIOR INSULATION FINISH SYSTEMS (EIFS)

EIFS Systems incorporate an exterior finish of polymer-modified cementitious stucco applied to a rigid plastic foam insulation applied to a steel stud or masonry back-up wall. In high-rise buildings, steel stud framing is usually employed, with the insulation and exterior coating secured to the framing and its exterior sheathing with adhesives, mechanical fasteners, or both. The sheathing used is gypsum board, cement board, or other noncombustible material. The exterior finish usually incorporates glass fibers and a glass or plastic mesh for strength and reinforcement. The system may be field applied or factory prefabricated.

Field-applied systems involve the erection of steel stud framing on site, with the application of exterior sheathing, foamed plastic insulation, and exterior finish undertaken from scaffolding or swing stage. Expansion or construction joints incorporate a preformed, semi-flexible metal strip or field-applied caulking to face seal the joint. The exterior finish usually involves a single basecoat followed by textured finish coats that may include larger aggregate particles. The basecoat and reinforcement is usually carried inward around window openings and the joint between the wall and window frame filled with caulking to achieve a face seal.

Factory-prefabricated panels are patterned after prefabricated concrete systems but are much lighter and can incorporate intricate and bolder sculpturing. They differ from field-erected systems in that they involve structurally designed, welded steel framing, and the exterior finish basecoat and reinforcing is carried much further inward at panel edges and at window openings.

Although the EIF systems offer distinctive aesthetic, insulation, and weight advantages, the fire behavior characteristics of the foamed plastic insulations inhibit their use in the more densely built office and commercial buildings of a town center. The spatial separation requirements for limiting the spread of fire between buildings is perhaps the primary concern of fire officials, but the upward, vertical spread of fire is also a factor. There is more frequent use of EIF systems on residential high-rise buildings because of the greater separation between buildings resulting from land use and zoning bylaws.

Problems with the exterior finish such as peeling, discoloration, or cracking are usually attributed to incorrect formulation or application, with poor workmanship cited as the main reason. Problems involving wetting and deterioration of the gypsum sheathing or delamination between the layers of components are more likely the result of design or construction features.

In steel-stud backed systems, when additional insulation is installed in the stud space, wetting of the gypsum sheathing from condensation from indoor air can occur even in mild winter climates. There is usually no provision for drainage from the system, and as a result corrosion of the lower channel, rusting of fasteners, mold and mildew growth, and saturation of the gypsum sheathing can all occur. Increasing the thickness of the exterior insulation or avoiding additional insulation in the stud space will usually eliminate or greatly reduce the problem. Moisture problems from rain or meltwater penetration are usually associated with failure at the joints in the exterior finish.

Face sealing is the usual approach to preventing water entry at the joints in both field-applied and factory-fabricated EIF systems. In the panel systems, the water-resistant base coating, and, in some cases, the finish coating is carried around the panel edges to span the junctions between the exterior finish, insulation board, sheathing, and steel framing. In the field-applied system, this may be done only at window openings. In the field-applied system, the face seal must be perfect and remain so, for any moisture that enters might penetrate the joints between layers or lead to the deterioration of unprotected moisture-sensitive sheathing. A two-stage weather-tightening approach involving a more "open" outer joint cannot be used. However, such a joint design could be used between panels having protected perimeter edges, and, if the holes in the perimeter steel frame could be closed, the inner seal could be made at the inner face of the panel perimeter.

Maintaining an effective face seal is made more difficult with larger panels and with wider spacing of joints in field-applied systems, particularly in cold climates. The greater length between joints and the wider range of temperature extremes can result in expansion and contraction movements at joints which exceed the movement capability of the seal. There is thus a need for more information on the expansion and contraction characteristics of the exterior finish in order to assess the magnitude of such movements [*18*]. When the outer seal fails and water gains entry to the joint, the edges of the components and the joints between them are open to attack. Vertical joints will tend to drain, but if horizontal joints are sealed, the water is effectively dammed and lateral moisture penetration between layers can lead to delamination, deterioration of moisture-sensitive cladding, or mold and mildew growth on organic components. It may be wiser under these circumstances to consider closer spacing and two-stage joints having some drainage provisions [*17,19*].

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Recommendations for Remedial and Preventive Actions for Existing Residential Buildings

by William B. Rose[1]

THE PURPOSE OF THIS CHAPTER is to provide information on moisture control in existing housing stock to building professionals and owners. Moisture problems must first be identified, so a problem/remedy checklist is provided in Table 1. See also Chapter 13 of this manual for troubleshooting and Chapter 15 for general construction principles.

The principal focus of this chapter is on moisture problems that occur in homes during heating seasons. This focus results not from a determination of the greater incidence of moisture problems under those conditions, but rather reflects the focus of the research literature of the last few decades. Moisture problems during cooling seasons in hot, humid climates will be treated explicitly in this chapter. If, in any discussion of moisture problems, the climate conditions are not described, they should be presumed to be heating season conditions. Of course, excess moisture problems are rare in arid climates.

There are three basic strategies for dealing with moisture problems in existing residential construction:

- identify and reduce the moisture source
- modify the building envelope
- provide mechanical equipment and control

In general, it is wise to apply these remediation strategies in this order—one should not modify the envelope or add mechanical equipment until all unnecessary excess moisture sources have been removed or reduced. This order is also the order of expense; source reduction, in addition to being effective, is also cost-effective. Often no purchases are required when reducing moisture sources. Modifications to the envelope may involve cost, but good planning can keep these costs down. Adding or modifying equipment for moisture control involves not only capital purchases but may also involve additional operating costs. It should be noted that source reduction is not simply a function of the lifestyle of the occupants. Many building professionals, such as designers and builders, tend to underestimate the extent to which source reduction is within the scope of their work.

SOURCE REDUCTION

Groundwater

Wet basements and crawl spaces are common. Large quantities of water can be evaporated into living space from wet foundation walls and from the floors of basements and crawl spaces. One estimate of the amount of water that can be released from a wet crawl space is 85 to 105 pt/day (40 to 50 L/day) [*1*]. Tests conducted by Britton in 1949 indicate that moisture release from a 1000 ft^2 (92.9 m^2) surface of finely textured soil when the water table was located 30 in. (76.2 cm) below the surface amounted to 97 pt/day (46 L/day) [*2*]. Figures given in *Construction Principles, Materials and Methods* [*3*] show daily evaporation for a crawl space floor of bare earth with a high moisture content being higher than from standing water—130 pt/day (62 L/day) from wet soil as against 118 pt/day (56 L/day) from standing water. If the soil in contact with the foundation is at saturation, there may be an additional moisture contribution from leakage or capillary moisture drive. Diffusion of vapor from soil gas through permeable foundation materials is a mechanism of smaller magnitude and concern than water seepage or leakage into the foundation, but is not insignificant.

Moisture control for houses begins with proper site drainage. The *CABO One and Two Family Dwelling Code* [*4*] sets explicit requirements for foundation construction and drainage for residential structures. Section R-304.2 requires that the top of a concrete or masonry foundation be a minimum 8 in. (0.20 m) above the soil grade for the entire perimeter of the house. In addition, it requires (R-301.3) that there be a minimum 6 in. (0.15 m) of vertical drop in the soil slope in the first horizontal 10 ft (3 m) from the house. This means that the top of the foundation should be 14 in. (0.45 m) above the highest point in the soil grade 10 ft (3 m) away from the house (Fig. 1). Other model building codes have similar requirements [*5–7*].

Unfortunately, these criteria are often unmet. In the first few years following construction, the backfill often settles, creating a soil grade toward the house (negative slope). If downspouts deposit rainwater onto soil surface with a negative slope, that water tends to saturate the soil next to the foundation and cause seepage problems. Downspouts which deposit water onto the surface should ideally deposit water onto undisturbed soil rather than backfill, at least until the backfill has settled and has been corrected. The undisturbed soil begins usually 2 to 3 ft (0.6 to 0.9 m) away from a crawl space foundation and 3 to 6 ft (1 to 2 m) away from a basement foundation (see Fig. 1).

Porches, patios, stoops, walks, and driveways present a common drainage problem. They are often of cast-in-place concrete cast on a gravel base. The soil grade beneath the gravel base is at a lower elevation than the remaining soil. If water is permitted to run to these basins, it tends to collect there and from there to seep into the foundation. Surface

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TABLE 1—Inspection checklist

Problem	Due to	Solution
Roof leaks	Workmanship, products	Roof repair
Ceiling spotting	Roof leaks	Roof repair
	Ice damming	Roof ventilation
	A/c condensate	Clear condensate line, install backup pan
	Cathedral ceiling penetrations (recessed light fixtures, exhaust fans)	Install fixtures designed for air-tight installation, good workmanship
	Duct condensation (cooling season)	Re-wrap ducts with insulation and vapor retarder
	Wind-blown precipitation through vents and louvers	Select vent design for water exclusion
	Uninsulated (cold) spots	Add insulation to bare spots
	Plumbing vent condensation	Gasket between vent pipe and top plate
Mold on walls (heating season)	High indoor humidity	Find & remove excess moisture source, clean with dilute bleach solution
Mold on walls (cooling season)	Cold side vapor retarder	Use vapor permeable interior finish, avoid depressurization of interior
Window condensation	High indoor humidity	Find & remove excess moisture source, place heat source beneath window, open drapes and blinds
Mold or decay on floor framing	High humidity in basement or crawl space	Place ground cover in crawl space, correct site drainage
Roof sheathing: frosting, mold, delamination	High humidity in attic	Close holes in ceiling plane, add balanced ventilation
Exterior paint peeling	Moisture transport to outside	Reduce interior moisture level, allow moisture to escape behind siding
Exterior mildew on walls	Natural conditions	Remove by scrubbing, repaint with mildicide-containing paint
Mildew on bathroom tile grout and shower curtains	High bathroom humidity	Remove mildew, install and use exhaust ventilation
Water in basement/crawl space	Site drainage	Correct gutters, downspouts, drainage
	Plumbing leaks	Repair plumbing
	A/c condensate	Drain to outside
	Rising water table	Sump pump, consult geotechnical engineer
Truss rise	Wood characteristics and truss geometry	Fasten edge of ceiling panels to partition, not truss chord
Efflorescence on masonry and concrete	Moisture movement through materials	Reduce leak or moisture source
Mold on framing or trim at windows	Window condensation	Reduce high indoor humidity or locate heat source near window

management of rainwater should be carefully designed to prevent water accumulation in gravel bases.

Retrofit and construction detailing for basement and crawl space construction is given in Chapter 17 of this manual and in council notes from the Small Homes Council-Building Research Council titled *Basement Construction* [*8*] and *Crawl Space Houses* [*9*]. Good practice recommendations from those publications are shown in Fig. 2, and in a Canadian publication *Investigating, Diagnosing and Treating Your Damp Basement* [*10*], and below in this chapter.

Many of the techniques for managing water on the site and in the soil are outlined in *Architectural Graphic Standards* [*11*]. These methods include swales, french drains, drywells, cisterns, storm sewer systems, pumped drainage systems, and others. In principle, the first 10 ft (3 m) of soil surface outward from the building should act as a continuation of the roof, diverting water outward from the building and protecting the soil beneath from saturation. The soil surface should be relatively impermeable to water penetration, while still supporting the growth of lawn. Special care should be taken at the ends of downspouts where rainwater will be concentrated to ensure that the rainwater is diverted well away from the foundation. Often downspout extenders and splash blocks are used for this purpose.

A source for guidelines regarding subdrainage, waterproofing, and dampproofing of foundations is given in the *Building Foundation Design Handbook* [*12*]. If leakage persists through the foundation, the services of the municipal building engineer or a geotechnical engineer should be sought.

Combustion Appliance Backdrafting

The combustion of any fuel produces water as a reaction product. And all combustion products should be vented to the outside. Regulations governing the venting of combustion-fueled appliances in one- and two-family dwellings are given in Chapter 15 of *CABO* [*4*] "Venting of Appliances." Despite these regulations, water from combustion remains a source of excess moisture in many houses. Estimates of combustion product strength can be found in Traynor [*13*] and its cited references.

Unvented heaters are not uncommon. Small, unvented kerosene and gas heaters are for sale in most northern localities. The widest spectrum of moisture problems, including severe window condensation and extensive mold growth, should be expected in any living space heated with an unvented combustion appliance. (The humidity problem may be minor, however, compared to the health problems associated with

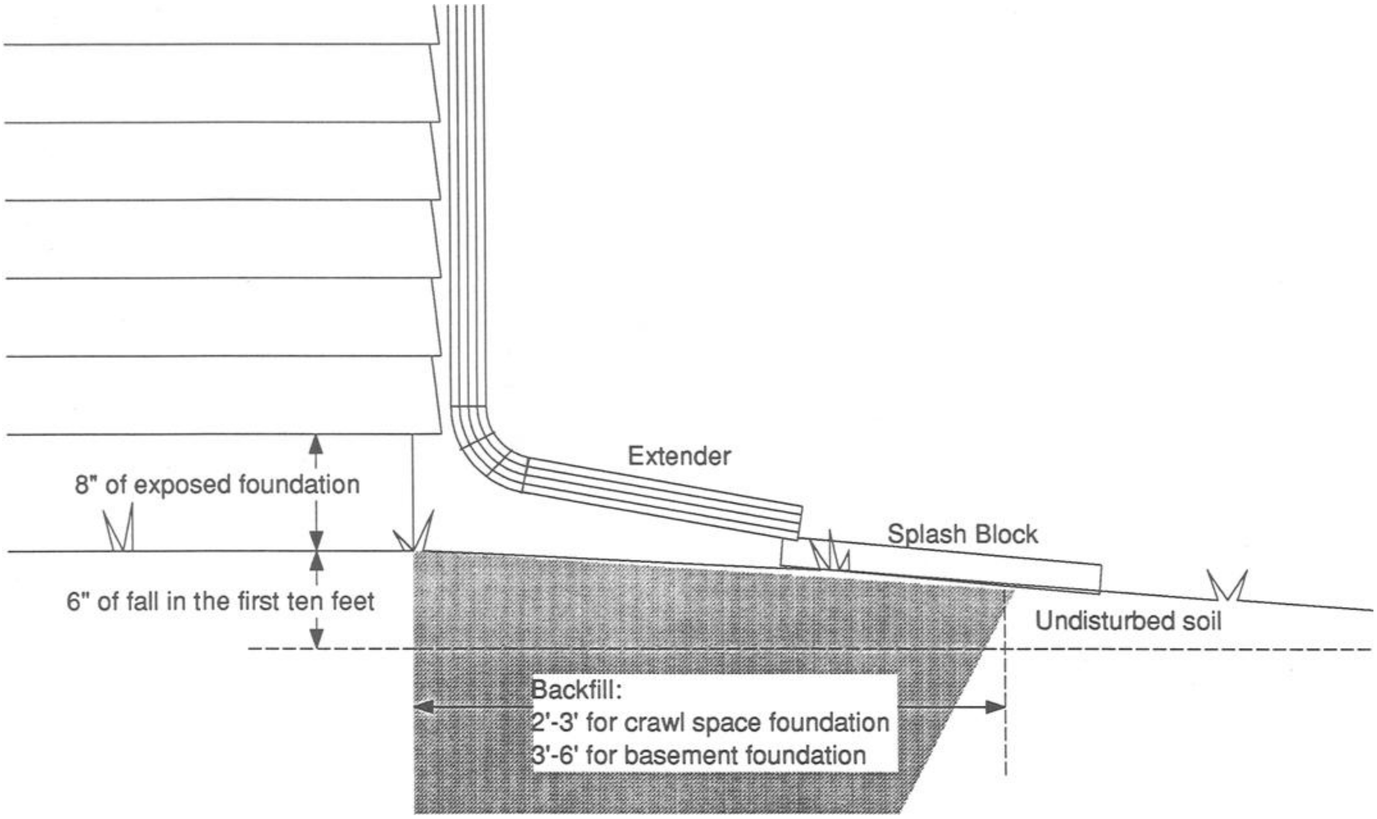

FIG. 1—The top of a residential foundation should extend 14 in. (35.5 cm) above soil grade taken at a point 10 ft (3.1 m) away from the foundation. This will provide satisfactory surface drainage and water protection. Water from downspouts should be deposited onto undisturbed soil, not into the backfill.

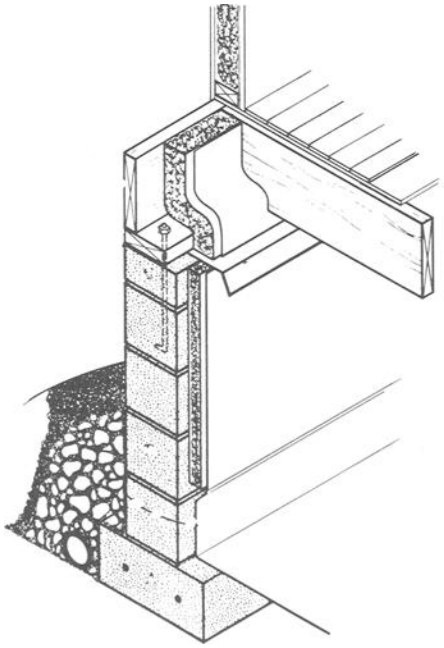

FIG. 2—Crawl space construction showing ground cover and insulation placement. If a crawl space is dry, the vents can be closed and the walls and band joist can be insulated.

accumulation of particulates, carbon dioxide, and carbon monoxide.) In some households, gas ovens and stoves are used as emergency space heating appliances; this is an unsafe practice which must be discontinued for safety reasons.

There are three generic types of venting systems for furnaces, boilers, and hot water heaters: draft hood equipped, forced convection, and closed combustion or condensing. The latter poses no risk that combustion products could enter the air space around the appliance. Backdrafting is the movement of warm humid air out of the draft hood of a combustion appliance. The amount of risk of backdrafting in an open combustion device depends on two factors: the design of the venting system, and the likelihood and magnitude of negative air pressures surrounding the equipment.

Any combustion appliance can be checked for backdrafting. The doors and windows of the house should be shut, the fireplace damper closed, and the appliance turned on. A smoke pencil can indicate the direction of airflow at the draft hood. The house should be tested with exhaust fans (bathroom, kitchen range, etc.) in operation, acknowledging that this presents a worst-case condition. Backdrafting may also occur with a fireplace or wood-burning stove in operation.

A long-term test for backdrafting can be conducted by placing carbon monoxide detectors (available at many hardware stores) or carbon dioxide detectors near the draft hood. These detectors can indicate accumulation of combustion products over time.

Recent federal legislation, the National Appliance Energy Conservation Act of 1987, mandates an improvement in the energy efficiency of many combustion appliances. To the extent that this legislation encourages the use of closed combustion appliances, it will have the effect of reducing the likelihood of combustion spillage. Whether or not more energy-efficient open combustion vent designs will affect the likelihood of combustion product spillage depends on the individual design.

If backdrafting is encountered, check the flue for blockage or excessive resistance, check the condition and height of the chimney cap or flue outlet, and consult with the equipment manufacturer regarding required installation practices. If the chimney and equipment installation follows the manufacturer's directions and backdrafting persists, the house may be subject to excessive depressurization.

Humidifiers

A common cause of winter discomfort is excessive indoor dryness. Tighter construction practices are tending to decrease complaints from dryness and increase complaints of excess humidity. Nevertheless, wintertime humidification is occasionally necessary [*14*]. When indoor relative humidity levels fall below 20%, static electricity shocks can occur. Vaporizers are sometimes recommended for certain mucous membrane, nasal, and bronchial conditions. At low indoor relative humidities, wood products can shrink, causing furniture joints to become unglued and some wood musical instruments to be damaged. For these reasons, the mechanical addition of water vapor during winter has become common. The pot of water on the stove or radiator has given way to central humidifiers in forced air heating systems. Humidifiers should be considered as appropriate equipment in northern climates provided that:

- the manufacturers recommendations regarding cleaning are heeded rigorously by the occupants
- the occupants are aware of indicators of excess humidity, such as mildew growth on walls or condensation running on windows, and are prepared to turn the equipment off, if necessary
- the limits of the accuracy of the control equipment are recognized by the homeowner

The most common humidifier control is a humidistat, which typically operates on the principle of physical elongation of a humidity-sensitive material (such as nylon or human hair). The most common error in the operation of humidifiers is the overreliance by occupants on the accuracy of the controls. Occupants should be instructed by manufacturers and installers regarding the normal operation and maintenance of the equipment.

If excessive dryness is noted in a house during the heating season, that house may be considered a good candidate for air change reduction in the interests of energy economy.

Many piano manufacturers include small local humidifiers in their catalogues, which can be effectively used to protect soundboards without necessarily elevating humidity levels throughout the house.

If a vaporizer or portable humidifier is used in a room during cold weather, local moisture damage may be anticipated. Window condensation may occur, and mildew may begin to grow behind furniture and in closets. If these effects do occur, the medical benefits of vaporizing must be weighed against potential allergy risks.

If excessive humidity is noted in a house, any humidifier should be turned off. It should be returned to operation only when excessive dryness appears as a problem.

Personal Moisture Sources

Humans produce water vapor which is discharged into the surrounding air through respiration and perspiration. Hite [*15*] found that a family of four with normal living and working habits (in 1948) generated 11 lb (5 kg) of moisture by metabolic processes in 24 h. This production rate is equivalent to running a humidifier continuously for 2 days [*15*]. These figures have, in general, been confirmed recently by Angell [*1*].

ASHRAE Standard 62-1989 requires minimum ventilation rates of 0.35 air changes per hour or 15 ft^3/min per occupant (0.42 m^3/min), whichever is larger. Where this standard is adopted, there is little likelihood of excess moisture being allowed to accumulate in houses, except in the case of excess moisture production or pressure imbalances. The most common form of ventilation in houses is exhaust from bathrooms and kitchens, which are often sites of moisture generation. Bedrooms, too, may have high concentrations of moisture due to respiration during sleep, occurring at night when room temperatures and air exchange rates may be lowest (see Trechsel [*16*]).

Only at very low air change rates, or in particularly dense quarters, can normal human production of moisture be viewed as contributing to moisture problems. Instead, most moisture problems in houses can be traced to excess moisture arising from foundation areas, backdrafting combustion appliances, or humidification. Solving moisture problems in houses should never involve discouraging occupants from normal habits of hygiene and cleaning.

Incidental Moisture Sources

A thorough inspection of a residence for excess moisture sources may disclose occasional significant contributions from atypical sources. The production rate from these sources has not been quantified, but they are listed here for the sake of completeness:

- dryer vented to the indoors, or clothes drying indoors
- gas pilot light on stove and oven
- refrigerator defrost
- drying firewood indoors
- plumbing leaks
- air conditioning condensate leaks
- roof leaks
- food processing
- excessive number of plants
- uncovered filled hot tubs and pools
- large uncovered aquariums

If any of these cases appear to contribute to excess interior humidity, the solution should be obvious.

MODIFICATIONS TO THE ENVELOPE

Modifications are often made to the building envelope, but usually for reasons other than moisture control. The most common reasons are for energy efficiency ("weatherization"), renovation, home improvement, or upkeep. The following discussion will review the implications for moisture control of common modifications to the envelope.

In this discussion, it is assumed that windows and mechanical devices are the appropriate means for providing fresh air to occupants and that accidental openings in the envelope (cracks, for example) are neither appropriate nor effective devices for providing necessary fresh air. That is, this section argues that continued tightening of the envelope is desirable and that provision of fresh air to the interior to meet minimum ventilation requirements and to dilute produced moisture should result from design intent rather than component fit.

Most residential envelopes are designed to resist moisture damage during heating seasons, when the vapor drive is from the inside out. During summers, with air conditioning in use, the direction of vapor movement is reversed. This reversal does not put the envelope seriously at risk except in hot humid climates and particularly in depressurized buildings—see below.

Basements

Basements should be dry. The most common source of excess moisture for basements is outdoor rainwater, which, in the absence of good site drainage, can saturate the soil surrounding the foundation. Water in saturated soil can migrate through cracks and capillaries in the foundation material and evaporate indoors.

Current codes [*4*] require dampproofing (which inhibits moisture diffusion) of all residential foundations and require waterproofing (which inhibits capillary movement and seepage) if the lower level is to be used as a habitable space. Dampproofing usually consists of an asphaltic coating trowel applied to the foundation. Waterproofing requires the design of a system for the removal of water from the foundation. Foundation drainage must be provided according to building code (*CABO*, R-305.1,2) in poorly drained soil, whenever the below-grade rooms are for habitable uses. Dampproofing, waterproofing, and foundation drainage in existing buildings can be achieved only after excavation of the soil surrounding the foundation; thus, they are rarely considered as retrofit strategies.

However, there are many structures in place which lack effective exterior dampproofing or waterproofing and which lack operating foundation drainage. Leakage and seepage of water into such basements is a common problem. If leakage occurs within hours after heavy rains, the problem is probably associated with surface drainage of rainwater, and corrective site drainage measures, described above, should be taken. If the water problem occurs at the basement floor level and with a longer delay after rains, the problem may be associated with rising groundwater. Temporary correction of groundwater problems requires the installation of a sump pump to evacuate water from beneath the floor slab. Water problems may occur in a basement with the failure of a municipal storm sewer system or sump pump designed to drain water from footing drains. Inspection, diagnosis, and repair of basement walls is discussed in CMHC [*10*].

If water problems occur in basement walls, then excavation around the walls and retrofit installation of foundation (footing) drainage and dampproofing or waterproofing may be considered. Excavation is often considered for the purpose of adding exterior thermal insulation. In any case, measures should be taken to discharge water that may accumulate against the foundation wall. Many new foundation wall drainage mats are being marketed that prevent the buildup of water pressure against the insulation or foundation wall. Adding a drainage mat increases the importance of providing dependable foundation footing drainage.

Most homeowners prefer to address wetness problems from within the basement. Certain paints, such as epoxy-based paints, may reduce moisture evaporation from wet walls. Any paint for this purpose must not only reduce the overall permeance of the wall, but must be able to adhere to a potentially wet substrate. Ordinary latex wall paint lacks the necessary adhesion. A number of basement dewatering systems are being marketed. They differ in effectiveness and should be considered only after site surface drainage measures have been exhausted.

Many homeowners wish to cover the concrete or masonry walls and to provide a finished interior surface in below-grade spaces. This should be done only with the assurance that water problems are unlikely. The following guidelines are offered for finishing interior basement walls:

1. Gypsum wallboard should not be applied directly to masonry or concrete foundations, but rather applied to furring strips or to framing. Insulation may be placed in the furring or framing cavity.
2. Installing a polyethylene vapor retarder is recommended to retard the overall flow of moisture through the wall. The vapor retarder may be placed against the foundation wall below grade in anticipation that the direction of potential flow is from the soil to the inside.
3. It is recommended that the bottom of wallboard products be held above the floor to reduce the likelihood that it be damaged from floor flooding or capillary rise. The gap can be covered with appropriate trim.
4. It is desirable to be able to inspect the top of the foundation wall for termites, infiltration, and condensation on the edge of the floor framing. For this reason, it is advised that a removable trim be applied at the top of the wall.

Crawl Spaces

Crawl spaces should be dry. Keeping them dry depends on site surface drainage, described above. Crawl spaces should be inspected seasonally. To encourage seasonal inspection, they should be constructed and maintained to be pleasant: access should be relatively easy; light fixtures with an accessible switch should be provided; clearance requirements (usually 18 in. or 0.5 m) should be respected; the soil surface should be level and free of debris.

All crawl spaces require a ground cover over the entire soil surface. This is often a layer of medium strength (6 mil) polyethylene sheeting, although ground covers can be of asphalted felt or concrete. Roofing felts may become brittle with time; concrete can crack if too thin, is more permeable than polyethylene, and is less comfortable on knees than soil or gravel. The ground cover should be strong enough to resist tearing during inspection or repairs. There is no need for ballasting ground covers in crawl spaces; in fact, unballasted ground covers are able to float above rising water in crawl spaces and to resettle in place with minimum evaporation. If a ground cover is damaged or becomes embedded in soil or buried beneath gravel, a second ground cover can simply be added on top. (The "double vapor barrier" concern does not apply.)

Crawl spaces should be inspected regularly. The inspector should look for exposed soil, puddles of water on top of the ground cover (which may be due to seepage through the foundation walls, plumbing leaks, or air conditioner condensate), and mold, mildew, or fungal growth on the floor framing overhead. Even dry crawl spaces may show signs of having had puddling and water accumulation. The source of any water should be located and corrected. Crawl space inspections for mobile homes should include an inspection for any possible water accumulation in the bottom board or belly paper. A crawl space inspection may also include a check of ductwork and other mechanical systems.

The living space should be insulated from the outdoors at the crawl space. There are two common insulating strategies: insulating the crawl space walls, and insulating the floor framing.

Building codes have historically required crawl spaces to be vented. The most commonly cited requirement [CABO R-309.1] is for a total vent area of at least 1/1500 of the covered crawl space floor area, with vents located within 3 ft (1 m) of the corners of the foundation. At the time of the introduction of this guideline in 1949 [*17*], insulation was not commonly used. Research into the relative effectiveness of wall-mounted versus floor-framing insulation has been hampered by the lack of a well-characterized test soil and by the lack of devices for accurately measuring the amount of moisture evaporated into crawl spaces under different construction configurations.

Nevertheless, wall-mounted insulation has been increasingly used in crawl space construction. Insulating material, usually 2 in. (50 mm) polystyrene panels, are spot-adhered to the walls and mineral fiber batts are cut to fit against the band joist. Once the crawl space is determined to be dry, the crawl space vents themselves are closed and insulated with foam panels. This method has the advantage of safeguarding pipes against freezing and reducing energy losses in duct work that runs through the crawl space. Insulating the walls of a crawl space is the preferred option provided the crawl space is dry. The crawl space vents may be helpful in the event of accidental water accumulation in the crawl space.

Alternatively, insulation may be applied in the floor framing, thereby insulating the living space from the crawl space. In this method, the floor framing cavity is filled with a mineral fiber or loose fill insulation. The undersides of the joists must not be allowed to remain exposed to the crawl space, but should be covered with a vapor retarder. Any exposed wood would be subject to the cold, saturated conditions often found in crawl spaces and may suffer microbiological deterioration. The insulating material should also be well fastened into the cavity, to the floor framing of the crawl space. This option has the disadvantages of risking frozen pipes and energy losses through ductwork.

An additional concern for floor-insulated crawl spaces occurs in areas with high ambient (outdoor) humidity and cold soil temperatures. In this case, insulated floor joists may be chilled by radiant exchange with the cooler soil. If the bottoms of the joists are cooled below the dew point temperature of outdoor air, then the moisture provided by ventilation may keep the floor joists near saturation. A review of local soil temperatures and ambient humidities should indicate whether or not this is a local problem.

The band joist is the outside perimeter floor framing member. In cold weather it may be a site for moisture condensation within wet crawl spaces. Frequently, insulating materials are applied to the band joist from the inside, which has the effect of lowering the surface temperature of the band joint and increasing the likelihood of moisture damage. Obviously, the band joist must be protected from humid air. The first step is to keep the crawl space dry. Further protection may be afforded to the band joint by covering the band joist insulation with a vapor-retarding material.

Crawl spaces should not be used as a plenum in any recirculating heating or cooling system. Problems with such an approach include not only moisture but also radon and soil treatment chemicals. Some designers successfully use the crawl space as an exhaust plenum in a mechanical house ventilation system. Such a design provides some protection against the movement of crawl space gases (including possibly moisture, radon, and soil treatment chemicals) into the living space.

The air from basements and crawl spaces has been shown to migrate upwards through partition walls and service chases into the attic. One strategy for preventing damage to attic sheathing from humid air from the basement or crawl space involves blocking airflow through these chases. However, to date, systematic details for achieving airtightness in the floor framing above basements and crawl spaces have not been presented.

Walls

Wall moisture problems may be exterior (paint peeling, deformation of siding, mildew on exterior finishes, efflorescence on masonry or concrete veneers), interior (nail popping, rusting of wallboard fasteners, mold and mildew) or interstitial (condensation in framing cavities, wetting of insulating materials).

Paint peeling may occur for many reasons, including poor substrate preparation, but in many cases it indicates excessive moisture drive through the siding material. A common solution is to provide for the free exchange of air between the back and front of the siding material—the rain-screen principle. Often the problem is solved by residing with a material less prone to damage from moisture drive or by removing the paint film and recoating with a stain product which is more permeable to moisture movement. The vapor drive can be reduced by identifying the moisture source—usually either indoor moisture or rainwater drawn behind the siding which reevaporates—and reducing the strength of that source. The thermal expansion and contraction of paint films due to effects of sun and ambient air temperature may play a significant role in the success of exterior paint finishes.

The same factors that govern the success of paint finishes—moisture drive and temperature swings—affect the condition of many wood siding products. The problems are solved as above by identifying the source of moisture and reducing the drive due to this source. Siding products should be installed to allow any water which may be drawn behind the siding to dry as rapidly as possible.

Mildew on exterior finishes is seldom associated with indoor moisture conditions. Instead, it seems to occur where the microstructure of the exterior finish allows dirt to collect, which serves as the growth medium for mildew. Mildew may be cleaned off using a detergent. The surface can be repainted or restained with a mildicide-containing finish. The effectiveness of any mildicide will degrade over time.

Efflorescence is the deposit of white salts from within masonry or concrete walls onto the surface. It is due to the effect of water moving through the wall, transporting soluble salts to the surface where the water is evaporated. Efflorescence indicates an unwanted moisture source on the face opposite the efflorescence. The possible sources may be interior moisture, roof leaks, flashing leaks, leaks at window joints, and many others. Excess moisture sources should be eliminated. Weep holes are included at the bottoms of masonry faces to relieve moisture buildup and to drain water which may accumulate in the cavity. Often weep holes need to be cleaned of debris. The salt deposition due to efflorescence may be removed either by abrasion or chemically. In removing efflorescence from brick masonry, care should be taken to leave the brick firing glaze intact.

Interior moisture problems in walls in northern climates are usually due to excess indoor humidity, to the inability of walls to withstand excess moisture, and to their inability to dry out after wetting events. These problems commonly include rusting fasteners, mold or mildew growth (often in closets, behind wall hangings, and behind furniture), and water spotting. Nail pops (protrusion of wallboard fasteners beyond the plane of the wall) are often attributed to moisture damage. However, they are most often due to wallboard being forced against the framing lumber after it has undergone normal shrinkage. The moisture source causing minor interior problems can be eliminated and the problem areas often simply cleaned and repainted.

In humid southern climates, however, the set of problems has a different cause and may more stubbornly resist solution. During seasons of extended air conditioning, the primary vapor drive is inward. If the interior wall covering or coating has a low permeance, then moisture can accumulate in the wallboard, leading in some cases to the formation of mildew behind the covering. The likelihood of damage is reduced if vapor protection is provided at the outside, so that the framing cavity is uncoupled from high outdoor vapor pressures. Mildew accumulation in the wall components can be relieved, as well, by using an interior finish which has a higher permeance. Mildew problems in hot, humid climates are most common in conjunction with depressurization of the interior spaces, as in hotel and motel rooms which typically require constantly running bathroom exhaust.

The traditional concern in both northern and southern climates has been the formation of interstitial moisture, i.e., condensation of vapor to liquid water on the cold side of framing cavities. Field studies [Tsongas, *18*] have shown that actual occurrence of interstitial moisture may be uncommon, even in cases where it had been most feared—i.e., in walls insulated without a vapor retarder. The amount of risk of interstitial moisture for any wall assembly is affected by factors such as moisture storage, moisture sorption and desorption, routes for drying, orientation, as well as air barriers and vapor retarders.

Inspecting for interstitial condensation is difficult. A full investigation would require removal of all the interior surfaces, so it is rarely done. A local, nondestructive inspection consists in: removing the cover plate from an electrical receptacle located on an outside wall, inserting a long thin probe (screwdriver or ice pick) in the crack between the outside of the electrical box and the wall surface (plaster or drywall), poking the sheathing to test for soundness, and replacing the cover plate, perhaps with a foam gasket to correct for the small hole made by the probe.

If softening of the sheathing is discovered, then the magnitude of the problem should be addressed before proceeding with a remedy. Surface molds can be cleaned from wood with a dilute (10:1) bleach solution. Structural members can be tested for strength (usually with a scratch awl or ice pick) and replaced if necessary. Interstitial moisture problems are most prevalent on the north and east sides of buildings because of colder temperatures on the north and the tendency for prevailing winds to charge east-facing cavities with indoor air.

The principles for correction are the same as those governing new wall construction (see Chapters 15 and 17 of this manual).

Walls are often weatherized for energy economy by the addition of insulation in cavities and the caulking and sealing of cracks. Weatherizing typically reduces the amount of air movement through the walls and thereby influences the moisture balance in a house. Some homeowners have discovered moisture problems in houses after weatherization due to high indoor humidity from an excess moisture source which is less diluted in a tightened home. The solution to these problems lies in identifying the source of excess moisture (usually foundation moisture, humidification, or backdrafting) and reducing it.

Studies have shown that moisture movement in walls is affected more by convective effects rather than by diffusion effects [*19*]. Thus, attempts to correct local wall moisture problems (indicated by paint peeling, siding deformation, etc.) should be focused first on preventing air movement from humid spaces into framing cavities. This can usually be done by caulking and sealing around electrical boxes, and at the base trim.

Diffusion is a smaller but nonnegligible participant in moisture transfer through walls. Retrofit membrane vapor barriers are not very common. All paint finishes provide a measure of vapor diffusion protection. Some paints are marketed as vapor retarder paints and are used primarily in retrofit applications. The permeance values of some typical paint products are listed in Chapter 3 of this Manual and in *ASHRAE Fundamentals* [*20*], Chapter 22. However, the values for specific paints should be verified with the manufacturer.

Windows

Windows serve as indicators of elevated interior moisture levels. While there has been no formal standardization of acceptable residential indoor humidity levels, a common rule of thumb is this: the indoor humidity is too high if condensation remains on the inside surface of a double-pane window unit [*21*].

Windows are often the building component most likely to be damaged by high indoor humidity. If window condensation occurs, the frame and surrounding trim may be water-damaged. Some units, particularly aluminum or vinyl frame units, may be designed to expel condensation through weep holes and act somewhat effectively as dehumidifiers. Moisture damage to windows can be corrected most effectively by reducing levels of indoor humidity. The likelihood of condensation on window panes is reduced with the selection of window units with higher thermal resistance. Double-pane glass sometimes shows condensation around the edge of the pane, indicating a high thermal conductivity of the edge spacer. Some recent research focuses on the development of more thermally resistive edge spacers. Increased thermal resistance of the glazing is usually accomplished with additional panes of glass or with a variety of heat-reflecting films. The likelihood of window condensation is decreased by placement of a heat source beneath the window and by opening drapes and blinds. Bay windows are often more prone to condensation because the heat supply is not directly beneath.

Most newer buildings in the United States use at least two panes of glazing. The glazing may be sealed or may be storm windows applied to other "prime" windows. Condensation or frost sometimes occurs on outside storm glazing during cold weather. Aluminum units cannot be damaged by condensation. Most storm windows have weep holes at the sill in order to equalize vapor pressures between the outside and the window cavity and also to provide for condensed water to drain to the outdoors. Condensation on storm windows is less likely to happen if the prime window is tight in the frame and is closed tightly.

With certain exceptions, every habitable room in a residential structure must be provided with operable windows [CABO R-203.1]. Every habitable room should be provided with a potential source of fresh air that can be controlled by occupants. This fact should serve to overcome objections to tight envelope construction—any possible reductions in air change rate through the envelope can be compensated for by opening windows. There is a significant amount of consumer objection to opening windows during seasons of energy consumption, either heating or cooling. A number of "window vents" are being marketed, which serve to maintain a uniform sized opening area in existing windows to meet ventilation requirements in tight homes.

Attics

In northern climates, moisture damage to roof sheathing in residences has been considerable [*22*]. The damage may first appear as frost on nail points and panel clips. Wood product panels used as sheathing may lose structural strength with prolonged wetting. At certain conditions of temperature and moisture content, mold and fungi may attack sheathing products. Water in attics may occur from a variety of causes, including condensation of vapor generated indoors, roof leaks, precipitation blown through vents and louvers, leaking condensate at attic-mounted air conditioning units, and poorly insulated air-conditioning ductwork.

Current construction practice regarding ventilation and vapor barriers was derived from work conducted by Rowley in 1939 [*23*] and Britton in 1948 [*2*] and was incorporated into U.S. government documents in 1949 [*17*]. The research showed that, at moderate levels of indoor humidity (Rowley: 40 to 60% RH), both vapor barriers and ventilation reduced attic moisture accumulation. Since these early studies, construction practices have changed considerably, in particular with the introduction of greatly enhanced levels of attic insulation. Venting and vapor barrier requirements, on the other hand, remain virtually unchanged. Most model building codes require that the "net free ventilating area" be $\frac{1}{150}$ of the area of the space ventilated or $\frac{1}{300}$ of that area when a vapor barrier having a transmission rate not exceeding 1 perm is placed on the warm side of the ceiling (see *CABO*, Section R-707) [*4*].

There is no single common practice regarding the use of ceiling vapor retarders. Many building professionals consider vapor retarders helpful in preventing the diffusion of moisture into cold attic spaces. Many installers and finishers of ceiling systems object to ceiling vapor retarder membranes during the fall and winter when the work schedules of the various trades may force the ceiling finishing before the placement of the attic insulation. In this case, moisture from construction processes or from unvented temporary heaters may accumulate between the membrane and the newly installed ceiling, causing sagging, rusting, or deterioration. Proper scheduling, however, would obviate this concern. At moderate indoor humidities, both strategies—membrane vapor barrier and no membrane vapor barrier—appear workable. The only common retrofit vapor retarder is paint (see the brief discussion on permeances of paints above).

The attic ventilation issue remains the subject of much discussion. The traditional view is that ventilation provides a means for diluting moisture which may accidentally enter attics through openings in the ceiling plane. Attic ventilation certainly reduces the temperatures of attic air and sheathing and reduces the likelihood of ice damming in northern parts of the country.

In general, attic ventilation can dilute moderate amounts of moisture which enter the attic from below via convection and diffusion. However, when the outdoor air is cold, the potential for dilution of attic moisture is greatly reduced. The air exchange through vents is primarily wind driven, not thermally driven. The effectiveness of venting devices will vary considerably depending on their design. Soffit vents, gable end vents, and roof pots allow air to move in and out of attics depending on their windward or leeward orientation. Ridge vents operate primarily as exhaust-only vents because of their placement in an aerodynamic air stream. It is important for ridge vents to be accompanied by soffit or other vents, without which the ridge vent could actually induce the flow of humid indoor air up into the attic [*24*]. Mechanically powered venting requires large inlet vents to avoid pulling indoor air into the attic during winter. Timer controls are usually preferred over humidistatic controls because of the poor performance of humidistats in cold dusty conditions found in attics.

The principal means of preventing damaging moisture accumulation in attics lies in keeping indoor humidity low and in reducing airflow across the ceiling plane from the indoors into the attic. One strategy for moisture control in attics is to seal any penetrations through the ceiling plane. The methods typically used for achieving airtightness are caulking, sealing, and gasketting. Ceiling light fixtures are a common leakage site, although more airtight fixtures are commercially available.

Even more critical to moisture damage prevention are the service chases (plumbing, electrical, ductwork, and appliance flue), which are direct conduits of air between the attic and the foundation area. Moisture problems in crawl spaces, in particular, have been shown to lead to attic moisture problems [*22,25*]. Steps may be taken to reduce or prevent air movement through service chases, but materials and methods for achieving closure are not sufficiently developed. The actual sealing may take place at either the low or the high end of the chase.

Venting devices should be designed and selected for water exclusion. The choice of venting devices will affect the pattern of airflows in the attic: ridge and soffit venting will provide air movement close to the sheathing, while gable end louvers will provide air movement along the ridge.

Exhaust fans from bathrooms and kitchens must be vented to the outdoors, not into attics. Exhaust fans manufacturers can specify the proper duct or hose, which may terminate at any soffit or roof vent.

In houses with truss roof framing, a crack sometimes appears where the ceiling meets a partition in the center of the house, illustrated in Fig. 3. This problem, called truss rise or ceiling/partition separation, is associated with humidity conditions in the attic. The insulated bottom truss chord may shrink, depending on the peculiar wood characteristics in the chord and temperature and moisture effects. As it shrinks, truss geometry may cause it to bend upwards. The most reliable solution lies not in forcing the chord downwards, nor in cutting or reconfiguring the truss, but in using special drywall clips or blocking to attach the ceiling wallboard at the parti-

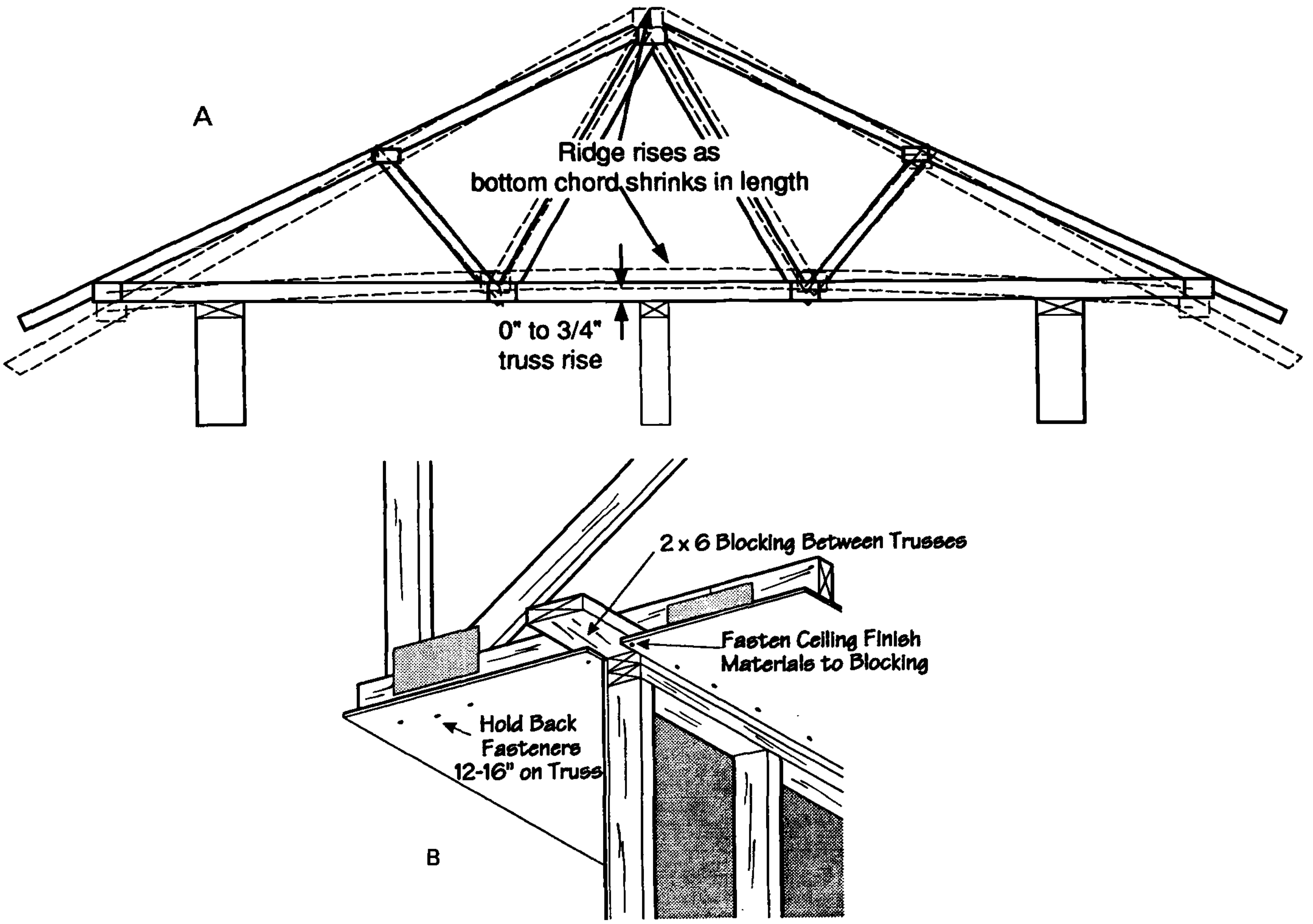

FIG. 3—(a) Truss rise, or ceiling/partition separation. This occurs when the bottom chord shrinks from dryness and is lifted upwards by the stable top chords and web members. It is solved cosmetically by attaching the edges of the ceiling drywall to the partition, not to the truss framing (b).

tion. This way the ceiling wallboard flexes with movement of the bottom chord, but the corner remains intact.

Cathedral Ceilings

Cathedral ceilings continue to be a troublesome building assembly. Water spotting on cathedral ceilings is, unfortunately, very common and may be due to a variety of causes: movement of indoor humidity into the cavity via diffusion, movement of indoor humidity into the cavity via convection, roof leaks, water entry through venting accessories, and ice damming. Inspection may not disclose immediately what the source of the water damage is because water entering at the top may run down. High spotting is usually associated with a roof leak or with rain or snow penetration through the vent.

Many builders seek to overcome cathedral ceiling problems by using scissor trusses, which permit interconnection of the roof cavities and thereby reduce the problems associated with individual cavity anomalies. Parallel-chord truss framing members achieve the same end.

In general, vapor retarders should be applied to the underside of cathedral ceilings. They provide effective assurance again diffusion transfer into cavities. In the life of a cathedral ceiling, the vapor barrier is often called upon to act as a secondary roof, which must discharge cavity water without damaging finishes. For this reason, it is often wise to install the barrier with "shingling" so that water entering high can run to the end, past the wall, without penetrating into the ceiling. This may be especially helpful in humid climates.

The airtightness of the ceiling plane is desirable in all cases. An airtight ceiling is effective protection against moisture damage where the moisture source is interior [*24*]. Any cathedral ceiling design in which venting induces the movement of humid indoor air into the cavity will be prone to failure.

In many designs of vented cathedral ceiling assemblies, certain cavities cannot be vented. These include hips, valleys, and roofs with skylights. Some designs, such as shed roofs, are difficult to vent while effectively excluding rain and snow. Recent work [*24*] indicates that under certain conditions, both vented and unvented cathedral ceiling cavities may guard against saturated sheathing under winter conditions. Further research on the performance of unvented cathedral ceilings is underway. In the meanwhile, code requirements (which usually require $1/300$ venting) and local practice remain as good guides to practice.

Vents should be designed to exclude water. Various designs make use of filters, baffles, screens, and angled openings to achieve this. In principle, vent openings should not point directly into the wind, but should make use of transverse air movement and buoyancy to assure air movement from the attic outwards through high vents; soffit vents should have small holes and should be located at the outer edges of overhangs. At ridges, hips, peaks, and eaves, vent designs can quite successfully exclude water. However, a particularly troublesome roof condition exists where the top of a sloped roof segment (a "shed" roof) intersects a portion of wall which continues upward from the roof. Any vent located at this intersection is subject to occasional positive air pressures, may not be able to fully exclude snow and rain, and should not be vented. By the same principle, roof areas subject to snowdrifts should not be vented.

Ceiling penetrations, such as recessed light fixtures, in cathedral ceilings may be troublesome. Water spotting can occur if humid indoor air passes through the fixture into cold cavities. In houses with high indoor humidities, ceiling light fixtures should be selected for airtightness.

PROVIDING MECHANICAL EQUIPMENT

Dehumidification

Any refrigeration coil with a surface temperature lower then the dew point temperature of the air serves as a dehumidifier. Mechanical dehumidifiers are self-contained units with chilled coils exposed to the indoor air. Dehumidifiers can effectively reduce humidity. The effectiveness depends on the rate of air movement across the coil, the temperature of the coil, and the rate of air movement within the house. There is an air characteristic, called the Lewis relation [*ASHRAE Fundamentals, Ref 20*], which states that the rate of moisture diffusion through open air is approximately the same as the rate of heat transfer through open air. This means that the room dehumidification effect is localized in a way similar to the heating effect of a room space heater.

Dehumidifiers are rated for their moisture removal capacity measured in pints/hour (L/h), which is measured at 80°F (26.6°C) and 60% RH. The units are designed for optimum performance at this temperature and humidity. If the actual conditions are less humid, then frosting may occur on the coil. Some models are equipped with defrosting cycles. In considering the purchase of dehumidification equipment, the removal capacity can be compared to the moisture production rate (see Chapter 8). The plastic water containers need to be emptied when the unit is in use unless tubing is used to drain the water to an outlet. Instructions from the manufacturer for cleaning the dehumidifier should be followed scrupulously.

Dehumidification equipment is rather expensive and is also expensive to operate. Most moisture problems in houses can be solved by source reduction or ventilation. In hot climates, air conditioning equipment is often a better choice for humidity removal than dehumidifying equipment because the unwanted heat produced at the air conditioning compressor unit is discharged out of doors.

Dehumidification occurs at the cooling coil in any air conditioning unit, whether central unit or room unit, whenever the cooling coil temperature is below the dew point temperature of the air. Residential cooling systems should be sized using standard industry methods, which are described in *ASHRAE Fundamentals*, Chapters 22 through 27 [*20*] and in "Manual J" [*64*]. For a given cooling load, a larger unit will provide the greater temperature-lowering effect (sensible cooling), and a smaller unit will provide a greater humidity-removing effect (latent cooling).

During the summer, the indoor conditions may feel "clammy," indicating that the ratio of sensible-to-latent cooling is too great. If the air-conditioning unit cycles on and off too frequently, condensed water may simply reevaporate into the air. Some cooling units may be adjusted to lengthen the cycle and thereby reduce the sensible/latent ratio. Alternatively, a second, smaller unit (a window or room air conditioner for example) may be used continuously to keep the humidity level low.

New technologies, such as heat pipes and desiccant wheels, may allow greater regulation of the sensible/latent cooling ratio.

Whole House Ventilation

House occupants need fresh air, of course. The rate at which outdoor air is provided depends on standards (such as ASHRAE 62-1989, which requires 0.35 ACH), implementation, and practice. Building envelopes are being built with fewer cracks and with reduced air change. Mechanical means are being more widely used to meet minimum ventilation requirements. Whole house ventilation is an excellent means for establishing and maintaining desired humidity levels in a residence.

Any system which actively exhausts house air and supplies outdoor air is a mechanical ventilation system. The principal types of mechanical ventilation systems include:

- simple exchange (usually exhaust-only)
- ventilation with heat exchange
- ventilation with enthalpy exchange.

A simple exchange system may be nothing more than a simple fan which exhausts air at a known rate to the outdoors. Makeup air comes through any accidental or intentional openings in the building. This strategy places the building in negative pressure with respect to the outside. Negative pressures in residences tend to keep building cavities more closely coupled with outdoor air, reducing the potential for interstitial condensation during cold weather. The reverse is true during warm weather.

Care must be taken to avoid backdrafting of combustion appliances. Most exhaust-only ventilation systems are used in conjunction with only closed combustion units. The fans which provide the exhaust may be those typically found in residences (bathroom and kitchen exhaust) or they may be installed for continuous use. As mentioned above, the venting device may exhaust into the foundation area (pressurizing it) with the aim of reducing the flow of soil contaminants into the house air.

Some of the cost of conditioning the air supplied for ventilation can be recovered using air-to-air heat exchangers or heat recovery ventilators. These devices can recover much of the heat of the exhausting air to heat up the incoming air. In cold climates, frost may form at the exhaust, and units must be equipped with a defrost cycle. These units are most useful in cold climates where the temperature difference indoors and out justifies the expense.

In humid southern climates, "latent heat recovery" or "enthalpy exchange" may be more important than "sensible heat recovery." Where a heating-season heat exchanger may use the heat of the exhausting air to heat up the incoming air, a cooling-season enthalpy exchanger may also use the dryness of the exhausting air to dry out the incoming air. Obviously, such equipment would be effective only in tightly constructed houses, and further equipment development may await the adoption of house-tightening techniques.

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20

Recommendations for Remedial and Preventative Actions for Existing Commercial, Institutional, and High-Rise Buildings

by Warren R. French[1]

Purpose

As WITH ALL SPECIAL APPLICATIONS of general principles, there are particular areas of concern when dealing with the design, construction, and maintenance of commercial, institutional, and high-rise buildings. This chapter will relate the principles previously stated regarding moisture migration, water vapor transmission, material properties, etc., to the special applications of some of these types of structures. Commercial buildings would include such occupancies as offices, retail spaces (including shopping malls), restaurants, and special purpose buildings such as business parks and light industrial facilities. Institutional buildings include hotels, hospitals, apartments, condominiums, schools, and prisons. Offices, hotels, condominiums, and hospitals are often designed with multiple floors in order to make the most use of available land. These mid- and high-rise buildings also have particular requirements with respect to roofing, waterproofing, and curtain wall construction. Two specific design requirements related to mid-and high-rise buildings involve the special exterior design wind pressures and internal pressurization arising from mechanical equipment (Figs. 1-3).

The best way to deal with moisture-related problems is during design and original construction of the building systems. The prevention of these types of problems is best accomplished by utilizing good design practice regarding roofing and waterproofing assemblies, including flashings, as well as the use of recognized industry standards such as "The NRCA Roofing and Waterproofing Manual," [*1*], SMACNA's "Architectural Sheet Metal Manual," [*2*], and the ASHRAE "1989 Handbook of Fundamentals" [*3*].

Troubleshooting

Before being able to develop remedial recommendations for repair or maintenance of a building, it is necessary to have a clear understanding of the problems being experienced by that particular facility. It is critical that this understanding include an identification of the moisture source, the mechanisms and paths of its migration, as well as related conditions that may have arisen from the original moisture problem. In addition, it is important to evaluate the possibility of associated problems—such as with structural, geotechnical, or mechanical systems—affecting the performance of waterproofing systems. Accordingly, it will most likely be necessary to develop and implement a testing and evaluation program appropriate to the particular facility and the problem being experienced. The reader is referred to Chapter 12 of this manual for proper steps to use in developing and using such a program. In addition, pertinent magazine articles have been written on this subject as well [*4*]. From the building testing and evaluation, a proper diagnosis of the problems and their cause may be derived; information provided in Chapter 13 of this manual will be helpful in establishing a proper diagnosis as required for each building.

After a diagnosis has been developed and appropriate recommendations developed, it is generally prudent to employ a small-scale or trial application of the proposed remedial work. This work could be implemented either on a small portion of the structure or on a limited number of acceptable units that are representative of the overall project. Upon proper retesting and reevaluation of system performance with the remedial work in place, the propriety and effectiveness of previous recommendations may be appraised. If required, appropriate modifications or adjustments may also be made to materials and methods of the remedial work in order to correct unforeseen, additional, or remaining problems. Once a satisfactory remedial program has been developed and evaluated, a full-scale and comprehensive application of remedial measures may be implemented on the entire building.

THE CONTROLLED SPACE

When considering the construction and performance of buildings for human occupancy, it is appropriate to think of these facilities as miniature environments in which an attempt is made to artificially control weather elements such as wind, water, temperature, and humidity. This miniature environment typically requires a space enclosure and a rather sophisticated "air conditioning" system. Interior spaces must be properly heated, ventilated, and cooled within acceptable parameters since inside activities can produce undesirable levels of humidity and carbon dioxide and outside weather conditions are usually in a state of flux and rarely "ideal." We will deal later with the composition and renovation of space enclosures, as well as the performance of this

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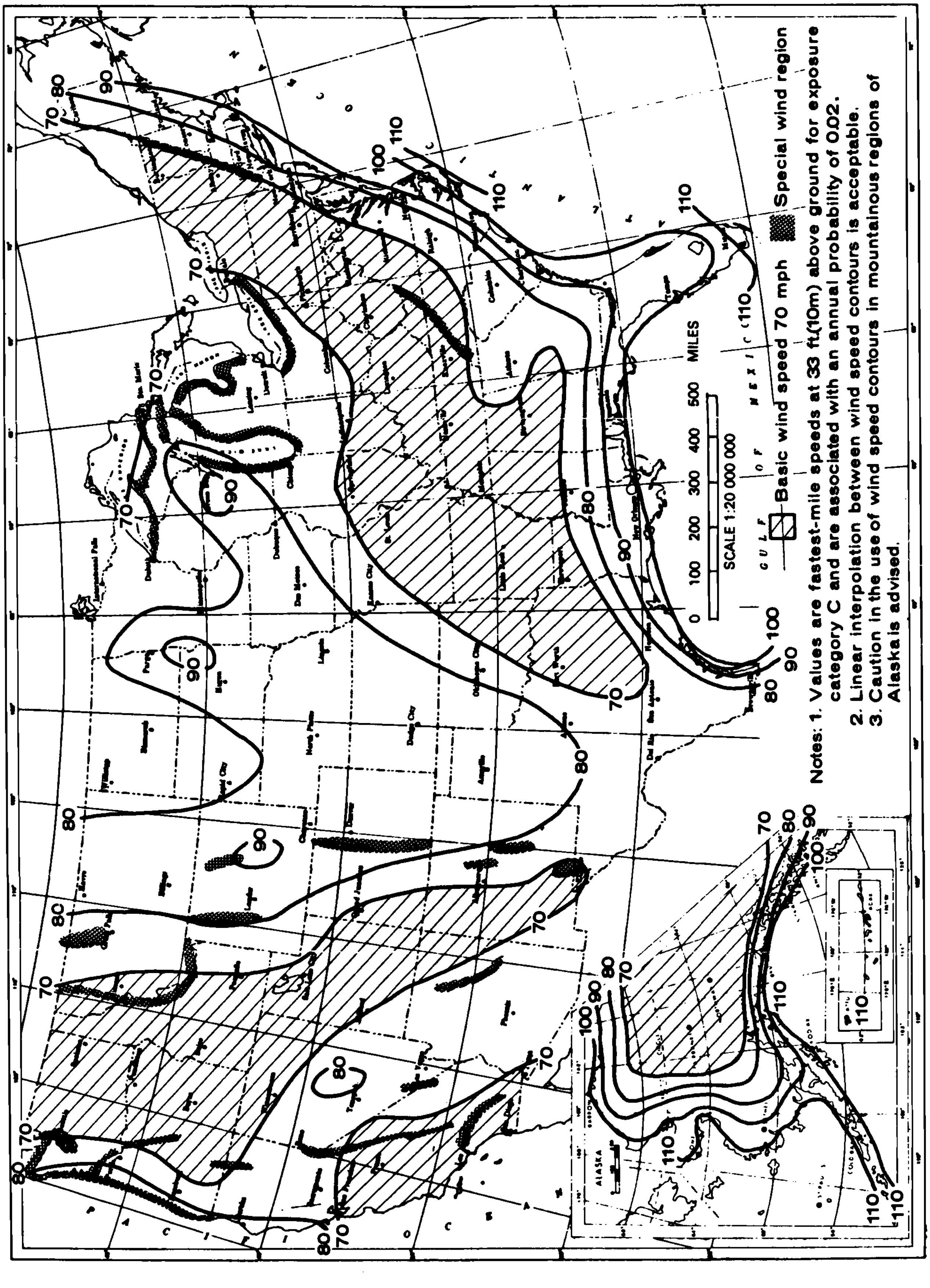
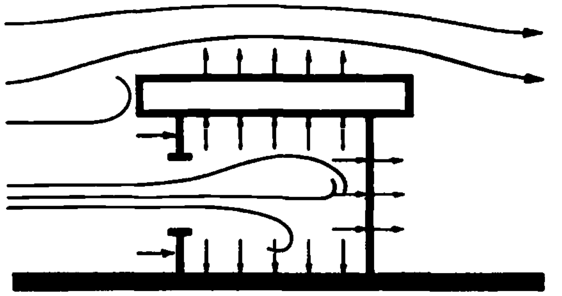


Notes: 1. Values are fastest-mile speeds at 33 ft (10m) above ground for exposure category C and are associated with an annual probability of 0.02.
2. Linear interpolation between wind speed contours is acceptable.
3. Caution in the use of wind speed contours in mountainous regions of Alaska is advised.

FIG. 1—Basic wind speed in miles per hour. Annual extreme-mile 30 ft above ground, 100-year mean recurrence interval.



Combined Pressure (windward openings)

FIG. 2—Wind striking a building causes pressure differentials.

physical space with respect to water leakage. At present, it would be beneficial to consider the operation of building mechanical systems on the controlled space and how this effects the space enclosure.

Performance of Mechanical Equipment

One of the primary areas of interest regarding the subject of controlling an interior space environment is related to the type of heating, ventilating, and air conditioning (HVAC) systems employed, including design and maintenance of these units. A comprehensive study of HVAC systems is beyond the scope of this chapter, but it is imperative for an investigator of building moisture problems to be familiar with several key concepts as they relate to moisture in buildings. A good understanding by the building investigator regarding Part 2 of this manual, and in particular Chapters 9 and 10, is recommended. If the investigator does not possess adequate technical skills and experience in this area, it would be prudent to retain the services of a specialty consultant to assist in evaluating existing systems within buildings experiencing moisture distress.

Although the initial costs and operating costs of HVAC equipment represent a significant portion of the building investment and expense, these systems may not have been properly designed, installed, or maintained. When one performs a forensic investigation of an existing building to address moisture intrusion problems, it is prudent to consider that flawed design and/or maintenance may be the cause of, or at least contribute to, the problem. All buildings are not designed and constructed with proper care and attention to detail as may have been required. For older buildings, changes in the ownership, occupancy, and usage of interior spaces may have occurred since original construction without associated revisions to the HVAC systems.

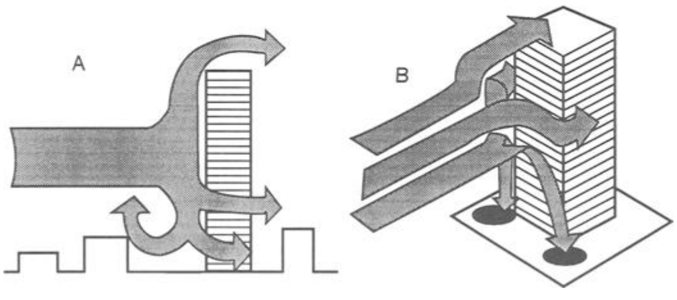


FIG. 3—Wind effects on tall buildings.

For these reasons, sizing of the building mechanical equipment must be reviewed for the interior spaces involved. Correct sizing of HVAC equipment requires a calculation of heating and cooling loads, air supply, circulation, and exhaust requirements, as well as proper duct sizing and configuration. Problems that may arise from deficiencies would include excessive temperature swings within the controlled space, inadequate ventilation, temperature layering, and room air "dead spots." Each of these conditions could promote or contribute to the formation of condensation, both within the space, as well as concealed within wall cavities, and to the growth of mold and mildew. Furthermore, HVAC equipment must be properly controlled within the space, preferably with automatic control devices that are independent of the need for manual operation by building occupants. It is desirable for some systems to be continuously operational, while the use of other systems will be seasonal or periodic. Each of these conditions must be evaluated with respect to their effect on the overall building performance. In any case, problems may again arise due to temperature extremes and from operating duration times for the various systems being"out of sync" with space requirements. Finally, it is important that the HVAC systems are balanced and adjusted in accordance with design specifications and in consideration of space conditions. Obvious anomalies regarding electrical power, motor gearing, air registers, return air obstructions, etc. should be corrected prior to attempting much involved analysis of the exterior building envelope.

Other than proper design and initial installation, there are very few conditions that affect HVAC performance more than appropriate system maintenance and service. The numbers of different types of equipment in use today would make it difficult to include a comprehensive listing of requirements related to this matter. Typically, for the best and most accurate information, the equipment manufacturer should be consulted. Generally, each manufacturer will provide recommended operating and maintenance procedures for his products. In some cases, it is prudent to obtain this data in order to assist in the evaluation. There are also obvious items of maintenance, such as regular replacement or cleaning of filters, replacement of belts, hoses, etc., and lubrication of moving parts. The frequency and effectiveness of previous maintenance activities could affect the performance of existing HVAC equipment and should be checked out. Obviously, if components of the system have become dysfunctional or of decreased capacity, overall system efficiency will suffer. These types of conditions should be repaired by trained and experienced service representatives familiar with the type of equipment in question.

Ventilation

One of the primary concerns involved in establishing an effective HVAC system is achieving proper ventilation of the occupied space. ASHRAE has established minimum guidelines for the design and installation of ventilating systems, including recommended air changes for specific activities and occupancies [5] (see Chapter 9). The principal subject to be reckoned with in regard to ventilation systems and moisture within the building (besides humidity levels) is the relationship between "outside" or make-up air and exhausted air. It is particularly critical that the overall volume or mass transfer of these two components are properly balanced. Typically, it is desirable to achieve a slightly positive pressure within occupied spaces in order to alleviate air and dust infiltration; however, this may change depending upon the overall design concept of the HVAC system developed by the mechanical engineer. Sometimes, if exhaust and intake air masses are not carefully controlled, an inadvertent reversal of the inside/outside pressure differential may occur with deleterious effects on the building moisture balance.

Humidification/Dehumidification

It is a well-known principle that proper ventilation can often help control humidity levels within buildings; however, it should be clarified that this is primarily effective only for winter time conditions, and specifically in the case when cool, dry outside air is infused into the occupied space in order to displace humid interior air. Obviously, introduction of excess outside air into a building located in a hot, humid climate would most likely not have a beneficial effect on interior humidity levels. Therefore, mechanical means of removing moisture from the air, or dehumidification, is commonly required for these conditions. Fortunately, the same equipment used to provide cooling of the room air, namely the cooling coil of a common air conditioning system, is quite effective at removing moisture, or latent heat, from the air. This process occurs due to the particular psychometrics of moist air when it is sufficiently cooled from a previously existing condition (see Chapter 8). Typically, sufficient dehumidification will occur due to room air passing through the coil to shed sensible heat and is usually adequate for most buildings. Of course, special dehumidification requirements could arise due to any number of unique conditions, both external as well as internal. For these types of applications, special sorption or pressure drying equipment must be utilized.

Humidification may be required in certain arid climates and during winter design modes where cool, dry outside air has been heated and introduced into the occupied space. These applications require atomization, heated pan, steam, or wetted element equipment to achieve the desired result.

Some of the external sources of moisture that must be dealt with can result from moist air leakage and infiltration, water vapor diffusion, and absorption and wicking of moisture into and through construction materials exposed to exterior weather elements. In addition, this exterior moisture can be moved through openings in the exterior envelope by a number of forces, including gravity, surface tension, kinetic energy, capillary action, air currents, or pressure differences (Fig. 4). This latter condition, when related to absorption and capillary action of water within building components in contact with the ground (i.e., foundations), is sometimes referred to as "rising damp." Some of the internal sources of moisture that may occur are related to special occupancies and usage, such as indoor or enclosed swimming pools, spas, shower rooms, greenhouses, laundries, kitchens, and other process areas.

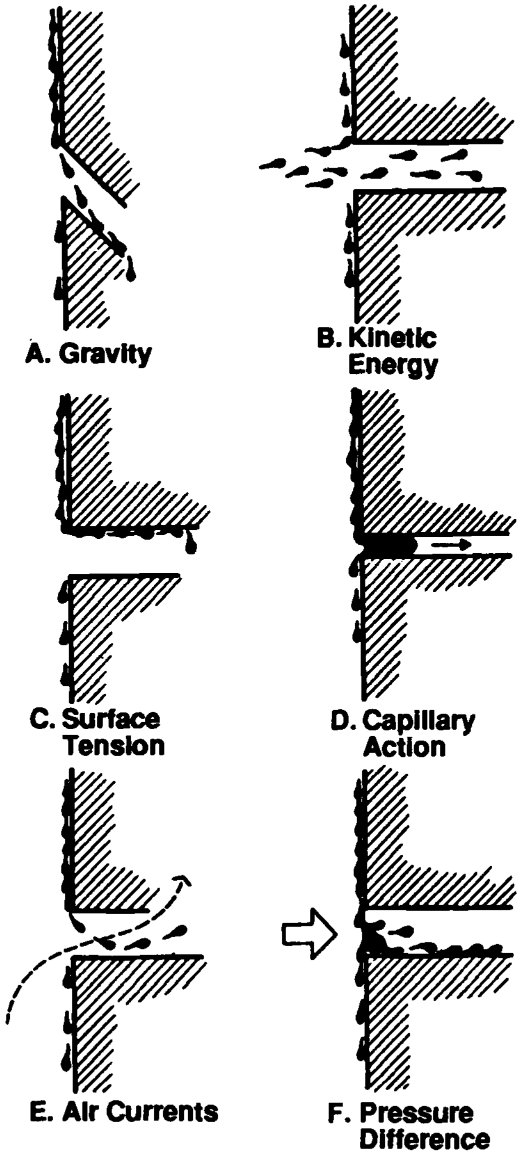


FIG. 4—Forces acting to move water through an opening.

Building Pressurization/Depressurization

Interior spaces may develop a negative differential pressure with respect to outside ambient conditions, or they may develop positive differential pressure. The former condition may arise due to a greater volume of air being exhausted from the space than is being supplied. Conversely, if a greater volume of air is being supplied to the space than is being exhausted or that can escape from natural openings, then the space pressure is likely to become positive. Under certain conditions, a slightly negative room pressure can result in excessive air and dust infiltration, as well as direct water leakage through faults and openings in the wall. Therefore, the building investigator is obliged to be aware of the particular HVAC design aspects of the project in order to accommodate them properly.

It is as important to achieve a proper pressure balance within the controlled space as it is to achieve proper temper-

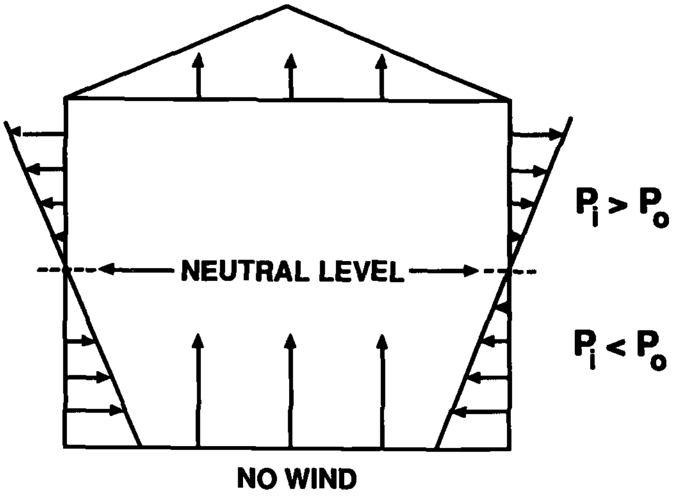


FIG. 5—Pressure differences caused by stack effect for a typical structure (heating). (Arrows indicate magnitude and direction of pressure difference.)

ature and humidity balance. Pressure balance differentials can result in drafts, doors being difficult to open, and confinement of air contaminants. Even if supply and exhaust systems are in nominal balance, wind pressures on the building exterior can upset this balance. Accordingly, it should be of particular concern to minimize wind effects on the HVAC system by alleviating envelope air infiltration, as well as appropriate use of air barriers.

One of the special conditions that must be considered with respect to high-rise buildings is the possibility of what is termed "stack effect" (Fig. 5). Stack effect occurs when there is a change in elevation and atmospheric air density within the enclosed space. It is particularly prevalent due to air leakage between floors at openings and through vertical shafts such as at elevators and mechanical chases. This condition can also be a problem in buildings having atriums open for several floors or even their entire height, a design feature that enjoyed quite a following in the late 1970s and early 1980s (Fig. 6). These design situations can also be affected by what is termed a"chimney" effect. A simplified example would be with respect to an atrium office building or hotel during winter design. For this condition, the heated air is less dense and will rise, resulting in a thermal and pressure-induced upward flow.

Each of the conditions discussed above will effect air pressure balance in the rooms, corridors, lobbies, and common areas of any particular building. Air pressure balance has a direct effect on the performance of the building with respect to moisture intrusion, retention, and dispersion.

THE SPACE ENCLOSURE

The effort and expense utilized to artificially control an environment for human use and occupancy would be wasted if there were not an efficient means for containment and retention of the desired interior conditions. Simply put, the controlled space requires a space enclosure. This portion of the chapter will provide an overview of some of the more common building systems used in the construction of modern high-rise buildings.

Roof Systems

The primary focus of this chapter is not specifically related to roof design and construction; however, some treatment of this topic is unavoidable. While roof areas typically make up a much smaller percentage of the building envelope for high-rise structures, recent litigation activity indicates that it is, nevertheless, an important building component. In general, common roofing principles related to all roof systems apply to high-rise buildings (see Chapter 16). Such principles include provisions for proper drainage, proper selection and compatibility of insulation, membrane and flashing materials, design of flashings along perimeters and at penetrations, as well as adequate quality control of the installation process.

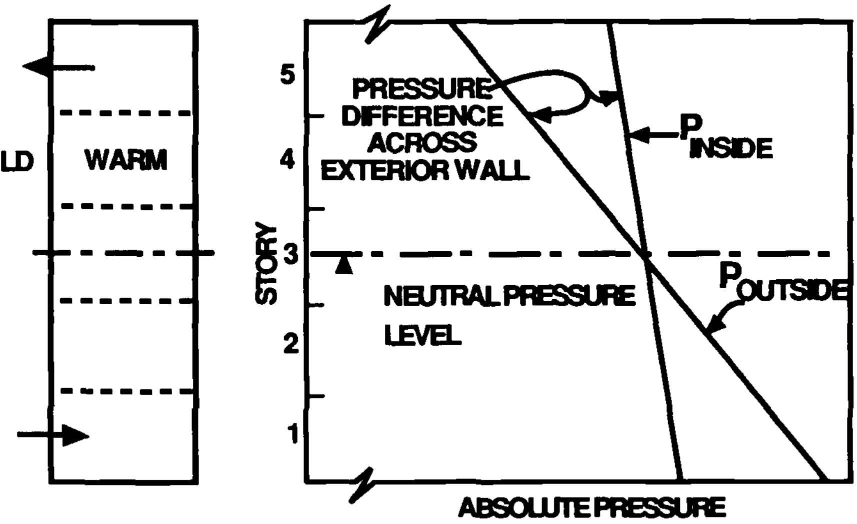


FIG. 6—Stack effect for an idealized building with no internal partition.

Periodic inspection and appropriate maintenance are also critical in order to achieve maximum effectiveness from the roofing system.

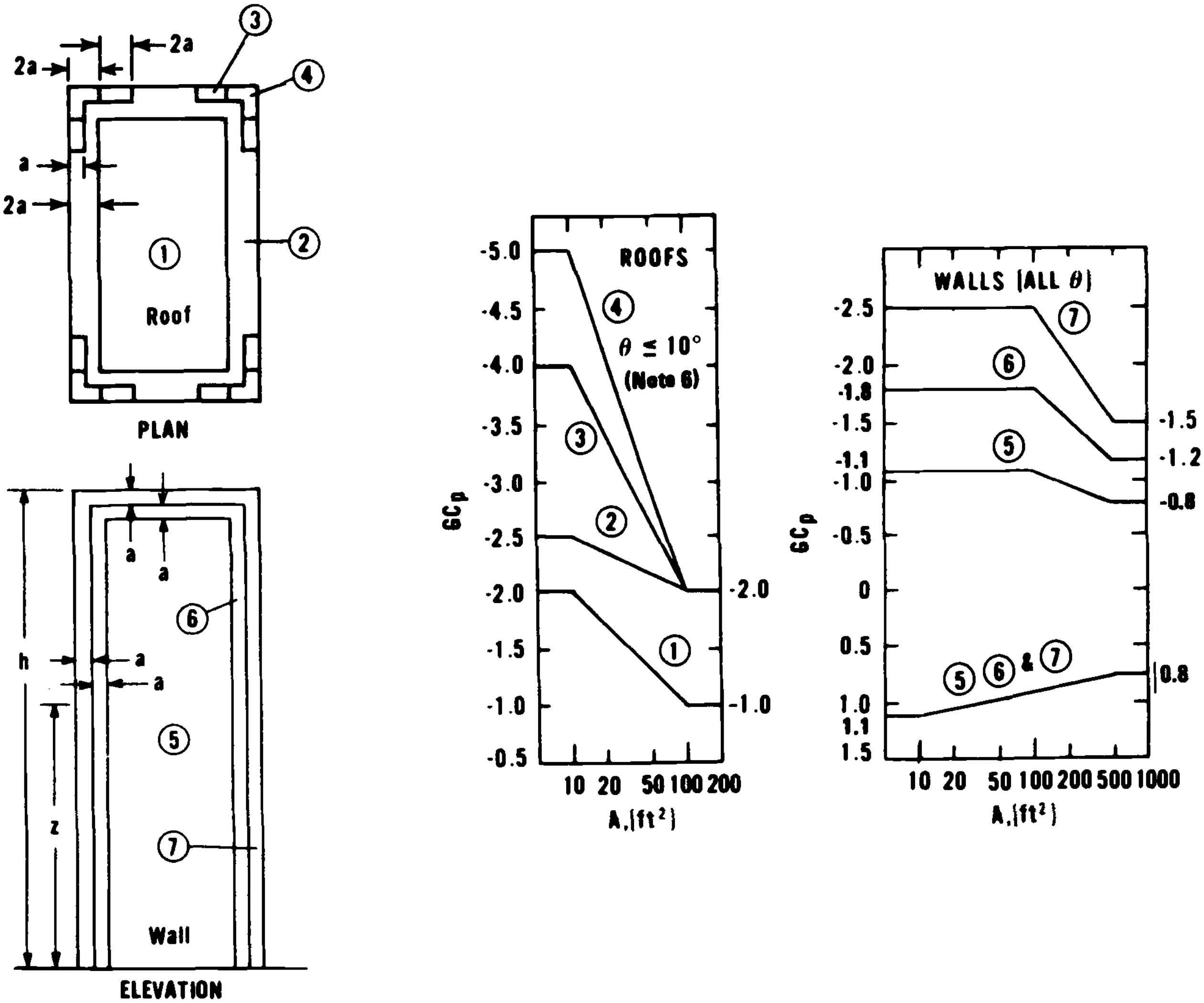
Wind Uplift

A particular area of concern regarding high-rise buildings is related again to the special fastening and ballasting requirements accruing from increased wind exposure and uplift. Studies have shown that wind uplift on roofs is a particular problem at narrow bands around the roof perimeter and at corners of the roof (Fig. 7). The American National Standards Institute (ANSI) [*6*] and the American Society of Civil Engineers (ASCE) [*7*] have developed minimum design guidelines for wind loads. In addition, Factory Mutual (FM) [*8–9*] has established minimum criteria for types of acceptable roof deck, as well as membrane and insulation attachment within each of these high uplift areas in order to minimize loss experience related to high winds. A more complete understanding of these phenomena and specific construction requirements can be achieved from a thorough study of these reference standards.

Wall Systems

Glass and Metal Cladding

One of the most prominent types of wall systems for high-rise commercial buildings in recent years has been glass and



NOTES:

(1) Vertical scale denotes GC_p to be used with appropriate q_z or q_h.

(2) Horizontal scale denotes tributary area A, in square feet.

(3) Use q_h with negative values of GC_p and q_z with positive values of GC_p.

(4) Each component shall be designed for maximum positive and negative pressures.

(5) If a parapet equal to or higher than 3 ft is provided around the roof perimeter, Zones 3 and 4 may be treated as Zone 2.

(6) For roofs with slope of more than 10 degrees, use GC_p from Fig. 3b and attendant q_h based on Exposure C.

(7) Plus and minus signs signify pressures acting toward and away from the surfaces, respectively.

(8) Notation: a: 5% of minimum width or $0.5h$, whichever is smaller; h: mean roof height, in feet; and z: height above ground, in feet.

FIG. 7—External pressure coefficients GC_p, for loads on building components and cladding for buildings with mean roof height h greater than 60 ft.

metal curtain wall, with noncorrosive aluminum alloys being the primary metal of choice for the support system. These systems first began to be critically evaluated and developed utilizing test criteria originally established by the National Association of Architectural Metal Manufacturers (NAAMM) [*10*]. Although this organization still exists with respect to other modern building components, the window and curtain wall related aspects of the industry are now more commonly assembled under the auspices of the American Architectural Manufacturers Association (AAMA) [*11–13*] and American Society for Testing and Materials (ASTM) [*14–22*]. The most definitive volume on the subject to date is probably the "Curtain Wall Design Guide Manual" published by AAMA. This manual deals with the design, fabrication, testing, and erection of all types of glass and metal curtain wall systems.

Masonry Cladding

Due to its long-term serviceability and low maintenance, masonry is still a prevalent material utilized on buildings of considerable height. However, instead of load-bearing masonry designs as utilized in the first part of the twentieth century, modern designs typically incorporate a true masonry curtain wall which is generally attached to the primary structural framing at each floor level and required to support only its own weight and any lateral loads. In addition, instead of depending upon the water absorption characteristics of a massive masonry wall, modern designs typically utilize other means for accommodating impinging moisture. Modern masonry may use brick, concrete masonry units (CMU), clay tile, terra cotta, glass masonry units, or natural stone. Thin veneer natural stone has been utilized in recent years as an aesthetic facing for precast concrete, as well as with steel support systems in order to achieve appropriate prefabrication and panelization. Whole industries have grown up around each of these material types. The Masonry Industry Advancement Committee has published their "Masonry Design Manual" [*23*], providing information on CMU and stone, and the Brick Institute of America [*24*] also produces timely technical bulletins and construction information. The "renaissance" of natural stone has been covered in a recent ASTM technical publication, STP 996, which is a collection of contemporary papers on this subject [*25*]. The Marble Institute of America also has well-established details and technical data for hand set and thin veneer stone [*26*].

Precast Concrete Cladding

The ease of fabrication, adaptability, and variety of finishes of precast concrete has resulted in a proliferation of this material over the last several decades. Long spandrel panels may be developed when properly designed and constructed. Publications on this topic are available from the American Concrete Institute (ACI) [*27–28*], the Post-Tensioning Institute (PTI) [*29*], and the Precast/Prestressed Concrete Institute (PCI) [*30*]. One of the most widely used technical guides is the PCI"Architectural Precast Concrete Design Manual," which covers all aspects of design, specification, and aesthetics for these types of panels.

Cementitious Membranes

Another common construction material that has been applied to high-rise building envelopes is both true stucco and synthetic stucco systems. True stucco would include portland cement plaster applied over metal plaster bases, as well as directly to masonry and concrete substrates. Synthetic stucco would include the Exterior Insulation and Finish System (EIFS) materials that have gained widespread acceptance in recent years.

Portland Cement Plaster

Portland cement plaster for exterior building use has been around for centuries; however, its utilization on high-rise buildings is a relatively new construction technique since these types of buildings were only technologically possible in this century. Later in this chapter, several recommendations for use of these materials on tall buildings will be presented. Although some of these recommendations may be objectionable to some parties as being too conservative or even unnecessary, they have been developed in response to a number of years experience in investigating buildings in distress and have been successfully implemented on several new and remedial projects. Numerous trade organizations related to stucco design and construction have been established throughout the United States. In addition, national and international organizations have developed general specifications and standards regarding stucco. A few of these organizations and their publications would include the Portland Cement Association (PCA) "Portland Cement Plaster (Stucco) Manual" [*31*], the NAAMM "Specifications for Metal Lathing and Furring" [*32*], as well as a number of specific standards and guides produced by ASTM [*33–38*].

Exterior Insulation and Finish Systems

Synthetic stucco, or exterior insulation and finish systems (EIFS), were developed in Europe approximately 20 or so years ago and introduced (with certain adaptations) in the United States during the mid-1970s. EIFS generally consists of a rigid foam insulation board either adhered or mechanically fastened to an appropriate substrate (Fig. 8). Rigid board insulations suitable for EIFS use and approved to date have included molded expanded polystyrene (MEPS) and extruded expanded polystyrene (XEPS). Over this base, one or more layers of a proprietary, acrylic-modified cement are applied

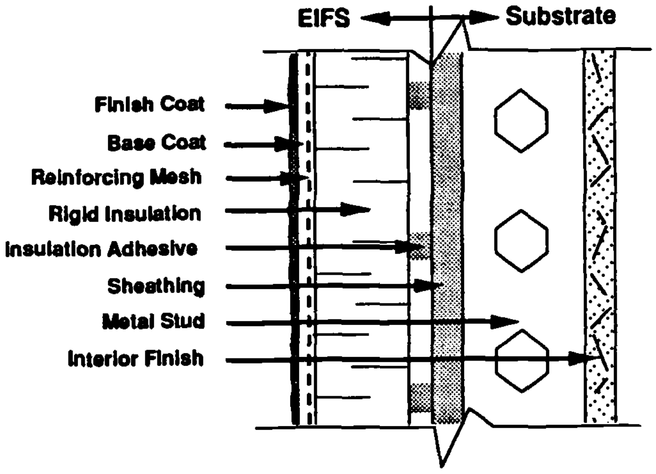


FIG. 8—Components of EIFS construction.

with some form of fabric reinforcement, usually woven or press-bonded glass fiber. Depending upon the type of system and building construction, the substrate may be either masonry or stud framing, to which a layer of water-resistant gypsum sheathing has been fastened. Although market and code acceptance of this new technology was at first slow, its acceptance and use has been growing significantly, particularly in the last few years. Today, EIFS have been generally classified into two categories based upon their assembly and physical characteristics [*39*]. The two categories are polymer-based (PB) systems, which are typically thinner and more flexible, and polymer-modified (PM) systems, which are usually thicker and more rigid. The overall physical characteristics of these products vary considerably between systems, as well as from manufacturer to manufacturer. It is pertinent to point out that there are currently no widely accepted general industry standards regarding design, fabrication, installation, and maintenance of EIFS materials. An industry organization has adopted a few standards [*40–41*], and a task force of ASTM Committee E-06 is presently working on this subject in a number of areas, although it may still be several years before this work is complete and appropriate standards are established. One current topic of concern is the phenomenon referred to as EIFS cohesive failure, in which the EIFS finish coat may soften due to prolonged moisture contact and allow delamination of the finish coat from the proprietary base coat [*42*] (Fig. 9). Until more widely recognized standards are established, it would be best to adhere to manufacturer's recommendations and guidelines and to acquire current information through technical articles and research papers which may be published on the subject. In addition, the stucco organizations mentioned above often address EIFS usage as well.

Cladding Design

Modern cladding design for buildings today has evolved into a sophisticated process, often involving specialty consultants and extensive testing procedures before, during, and after construction. This evolution has come about due to the proliferation of materials utilized in wall assemblies, as well as new systems which have entered the market. But despite this difference in materials and assemblages, there are several design principle applicable to almost all curtain walls. An attempt will be made in this section to discuss some of these design principles and how they effect remedial work on existing buildings. With respect to remedial work, it is necessary to have at least a basic understanding of these design principles in order to evaluate their contribution (or lack of) to the exterior building envelope performance.

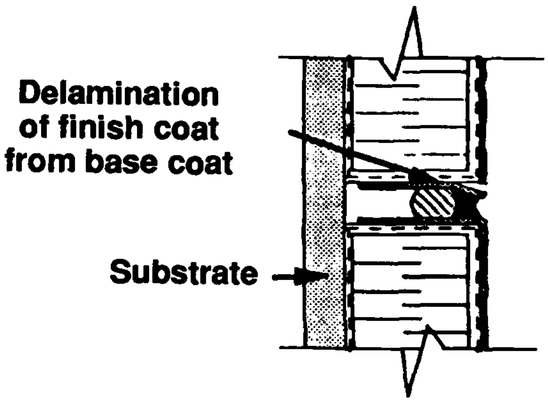


FIG. 9—EIFS cohesive failure.

Pass-Through Water Collection

One very important design issue is related to the basic method of dealing with entry of water into the wall and its removal. There are three design philosophies that have arisen with respect to this subject. The first philosophy is the one that has been used for most traditional wall systems and is usually termed a "weep" system or "pass-through" system. This philosophy attempts to provide "back-up" protection against water intrusion so that any leakage into the wall is collected by integral flashings, etc., and discharged back to the exterior via weep holes or other drainage structures. Because of this redundancy, pass-through systems have performed successfully under extremely severe conditions when designed and constructed properly. However, the redundancy of these systems also involves a slightly higher initial cost, which recently has prompted some decrease in the use of these concepts.

A typical masonry cavity wall is the most familiar assembly of this type and utilizes through-wall flashings at each floor with periodically spaced weep holes. Other versions of this concept are recommended for plaster and stucco constructions in which special draining accessory metals have been developed. Even with these common systems, however, it is not unusual to find architectural designs that incorporate these components into a wall ineffectively or else in a completely improper manner. In addition, detailing of the integral flashing assemblies can be inadequate or ignored, resulting in inappropriate construction or else damage to key flashing components during the work of related and adjacent materials. Nevertheless, by far, this is the most common type of assembly utilized for glass and metal curtain wall, due primarily to the recognition that leakage will be inevitable at glass and glazing interfaces within the metal frame. Several standard architectural references have provided details for such systems [*43–44*].

Barrier Wall Water Exclusion

The second major design philosophy related to handling of water entry is termed a "barrier" wall system, which attempts to achieve a "zero defect" construction and essentially provides a single line of defense against water intrusion. This philosophy is relatively new with respect to commercial wall construction and has been developed only in conjunction with the advent of modern sealants and wall materials. An example of this type of assembly would be EIFS wall construction, which has become increasingly used on buildings of all types. Other popular construction assemblies erected in the recent past utilizing this concept have been thin natural stone veneers on steel support systems or "strong backs," structurally-glazed window systems, and all types of precast concrete panels (Fig. 10). On each of these systems the justification for omitting the back-up systems generally stem from a desire to save costs and "simplify" construction.

In the typical barrier wall assembly, a more or less monolithic mass is attempted with high-performance elastomeric

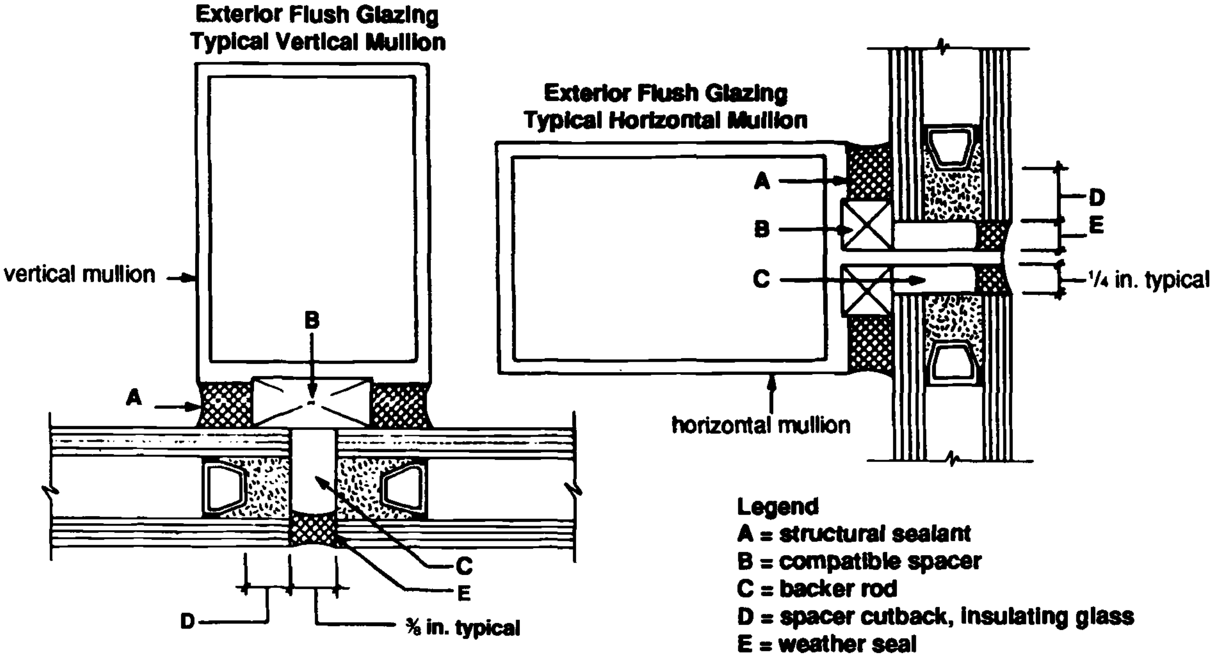


FIG. 10—Structural glazing.

joint sealants used to seal between panels and at terminations and perimeters. The obvious advantage of this concept is the reduced first cost for materials and labor. In addition, some modern architectural designs lend themselves to a sleek and uninterrupted appearance. The biggest drawback, however, to this method of water management is inherent within its design, namely, that there is one line of defense against water entry and no backup in case of failure of the envelope at any point. In this case, it is imperative that wall materials be capable of accepting this moisture intrusion by absorption without long-term detriment. Unfortunately, some of the very systems employing this concept are the ones most susceptible to damage to their own constituent materials, as well as interior finishes and structures. Interior damage can occur due to water staining, deterioration of materials, and potential ancillary results such as growth of mold and mildew. Structural damage can occur due primarily to corrosion and deterioration of critical components.

Pressure Equalization and the Rain Screen Principle

The third wall design philosophy has perhaps found its highest development with respect to metal curtain wall, but it is also applicable to other types of materials. This design concept is perhaps the most sophisticated of all and is referred to as the rain screen principle and pressure equalization concept. Because of its sophistication, it is also the easiest to inadvertently fail to achieve if its design principles are not fully understood. However, several traditional wall assemblies have utilized at least some portion of the pressure equalization concept (Fig. 11). Essentially, this design method consists of an exterior wall panel composed of relatively small, isolated chambers constructed over an interior

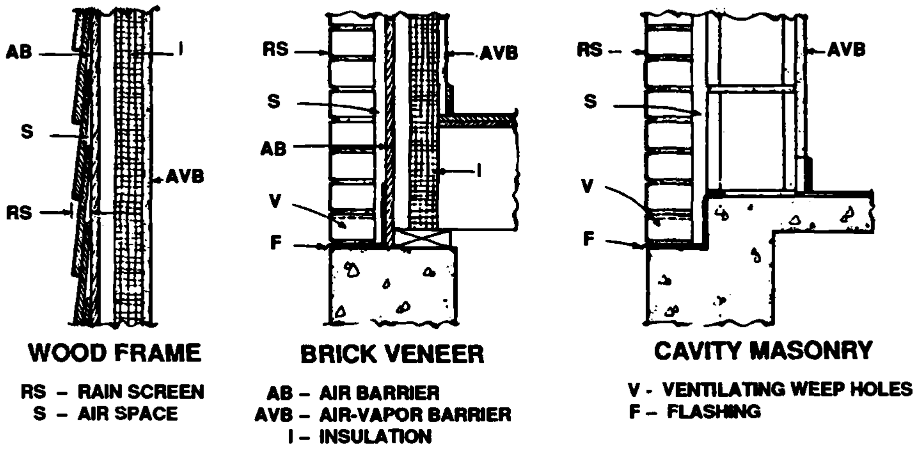


FIG. 11—Traditional walls that resist rain penetration.

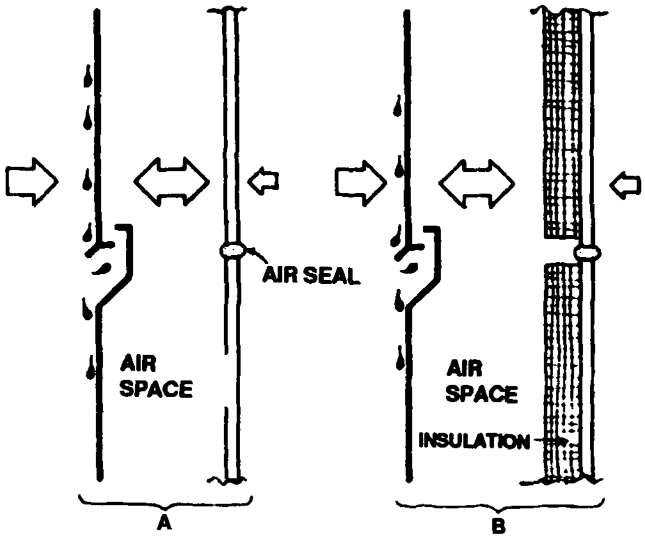


FIG. 12—Essentials of the rain screen and a pressure-equalized wall construction.

wall sealed against air leakage. The exterior wall is designed to shed water (the rain screen), but not necessarily be watertight (Fig. 12). The space between the inner airtight wall and the outer water-shedding wall is subdivided into specific chambers with appropriate openings to the exterior (Fig. 13). These openings are provided at regularly spaced intervals throughout the wall in order to allow pressure equalization between the isolated interstitial wall spaces and the outside atmospheric pressure. The idea is that if there is no air pressure difference between the outside ambient condition and inside the isolated chambers, there will be no driving force to move water into the inner chamber. The full description of this design method and the criteria for establishing pressure equalization chambers has been presented within the AAMA "Aluminum Curtain Wall Design Guide Manual," as well as other references [*45–46*] (see Fig. 14).

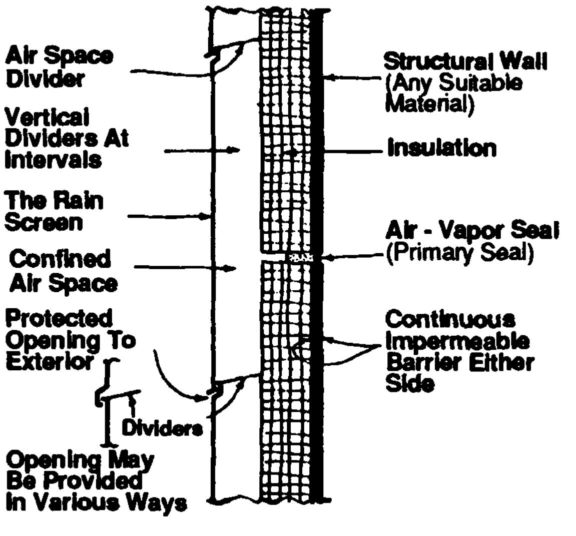


FIG. 13—Typical dividers for confined air spaces (pressure-equalized design).

Climate and Weather Conditions

One of the principle criteria to be considered for investigation of any wall system is related to anticipated climate and weather conditions that the proposed building will experience. Moisture control practices will vary somewhat depending upon the type of climate experienced on a local basis. A reference standard published by the Oak Ridge National Laboratory for the United States Department of Energy has recognized this fact and provided moisture control schemes appropriate for each major type of climate, the heating climate zone, the cooling climate zone, and the mixed climate zone [*47*]. This subject is too broad to be fully covered in this chapter. Chapter 7 of this book covers climate data in detail. However, at least some discussion will be required here as it relates to exterior building envelopes. The primary topics of concern generally revolve around temperature, wind, and precipitation, as well as their effect on building performance.

Temperature

The primary concerns related to temperature are the overall coefficient of thermal transmission of a particular wall or roof assembly, as well as how components of the assembly will be affected by temperature differences. The overall coefficient of thermal transmission, *U* value, is a separate study in itself and is beyond the scope of this manual. However, an excellent reference on this matter is *ASHRAE Fundamentals* [*48*], which treats the subject in some detail. Although overall thermal performance is important to the general building designer, the individual responsible for building envelope investigation will be more interested in considering thermal *gradients* through the wall or roof section in order to evaluate the potential for concealed and detrimental condensation. In addition, the curtain wall investigator will want to carefully consider ambient temperature extremes, surface temperatures of various curtain wall materials, effects of solar radiation and heat gain, as well as differential temperatures between adjacent materials. Ambient temperature, surface temperature, and solar radiation will affect the design temperature *range* to which the curtain wall will be subjected. The design temperature range, in turn, affects the degree of thermal expansion and contraction experienced by these components and the amount of movement that will have to be accommodated within the design. Schemes for accommodation of thermal expansion and contraction typically consist of providing moving joints within the building skin, which are then sealed against water leakage. The size of these joints, as well as their spacing and arrangement, will be determined by the type of sealant utilized and the movement "range" provided by the seal (Figs. 15–16), as well as Table 1. In addition, the materials making up the constituent components of the curtain wall will determine coefficients of expansion to be utilized in calculating estimated movement over the design temperature range. For existing buildings, this aspect of the original design should be evaluated during investigations in accordance with ASTM Guide for Use of Elastomic Joint Sealants (C 962).

Design of Joints

The primary method of accommodating thermal expansion and contraction within materials of wall-cladding systems is

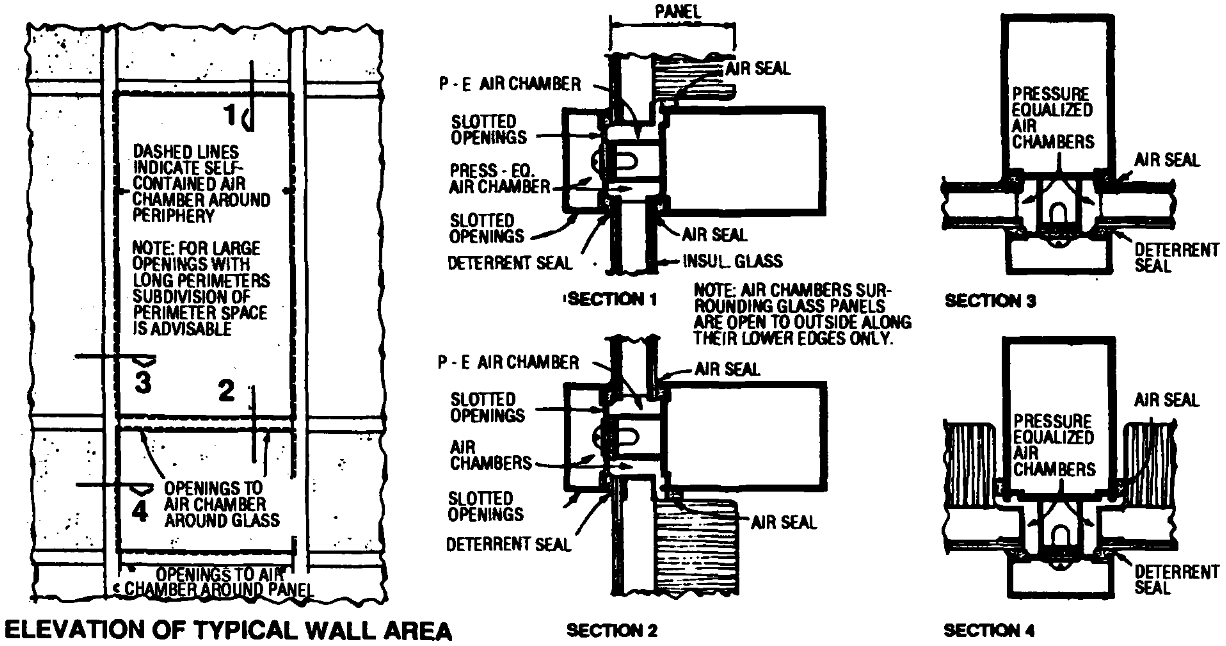


FIG. 14—Pressure-equalized standard wall system.

to provide preplanned joints in regular patterns and spacings throughout the building wall. In order to achieve adequate performance of the cladding system, these joints should be designed just like any other part of the building. The design of these components and their incorporation into the wall cladding should not be left up to tradesmen without proper training nor to construction administrators in the field under the duress of a compressed time schedule. Appropriate care should be taken to consider the coefficient of expansion of the materials involved, the total estimated joint movement, the range and modulus of the particular sealant product proposed for use (in both the compression and extension modes), and the use of proper backer rod materials. Taken together, these aspects of the building construction can be used to estimate the joint movement requirements and the required joint size, as well as sometimes indicating the correct sealant to use. One of the more helpful references on this subject is published by ASTM which prescribes a standard method of estimating joint size [*49*]. This author recommends using such aids whenever possible.

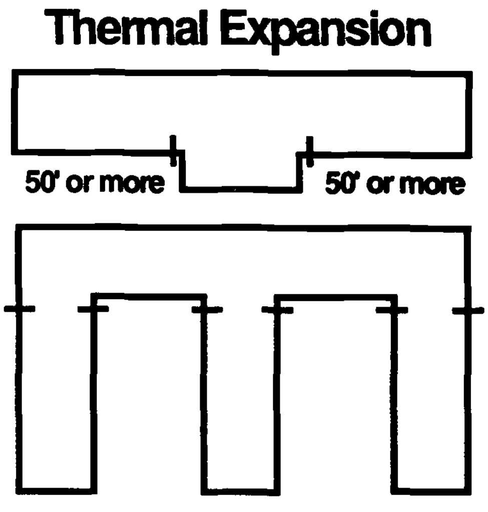
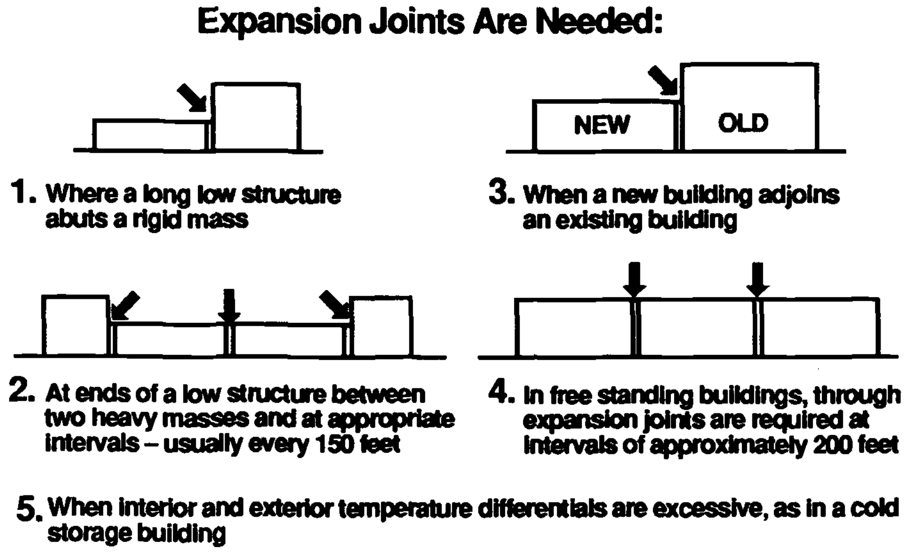


FIG. 15—Location of expansion joints.

Another consideration with regard to joint design is whether to utilize one-stage or two-stage sealant applications (Figs. 17–18). Although more expensive to install initially, two-stage sealant joints can provide benefits due to their natural redundancy, as well as protection of the inner seal from exposure to water and ultraviolet light. Two-stage joints can also be designed to weep water, and if properly planned and installed can incorporate elements of the pressure equalized design concept (Fig. 19).

Wind Forces

Some discussion of wind forces has been previously presented in this chapter regarding the special needs of high-rise buildings. Specific criteria for testing the wall systems of a building may be based upon this empirical data in order to achieve adequate structural capability, as well as resistance to air and water leakage. Such tests are appropriate whether you are dealing with new construction or with remedial work on buildings suffering moisture distress. The forensic investigator now has the option of various standardized tests related to both static and cyclic pressure differences in order to simulate anticipated weather conditions. An objective evaluation should be made for each project regarding which tests and what level of pressure is required. Perhaps the cutting edge of this technology involves what has been termed boundary layer wind tunnel testing (BLWT), which utilizes wind tunnel testing for buildings similar to what has been used for many years in aeronautical engineering. AAMA has published a primer on the subject [*50*], and today virtually all monumental or high-rise buildings of note are modelled using this procedure to assist in structural design for the main force resisting frame, as well as for components and cladding.



1. Where a long low structure abuts a rigid mass
2. At ends of a low structure between two heavy masses and at appropriate intervals – usually every 150 feet
3. When a new building adjoins an existing building
4. In free standing buildings, through expansion joints are required at intervals of approximately 200 feet
5. When interior and exterior temperature differentials are excessive, as in a cold storage building

FIG. 16—Typical locations for building expansion joints.

It is in regard to cladding design that BLWT can be most significant in providing reliable information regarding the location of increased wind forces and their values at perimeters, corners, eaves, and other "hot spots."

Precipitation

With regard to precipitation, the amount of rainfall experienced and its typical intensity are criteria that will affect remedial work related to runoff drainage of roofs, plazas, and other surfaces. In addition, a choice should be made in regard to rainfall criteria selected, for example, whether 1-h/50-year storms are adequate, or if 15-min/100-year storms are more representative of the types of runoff to be expected [*51*]. For cities experiencing significant precipitation but where the rainfall event constitutes a continuous, slow, steady drizzle, the former design criteria may be sufficient. However, in locations where rainfall events consist in a severe, intense deluge, lasting only several minutes before subsiding to a more consistent rain, the latter design criteria (or even shorter duration rainfalls) may be more appropriate. Of course, the primary concern is to remove water accumulation and runoff from the roof membrane and roof structure as soon as is practically possible. In evaluating existing systems, consider the possibility that the drainage system has become *less efficient* during the passage of time due to partial blockage of drain inlets and piping by debris, obstruction of the drain surface by equipment, planters, and other appurtenances.

Thermal Envelope

As discussed above, the building investigator will want to preserve overall thermal performance of the building in order to maintain energy efficient building use and operation. The primary means of controlling this aspect of building performance is to confirm the adequacy of existing thermal insulation within the roof or wall assembly (see Chapter 6).

Weather Data

In addition, the building investigator should determine the possibility of condensation within the roof or wall. This is best accomplished by evaluating the temperature and psychometric properties of proposed roof or wall assemblies over a broad range of anticipated weather conditions. It is important to consider the *average* summer and winter conditions, as well as the *extreme* summer and winter design conditions,

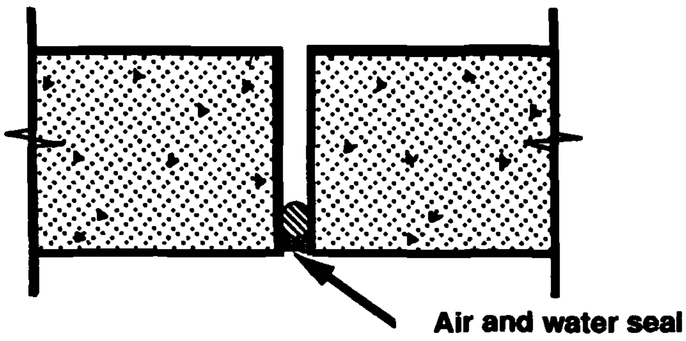


FIG. 17—Section of vertical, one-stage joint.

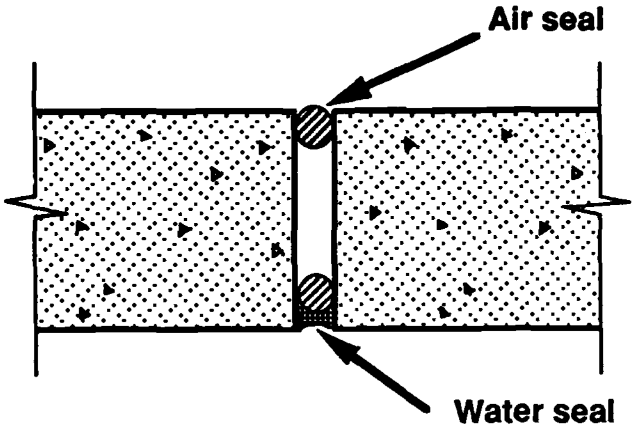
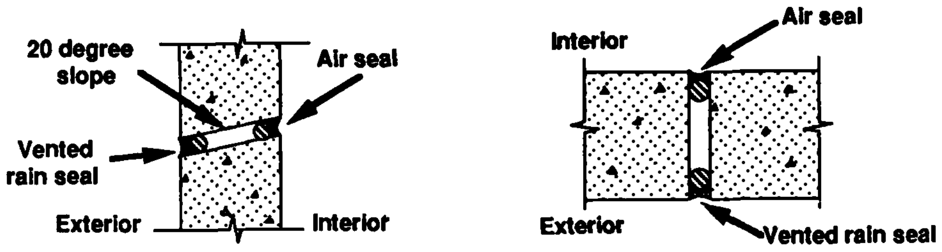


FIG. 18—Section of vertical, two-stage joint.

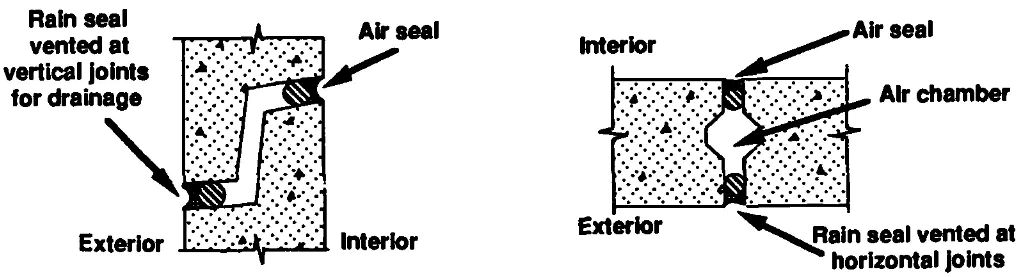
TABLE 1—Characteristics of common elastomeric sealants.

	Acrylic (Solvent Released) (One-Part)	Polysulfide		Polyurethane		Silicone (One-Part)
		Two-Part	One-Part	Two-Part	One-Part	
Chief ingredients	Acrylic terpolymer, inert pigments, stabilizer, and selected fillers	Polysulfide polymers, activators, pigments, plasticizers, inert fillers, gelling, and curing agents		Polyurethane prepolymer, inert fillers, pigment, plasticizers, accelerators, activators, and extenders	Polyurethane prepolymer, inert fillers, pigment, and plasticizers	Siloxane polymer, pigment, and selected fillers
Percent solids	85–95	95–100	95–100	95–100	95–100	95–100
Curing process	Solvent release and very slow chemical cure	Chemical reaction with curing agent	Chemical reaction with moisture in the air	Chemical reaction with curing agent	Chemical reaction with moisture in air	Chemical reaction with moisture in the air
Curing characteristics	Skins on exposed surface; interior remains soft and tacky	Cures uniformly throughout; rate affected by temperature and humidity	Skins over, cures progressively inward; final cure uniform throughout	Cures uniformly throughout; rate affected by temperature and humidity	Skins over, cures progressively inward, final cure uniform throughout	Cures progressively inward; final cure uniform throughout
Primer	Generally not required	Manufacturer's approved primer required for porous surfaces, sometimes for other surfaces		Manufacturer's approved primer required for most surfaces		Manufacturer's approved primer required for most surfaces
Application temperature (°F)	40–120, must be heated	40–100	60–100	40–120	40–120	0–120
Tackfree time	1–7 days	6–24 hr	6–72 hr	1–24 hr	Slightly tacky until weathered	1 hr or less
Hardness, Shore A Cured 1 to 6 months, aged 5 years	0–25 45–55	15–45 30–60	25–35 40–50	20–40 35–55	25–45 30–50	20–40 35–55
Toxicity	Nontoxic	Curing agent is toxic	Contains toxic ingredients	Toxic; gloves recommended for handling		Nontoxic
Use characteristics	Excellent adhesion; poor low temperature flexibility; not usable in traffic areas; unpleasant odor 5–12 days	Wide range of appropriate applications; curing time depends on temperature and humidity	Unpleasant odor; broad range of cured hardnesses available	Sets very fast; broad range of cured hardnesses; excellent for concrete joints and traffic areas	Excellent for concrete joints and traffic areas, but substrate must be absolutely dry; short package stability	Requires contact with air for curing; low abrasion resistance; not tough enough for use in traffic areas



Section of Horizontal Joint

Plan of Vertical Joint



Section of Horizontal Joint

Plan of Vertical Joint

FIG. 19—Two-stage pressure equalized joints.

which are typically utilized for HVAC design. This latter data is commonly available from recognized sources such as *ASHRAE Fundamentals* [*52*], but to obtain the average dry bulb and wet bulb temperature it is necessary to refer to Chapter 7 of this book or to utilize other sources, such as the "Facility Design and Planning—Engineering Weather Data" (NAVFAC P-89) [*53*], available from the National Technical Publications Center. Once this evaluation is accomplished, the investigator can then determine whether a vapor retarder is required and where within the assembly it should be located. Accordingly, selective demolition at the site can be performed to determine the existence and condition of such construction components (see Chapters 1–3 of this manual for more details on this process and the procedures involved).

Air Barriers

The use of air barriers is probably one of the most misunderstood concepts within modern construction today. Although utilized fairly extensively in the single-family residential market [*54*], widespread commercial use has been limited. It is not unusual to find relatively new buildings designed by large, well-known architectural firms in which the proper use of air barriers is totally ignored or else ineffectively implemented. However, the concept is simple to utilize and will provide innumerable benefits when the thermal and psychometric evaluation indicates their use. For instance, the designer of a high-rise building located in Minneapolis has spent much design time and effort in developing the typical building wall section which exhibits acceptable thermal performance. Having opted for "punched" windows within the building fenestration, he then writes a strict specification for window thermal performance using insulated glass, mullions with thermal breaks (Fig. 20), and, possibly, specifying or limiting the condensation resistance factor (CRF) [*55*]. Then, when details of punched window openings are developed, the windows are shown to be simply fastened into place using an elastomeric sealant to fill metal-to-substrate perimeter joints. The space occurring between window frames and rough openings is all but forgotten with respect to thermal performance and the potential for incidental air leakage, conden-

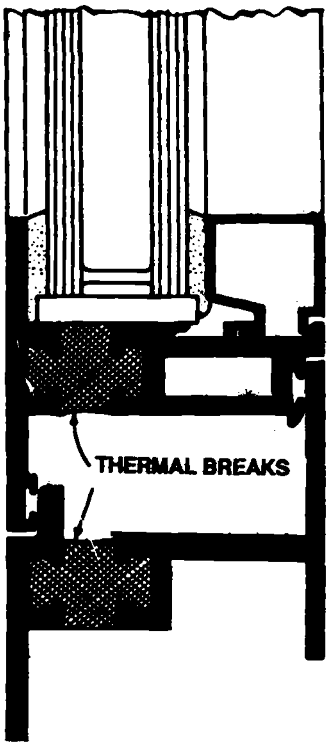


FIG. 20—Typical thermal break for curtain wall.

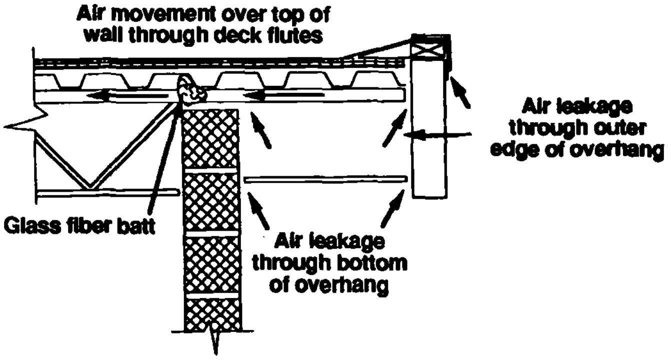


FIG. 21—Air leakage at roof overhang.

sation, etc. Another common example occurs at roof overhangs (Fig. 21) or beams that cantilever from an insulated wall. It is at such junctures within the building envelope that problems are likely to occur. The solution consists in simply stuffing the void with a batt insulation material and constructing an effective air barrier/vapor retarder between the aluminum frame and the surrounding substrate. Several kinds of sheet membranes (including self-adhering types) have proven themselves suitable for this purpose, but it is important to consider vapor permeance and longevity of the membrane and it is crucial that they are thoroughly integrated into any vapor retarders and air barriers that may exist within the wall all around the window perimeter. For more information on vapor retarders and air barriers and their use, see Chapters 2 and 9 of this manual.

Thermal Bridges

One other consideration for exterior building envelopes is the presence of thermal bridges and their effect on overall building performance. A study conducted on this subject by the National Program for Building Thermal Envelope Systems and Materials at Oak Ridge National Laboratory reports that thermal bridges within the building envelope can reduce overall thermal efficiency by as much as 30% from the calculated values [*56*]. In addition, severe thermal bridges may provide cold condensation surfaces upon which moisture may accumulate and affect wall performance. The BTECC study is currently focusing on thermal bridges occurring within commercial and multi-family residential construction, as well as mathematical models for evaluating their effects. In general, information is still somewhat limited, and since identification of thermal bridges and their complete effect on envelope performance is uncertain to a degree, it is best to eliminate or at least reduce the presence of thermal bridges within the building skin wherever possible. The opportunities to correct such defects during remedial work may be limited, but should be considered nonetheless.

ENVELOPE WATER LEAKAGE

Above Grade—Horizontal and Vertical

When dealing with water leakage within an exterior building envelope, it is necessary to consider all the potential locations at which moisture can impinge upon the structure. Obviously, this would include both above-grade and below-grade sources, as well as horizontal and vertical planes of the building envelope. A certain amount of investigative effort will be required to eliminate the possibility of multiple leak sources involving both types of leakage. The reader is referred to Chapter 16 of this manual for specific techniques and recommendations related to roofs and roofing.

Wall Performance Evaluation

Investigative techniques for evaluating walls has been generally covered in Chapter 13 of this manual. With respect to high-rise structures, again, the primary difference in dealing with these buildings is related to the magnitude of wind forces, lateral movement, etc. In addition, the level of sophistication regarding the curtain wall system is generally higher, and there is more likelihood that the system is a custom design. Accordingly, it is extremely important that the investigator obtain shop drawings (and preferably "as-built" shop drawings) of the wall system if at all possible.

Wall Cladding Components

All wall cladding is typically composed of two basic components: vision panels and solid or spandrel panels. Vision panels would consist of punched windows, true floor-to-floor curtain wall systems, and sloped glazing. Spandrel panels would consist of masonry, precast, plaster, EIFS, or opaque glass, with the latter typically being part of a true curtain wall system. The potential problems that may be experienced by these systems are generally related to connections for gravity and lateral loads, provisions for thermal expansion and contraction, integration into and with surrounding components and substrates, as well as exclusion of water leakage via a barrier wall design or by through-wall collection and drainage. It is particularly relevant to pay attention to detailing of penetrations through the wall system, perimeters and terminations, as well as transitions between adjacent dissimilar components. Rehabilitation of these problems, obviously, would entail correction to the greatest extent possible of those areas experiencing deficiencies, realizing that at times remedial efforts will represent a "second best" construction since the root problem may not be correctable and only water leakage "symptoms" may be dealt with. In these situations, an evaluation of cost/benefit regarding each of the available alternatives would be in order. Although completely replacing building components and spending a million dollars might resolve the problem, it may be more cost effective to consider a less comprehensive remedial measure and include an evaluation of shortened service life and increased maintenance. Life cycle cost (LCC) analysis can be a useful tool in developing information to present to building managers in order for them to make a decision [*57*].

Building Seals and Sealants

One of the chief methods utilized today for waterproofing the exterior building envelope is the reliance placed on building seals and sealants. Technology has advanced significantly in this area over the past 20 years. Due to its importance, it is imperative that the building investigator and those responsible for its maintenance be familiar with this aspect of the construction or else utilize specialty consultants in this field. An evaluation of components and cladding materials and assemblies will assist in selection of proper materials, while the manufacturer's technical literature provides information on application restrictions and procedures. For some projects and materials, it is prudent to specify adhesion and stain testing in accordance with recognized procedures [*58–59*]. In addition, it is critical that surface preparation procedures be developed by test panels and that steps be taken to assure that such information is properly disseminated to all field installation personnel. Further, this matter is of such importance that appropriate quality assurance procedures should be initiated during proposed renovation work in order to monitor adequacy of the work. A number of excellent references are available on the subject, including ASTM STP 606 [*60*] and ASTM STP 1069 [*61*], the Sealant and Waterproofing Institute's "Sealants: the Professional's Guide," [*62*], Panek and Cook's "Construction Sealants and Adhesives," [*63*], as well as numerous technical articles and papers [*64–65*].

Expansion Joints

Particular care should be given to the design, function, and aesthetics of building expansion joints. In all cases, an estimate of thermal expansion and contraction should be made and joints designed accordingly. Consideration should be given to the use of proprietary joint covers where joint size or movement exceeds the capabilities of elastomeric sealants.

Problems that occur during retrofit and renovation of building sealants are somewhat varied from new construction; however, it is important to evaluate the affect original problems or deficiencies may have had on sealant failures in order to avoid repeating the same mistakes. As has already been alluded to, it may be necessary to initiate a series of adhesion and compatibility tests for the proposed renovation work prior to specifying an appropriate material. In addition, surface preparation becomes particularly critical since existing materials will have to be completely removed in order to allow the new products to perform properly and to avoid incompatibility. Complete removal of original sealants to allow proper surface preparation may be hindered or rendered more difficult by certain substrates and materials, such as heavily textured EIFS or the veins and irregularities occurring in natural stone.

Below Grade—Horizontal and Vertical

Commonly, high-rise commercial buildings will incorporate below-grade levels for utilities, parking, support areas, etc. Accordingly, this chapter will deal briefly with this subject in regard to vertical and horizontal waterproofing. Waterproofing of vertical surfaces is typically desirable for basement walls constructed against fill and lagging, some retaining walls, as well as at built-in planters, utility vaults, and pits. In the event that upper surfaces of a facility do not project above grade and are "buried," horizontal waterproofing is also often required.

Design Concepts

Several key concepts should be understood prior to discussing investigation of materials for this type of construction. These concepts relate to (1) membrane placement and protection, (2) substrate design, and (3) water environments. The water environment of the waterproofing would consist in the presence or absence of liquid water experienced by the membrane (i.e., constant, seasonal, flowing, etc.) and what measure of hydrostatic head is required to be resisted by the waterproofing. Accordingly, it is important to choose materials that provide true waterproofing, not just damp proofing, where it is required. In making this distinction, reference is made to ASTM definitions which designate "waterproofing" as a product or system capable of preventing water migration in the *presence* of a hydrostatic head and "damp proofing" as a product or system capable of resisting water migration in the *absence* of a hydrostatic head [*66*]. In addition, substrates should be structurally sound and not subject to movement or excessive deflection. Moving joints, such as expansion joints, should be kept to an absolute minimum, and construction or cold joints should be properly treated. Sharp interior and exterior corners consisting of acute angles (i.e., less than 90°) and irregular bends are difficult to waterproof and should be avoided in favor of 90° corners with chamfers and smooth transitions. Investigation of water leakage problems below grade for any building should include an evaluation of the success of the original designer in achieving these concepts.

Acceptable Substrates

Waterproofing substrates should consist of hard, dense materials that are not porous. Based upon the experience of this author, concrete masonry units (CMU) typically do not provide an adequate substrate for waterproofing applications without parging. Also, insulating concrete with perlite or vermiculite aggregates and other fill materials and grouts typically do not make good substrates to which waterproofing may be applied. In general, the waterproofing membrane should be placed or applied directly to the surface at which waterproofing protection is desired. Overall, it is not a good idea to place any "layers" of the construction assembly between the substrate and the waterproofing, particularly for adhered systems. Further, it is generally recognized that the waterproofing substrate should be adequately sloped for drainage and a drainage course employed to facilitate water removal. Sometimes these general guidelines and design criteria will conflict. For example, if the structural slab at which waterproofing is desired is designed and constructed flat, then in order to achieve slope and drainage at the waterproofing level (see "The Importance of Drainage" below) it will be necessary to interject a sloped fill material. This material should be dense and nonporous, and the temptation to substitute more economical materials should be resisted. If a concrete fill is utilized, it should be thick enough to avoid cracking at its thinnest part, keyed in to the previous substrate, protected from thermal expansion and cracking by using temperature reinforcement, and provided with appropriate expansion and control joints.

Protection

Finally, all below-grade waterproofing membranes should be protected from the hazards of backfilling and compaction, as well as the potential for renovation traffic. It is often rationalized that it is wasteful to spend part of the renovation budget for something that once the fill is in place serves no purpose. However, protection courses are more than worth their minimal cost when compared to the cost, inconvenience, and damage arising from an ineffective waterproofing membrane which has been punctured during backfilling operations.

Membrane Placement

The waterproofing principles outlined above generally relate to the normal concept of waterproofing, i.e., applying the waterproofing material on the surface which is expected to experience the presence of water and hydrostatic head. This kind of assembly is referred to as "positive side" waterproofing. The opposite of this, of course, would be "negative side" waterproofing, and involves application of materials on the surface opposite that which experiences the presence of water and a hydrostatic head. Negative side waterproofing is generally only practical with below-grade construction consisting of dense, well-placed concrete since the wall material must be able to resist long-term water absorption without detriment or deterioration. In addition, the negative side waterproofing concept relies heavily on the integrity of the substrate to achieve success. It is pertinent to point out that dense, well-placed concrete having no supplemental waterproofing applications is virtually water impermeable. However, the occurrence of terminations, penetrations, and cold joints during construction, as well as eventual cracking, make waterproofing of below-grade structures necessary. Also, since water is always present with this type of design, the investigator must be careful to evaluate the presence of any "booby traps" into the wall, such as piping or conduit runs, which would provide an avenue for moisture to travel. For these reasons, negative side waterproofing may not be practical for commercial applications, particularly for occupied spaces, except perhaps as a second best or remedial application. If at all possible, below-grade spaces should be properly waterproofed from the exterior during original construction. Even when the exterior wall is formed against sheet piling, positive side waterproofing can usually be achieved utilizing bentonite clay materials.

Waterproofing Materials

Materials available for both vertical and horizontal applications include sheet membranes, fluid-applied elastomers, cementitious waterproofing, and organic gels which are generally composed of bentonite clay.

Sheet Membranes

Sheet membranes may be composed of bituminous materials or single-ply membranes such as EPDM or PVC and may be either hot or cold applied. Some materials are self-adhering, while others must utilize separate adhesives. Typically, these membranes have an inherent advantage with respect to consistency of material quality and thickness since they are factory produced and subject to the manufacturer's production quality control. However, the limited size of these membranes results in numerous seams and terminations that must be adequately bonded to resist a head of hydrostatic pressure. Since this aspect of the assembly is dependent upon proper workmanship, the installer should be trained and experienced in application procedures for the particular product utilized. In addition, this is an aspect of the renovation which should be monitored the closest by project administrators. Design and construction guidelines can be found in standard ASTM references [*67–68*] and certain ASTM special technical publications [*69*]. Rehabilitation of sheet membranes can really only take place if access can be gained to the waterproofed surface by excavation. Short of this, alternative or supplemental waterproofing, such as negative side waterproofing, injected chemical grouts, etc. may be utilized with some success in localized areas.

Fluid-Applied Waterproofing

Fluid-applied waterproofing may be composed of modified bitumens or elastomeric coatings such as polyurethane and neoprene, as well as traditional built-up waterproofing methods. However, built-up waterproofing has experienced a decreased utilization since the advent of specialty waterproofing products. This decreased use is due primarily to the fact that built-up waterproofing originally utilized organic felts which deteriorate readily with constant moisture presence and absorption. By the time more water-resistant glass fiber felts became available, the move away from traditional built-up waterproofing and the successful introduction of specialty waterproofing products had already begun. In addition, it is questionable that glass fiber felts would be able to conform readily to the corners and bends of below-grade substrates, since these felts have a "memory" and would try to retain a flat shape. For design and application of built-up waterproofing consult available ASTM guides [*70*] and the NRCA "Roofing and Waterproofing Manual" [*71*].

Fluid-applied waterproofing materials may be hot-applied in some applications, but cold-applied materials are more common for vertical applications since higher temperatures increase material viscosity, making it more difficult to apply an adequate thickness of the material to vertical substrates. Further, heating of the hot-applied bituminous materials commonly requires special equipment such as oil-bath kettles and insulated distribution buggies. Cold-applied bituminous materials and other chemically cured or moisture-cured waterproofing materials do not exhibit these restrictions and may be applied to either vertical or horizontal surfaces with good success. The key application concepts here involve obtaining adequate surface preparation and achieving specified membrane thickness.

In general, fluid-applied waterproofing enjoys the advantage commonly attributed to adhered roofing systems in that, should a breach in the membrane be incurred, the water cannot readily travel or migrate under the membrane. If a suitable avenue of water migration, such as a crack, does not exist in the substrate and the substrate is not porous, then minimal detriment will occur. However, fluid-applied waterproofing materials are particularly sensitive to substrate preparation and cleanliness (attributes that are difficult to maintain in a construction excavation) and require expert workmanship to achieve good results. Design and construction guidelines for these materials can be found in ASTM standards and certain technical publications [*67–69*]. Like sheet membranes, rehabilitation of fluid-applied waterproofing membranes can really only take place if access can be gained to the waterproofed surface by excavation. Short of this, alternative or supplemental waterproofing, such as negative side waterproofing, injected chemical grouts, etc., may also be utilized with some success in localized areas.

Cementitious Waterproofing

Cementitious "membranes" are generally proprietary formulations of modified portland cement with appropriate aggregates and are typically premixed and prepackaged for small jobs. The chief advantage of this waterproofing type is the economy of their material cost and nonspecialized labor requirements. In addition, some manufacturers claim a benefit for use of cementitious waterproofing products in "negative side" waterproofing applications (see discussion above), but claims for acceptable performance at occupied spaces have not been substantiated in actual use over the long term. Since these materials do not accommodate substrate movement or cracking, the use of cementitious waterproofing is generally restricted to noncritical locations such as parking garages and elevator pits. In recent years, several manufacturers have developed cementitious products having enhanced performance capabilities, but the basic weakness of these materials still remains. Rehabilitation of cementitious waterproofing materials would generally consist of reapplication of the materials in those areas experiencing deterioration or failure. In addition, should direct water entry or wetness be encountered, it may be necessary to utilize materials manufactured specifically for these conditions, which are often called "wet patch" materials.

Organic Clay Barriers

Finally, there are bentonite clay products, which may be job mixed and spray applied or provided in granular form packaged in degradable cellulose panels in which the "cardboard" corrugations are filled with the bentonite granules. Bentonite waterproofing is applied in a thin layer on appropriate surfaces and, when wetted, reacts by swelling to restrict further water flow. This method of waterproofing can be quite effective when installed properly; however, it is imperative that adequate thickness be maintained, that corners and penetrations be properly treated, and that the bentonite is not diluted or removed by acidic soils, flowing water, and improper backfilling. In addition, these materials have a very limited tolerance for exposure and inadvertent moisture absorption; therefore, backfilling and adjacent construction must be carefully and closely scheduled with the waterproofing. It is typically not possible to leave bentonite products exposed to wet weather for any appreciable time or to install them in a "wet" excavation. For best results, the manufacturer's recommendations and guidelines should be strictly adhered to. Rehabilitation of bentonite waterproofing is generally difficult, if not impossible to achieve, since it is only accessible by excavation which would effectively disturb or remove the hydrated bentonite from the waterproofing substrates, requiring complete reinstallation.

Plaza-Deck Waterproofing

Due to the special nature of plaza deck waterproofing, particular consideration will be given to these types of assemblies. In general, the same materials discussed above, with their inherent advantages and disadvantages, are applicable to plaza deck waterproofing construction. In addition, the design concepts discussed earlier in this chapter in regard to below-grade waterproofing would apply to these conditions as well. However, since these assemblies are normally designed and utilized for pedestrian or vehicular traffic, some special requirements occur. The design decision having the biggest impact on these assemblies is related to the materials and construction utilized for the wearing course or traffic surface. Some waterproofing membranes, such as fluid-applied polyurethanes, incorporate an integral wearing course into their design. However, the other waterproofing types and many fluid-applied membranes will utilize a separate wearing course. Typically, these materials will consist of cast-in-place topping slabs or pavers which may be either permanently set in sand or grout beds, installed over rigid board thermal underlayments, or utilized with pedestals and shims. Pavers may be precast concrete, natural stone, brick, or tile. Obviously, once a topping slab is placed, there will be no ready means of accessing the membrane for repairs or future maintenance. Accordingly, it is imperative that appropriate leak testing be implemented prior to placing topping slabs and that appropriate protection courses be utilized, if for no other reason than to protect against the traffic and equipment used to place the topping slab. In general, it is best to avoid permanent toppings altogether since all materials will eventually require repairs or maintenance. Accordingly, pavers utilizing a pedestal system or installed over appropriate insulation board would be preferred for most applications other than perhaps vehicular traffic. However, vehicular traffic waterproofing applications that utilize a separate wearing course consisting of special pavers have been successfully used [73]. Pavers with pedestals are also preferred to pavers on a setting bed since the setting bed would tend to restrict drainage above the waterproofing membrane or else wash out, causing efflorescence, staining, and possible deterioration of the paver support. If a thermal underlayment is used, it should be composed of a durable, nonabsorptive insulation board which exhibits adequate compressive strength to resist anticipated traffic. In addition, insulation board should utilize drainage grooves on the underside of the board in both directions in order that water flow is not restricted. Water leakage through plaza deck waterproofing can create severe problems because these assembles commonly occur over occupied spaces which sometimes have critical importance. Again, quick and easy access in order to effect a speedy and appropriate repair are advantages offered by a paver/pedestal type system. For a good discussion regarding design principles for waterproofing of plaza decks, the reader is referred to "Principles of Design and Installation of Building Deck Waterproofing" by Ruggiero and Rutila [72]; however, this resource presents an apparent preference for unadhered or loose-laid waterproofing membranes. Whereas that type of waterproofing may be appropriate for plaza decks where a great deal of movement is expected (e.g., precast double-tees), it would not necessarily be preferable in all other substrate conditions, particularly where it might tie-in to adjacent waterproofing applications at vertical walls, which should always be fully adhered.

The Importance of Drainage

With the exception of bentonite waterproofing products, it is critical that proper drainage of the waterproofing membrane be achieved over the life of the building. For plaza deck waterproofing, drainage must occur at the *membrane level*, not just at the wearing course above. Accordingly, special drains having multi-level openings for water entry must be specified and utilized to achieve not only surface runoff from the wearing surface, but also removal of water from the membrane surface. Further, steps should be taken to prolong the service life of the drainage course by using proprietary drainage boards which facilitate water flow, filter fabrics to reduce sedimentation and clogging of drains, and by avoiding incorporation of materials into the assembly that would contribute fines or leached chemicals into the drainage paths.

For other below-grade waterproofing applications, supplementary drainage methods in the form of French drains, under-slab drainage networks, and forced ejection systems in the form of sump pits with motorized pumps, should also be utilized where subterranean water conditions and below-grade occupancy indicate their use. As a general rule, it is always more cost effective to install these systems during the original construction, as opposed to devising "second best" solutions to water infiltration problems after the fact. For example, a recent high-rise constructed in the Great Lakes area had soil and water table conditions discovered during excavation of the three-level basement that threatened to develop significant hydrostatic pressure on the basement walls, particularly once de-watering activities associated with the excavation were ceased. Waterproofing and drainage schemes were developed to accommodate this potential problem, and a sump pit with pumps was installed for a nominal cost when compared to the multiple million-dollar construction budget. Without these devices in place, the basement could have become a damp, dank place which would have been difficult and costly to maintain. Unfortunately, modern construction projects will often "value engineer" these types of drainage components out of the design, resulting in less than satisfactory waterproofing performance. Unless the below-grade use is a noncritical occupancy, such as a parking garage, the slightly higher initial cost and operating costs are more than outweighed by the long-term benefits derived from these construction procedures.

RECOMMENDATIONS

The following recommendations are presented as a summary of items related to, and growing out of, the cumulative inspections and observations related to remediation of high-rise buildings with respect to roofing and waterproofing. Obviously, such a summary cannot be comprehensive, since each architectural project will have its own individual design considerations. However, it is intended that this summary be utilized as a check list of some of the matters to be considered during renovation of high-rise projects.

General Concepts

1. As much as is practically possible during the renovation process, try to anticipate problems related to roofing, waterproofing, and the overall building envelope, and develop solutions to these potential problems before they become an actuality. In virtually all conceivable cases, it will be more cost effective to provide up-front resolutions as opposed to performing after the fact remediation.
2. Renovation applications may sometimes require innovative use of roofing and waterproofing systems that are new to the market or which have had a limited use history in the past. The past or potential performance characteristics of these materials should be thoroughly investigated to analyze the possibility of potential incompatibilities between these systems and adjacent substrates. If possible, visit previous installations in your area and talk to the manufacturer, as well as consultants, other design colleagues, etc. If the size of the project merits it, consider the possibility of having recognized industry tests performed in order to evaluate potential field performance.
3. When troubleshooting problem assemblies, as much as is feasible, utilize recognized industry test procedures and field methods. Even if the project is not the subject of litigation, it later could be and the credibility of your evaluation could be called into question. More importantly, standardized tests will generally result in more consistent results and may be more readily compared to test results achieved previously at this project or at other projects having similar construction. This recommendation does not preclude innovative approaches or adaptation of existing suitable test methods to new uses where appropriate. Such cases would include circumstances when new materials are being tested or evaluated, particularly when nationally recognized standards do not exist.
4. Always evaluate the potential for inappropriate HVAC design, construction, and maintenance procedures and practices; it is generally always prudent to use tried and proven equipment and components in order to achieve predictable results. When investigating poor performance of buildings with respect to moisture intrusion, be prepared to evaluate the effect that improperly designed, constructed, or maintained mechanical equipment may have on the problem. In some cases involving chronic moisture conditions or the presence of mold and mildew, it may be necessary to conduct a comprehensive study of the exterior and interior temperatures and relative humidities in order to have adequate data upon which to base your investigation.
5. Evaluate the relative permeabilities of roof and wall assemblies at each portion of the exterior building envelope by performing a thermal and vapor flow analysis. Be sure that both winter and summer design conditions are considered and remember to apply good principles of design regarding dew point, condensation, moisture accumulation, and the use of vapor retarders and air barriers.
6. Recommendations should be made to encourage building owners and managers to utilize good maintenance as a tool to acquire the most cost effective use of their facility. Although regular maintenance becomes a constant operational expense (which can be readily planned for and budgeted), it generally results in lower long-term costs due to fewer shutdowns and emergency repairs. Maintenance is key to achieving acceptable performance from mechanical equipment, including airflow, ventilation, humidification/dehumidification and pressurization. Further, the exterior building envelope should be periodically inspected and any repairs made in order to retain adequate performance.
7. Make certain all personnel involved in the renovation work are adequately trained and competent to perform their assigned tasks. Supervisors should be sufficiently

experienced with proposed renovation procedures and materials to allow close monitoring of the work.

8. Establish an internal quality assurance program regarding installation of remedial measures. Particular attention should be given to monitoring all aspects of the exterior building envelope, from planning and scheduling of remedial work to punch lists and final inspection.
9. For all remedial building systems, follow through with quality assurance programs which may have been developed for the renovation. Resist the temptation to take shortcuts which could affect long-term performance of the remedial wall system measures. Also, conduct a training program for associated renovation personnel in order that the proposed renovation system installation, its performance, and limitations are at least somewhat familiar to these workers.
10. Make certain that flashing assemblies are correctly constructed and coordinated between the trades of related work. Also, plan and schedule overall renovation so that interfacing components are sequenced properly.
11. Owners and property managers should closely monitor any activities that would affect the performance of installed renovation system assemblies. An inspection of the building exterior should be made before and after performing maintenance work that requires use of a motorized swing stage. If any damage is discovered, immediate repairs should be made.
12. Establish a program of inspecting and maintaining the exterior building envelope on regular, periodic intervals, for example, every two years. These inspections should be performed using equipment that allows close visual inspection and should include an evaluation of the overall building envelope condition, weathering of and defects within sealants, and condition of adjacent building components, such as roofs, doors, windows, flashings, etc.
13. Whenever maintenance or repairs to the building envelope are required, make sure only qualified personnel are employed that are experienced in working with the installed systems. Such work might include roofing repairs or replacement, sealant renovation, and window washing.

Related to Roofing

1. Investigation of suspected roof problems should always include a thorough visual inspection of the roof installation and condition, particularly at perimeters, penetrations, and flashings. In many cases, visual inspections will have to be supplemented by appropriate test methods which may be available, including core cuts, moisture surveys, and certain nondestructive test methods.
2. Based upon the investigator's judgment, accurate analysis of many problems will necessarily involve some selective demolition or at least partial disassembly and examination of components. Do any selective demolition to the extent necessary to confirm adequate construction assemblies, the absence or presence of moisture (and the extent and degree of moisture, if possible), as well as compliance with applicable codes and guide standards.
3. For all roofing systems, make sure underlying substrates are acceptable for application of the materials involved and assure that adequate slope will be achieved after construction.
4. Consider and fully evaluate the effect that differing weather conditions have had on existing roof systems or will have on the roof system intended for use. Prior to any comprehensive renovation, evaluate the initial cost and potential payback of upgrade options related to roof thermal performance. Utilize life cycle cost studies to assist in this analysis and fully advise the building owner of the most promising alternatives. Since the new roof will most likely be in place for the next 15 to 20 years, there will be no more opportune time than during the anticipated replacement to obtain these benefits.
5. Consider the use of vapor retarders where indicated by an evaluation of thermal and vapor characteristics for the specific roof assembly being studied. Avoid materials and assemblies that incorporate thermal bridges into the construction or else design compensating mechanisms for the installation.
6. Always follow good roofing techniques and practices in accordance with recognized roofing industry standards, as well as material manufacturer's requirements for the systems being installed.
7. For roof remedial work, try to anticipate problems regarding tearoff and replacement, future maintenance and use, and eventual replacement of the retrofit roof. Due to the reasons discussed in Item 4, above, consider the benefits of correcting any existing problems while the renovation work is being planned. Correction of inadequate or marginal roof drainage, raising HVAC equipment to provide sufficient maintenance clearance, establishing proper flashing heights, rerouting of piping or electrical conduit, etc., will probably never be as economical as when the roof work is being done.
8. Evaluate the existing building in conjunction with performance capabilities of materials proposed for use with respect to accommodation of movement arising from thermal expansion and contraction, as well as structure dynamics. Provide expansion joints at appropriate locations and install area dividers within the replacement roof installation, where required.
9. For roofs constructed over critical or sensitive interior spaces, and particularly if roof assembly methods are dependent upon field workmanship, consider the use of water flood testing to assess the level of workmanship achieved and to confirm acceptable roof performance. Prior to conducting flood tests with their large live loads, always check with the building engineer regarding roof structural capacity or else commission an independent structural assessment of the roof framing and deck by a professional engineer.

Related to Wall Systems

1. A comprehensive assessment of window or curtain wall performance for an existing building should include a thorough review of original architectural drawings and specifications, as well as fabrication and erection shop

drawings. A determination should be made regarding the original design intent with respect to accommodation of water (i.e., pass-through or barrier wall), since this information will affect how remedial work should be approached.

2. Investigation of suspected curtain wall problems should always include a thorough visual inspection of the exterior building envelope, particularly at windows, doors, other penetrations, upper and lower terminations (i.e., at ground level and at the roof), and at flashings. In many cases, visual inspections will have to be supplemented by appropriate assessment methods which may be available, including field tests for water penetration and air infiltration, selective demolition, and certain nondestructive test methods.
3. Accurate analysis of many problems will necessarily involve some selective demolition, or at least partial disassembly and examination of components. Perform or direct any selective demolition to the extent necessary to confirm adequate construction assemblies, the absence or presence of critical seals and anchorage, as well as compliance with applicable codes and guide standards.
4. Consider and fully evaluate the effect that differing weather conditions have had on existing curtain wall systems or will have on proposed remedial work. Prior to any comprehensive renovation, evaluate the initial cost and potential payback of upgrade options related to wall thermal performance. Utilize life cycle cost studies to assist in this analysis and fully advise the building owner of the most promising alternatives. Since any new wall system will most likely be in place for a significant length of time (and possibly the remaining life of the building), there will be no more opportune time than during the anticipated renovation to obtain these benefits.
5. Consider carefully the remedial options available and evaluate viable alternatives in the light of initial costs, maintenance costs, and long-term serviceability. With respect to corrective work on existing systems and the design approach to accommodating water, in some cases it will be necessary to stay within the constraints of the original design, while other conditions may require significant modification of the original design and assembly. In the worst-case scenario, remedial efforts may not be feasible, practical, or cost effective, and total replacement may be required. Although each building will be different and a final determination of the type and extent of remedial work will be dependent upon the judgment of the evaluator, the following general rules may be helpful.
   a. If the original design was a pass-through system and has exhibited poor performance related to water leakage, then you can either attempt to reestablish water collection and weep devices, if feasible, or else attempt to achieve a barrier wall on the previous assembly, making sure that continued unanticipated water leakage will not become trapped within the system and result in further damage.
   b. If the original design was a barrier wall system and has exhibited poor performance related to water leakage, then it may be possible to simply reestablish performance capabilities of the wall system by utilizing appropriate remedial applications or else by completely replacing nonperforming components. In most cases, it will probably not be feasible or practical to interject retrofit water collection and weep devices within the wall system.
6. Maintain or else reestablish proper tolerances for erection of major building components and adequate clearances between adjacent construction materials and components so adequate joint tolerances are retained. This recommendation applies to the overall building framing systems, which should comply with industry standards such as AISC and ACI, as well as building joints occurring panel-to-panel and at rough openings, such as panel-to-door, window perimeters, penetrations, and terminations, etc. For renovation work, it may be necessary to perform appropriate corrective procedures in order to achieve adequate joint widths.
7. Consider the use of vapor retarders where indicated by an evaluation of thermal and vapor flow characteristics for the specific wall assembly being studied. Continuity of the vapor retarder should be maintained at wall perimeters, terminations, and penetrations such as windows, doors, and utilities. Avoid materials and assemblies that incorporate thermal bridges into the construction or else design compensating mechanisms for the installation.
8. Also consider the use of air barriers within the wall when indicated by an evaluation of thermal and vapor flow characteristics for the specific wall assembly being studied. Continuity of the air barrier should be maintained at wall perimeters, terminations, and penetrations such as windows, doors, and utilities. For air conditioned buildings in hot, humid climates, consider the detailing and extra care required to provide air barriers and seal penetrations through exterior walls, as well as the advisability of blocking off the intersection of interior partitions at exterior walls, particularly for hotel buildings, where moist air from the exterior can travel into these partitions.
9. For wall remedial work, try to anticipate problems regarding corrective work and replacement, as well as future maintenance and use. Due to the reasons discussed in Item 4, above, consider the benefits of correcting any existing problems while the renovation work is being planned.
10. Evaluate the existing building in conjunction with performance capabilities of materials proposed for use with respect to accommodation of movement arising from thermal expansion and contraction, as well as structure dynamics. Provide expansion joints at appropriate locations and install appropriate sealants and backer rods at all working joints within the building envelope. Fillet bead sealant joints should be used sparingly if at all, and only at locations where joint movement is not anticipated. Sealant joint designs and selection of sealant materials should take into consideration the range and modulus of particular sealant materials proposed for use, in conjunction with anticipated joint movement which should be estimated in accordance with ASTM Guide for Use of Elastomeric Joint Sealants (C 962). Each contributing aspect of the building construction and condition,

including material compatibility, should be evaluated with respect to its effect on sealant performance.

11. Always follow good general construction practices in accordance with recognized curtain wall industry standards, as well as material manufacturer's requirements for the systems being installed.
12. Sealant installers should make sure that all wall system surfaces upon which they apply their materials are properly and completely finished. If deficiencies exist, interrupt sealant work until corrections can be made. Make certain that all openings that could allow direct water leakage (and even moist air leakage in humid climates) are thoroughly and appropriately sealed.
13. Consider the use of two stage sealant designs where appropriate panel depth and wall configurations will allow this type of building seal.

Related to Waterproofing

1. Investigation of suspected waterproofing problems should, if possible, include a visual inspection of, at least, representative samples of the waterproofing installation and condition, particularly at expansion joints, perimeters, penetrations, flashings, and other suspected problem areas. In virtually all cases, visual inspections will have to be implemented utilizing destructive methods in which excavation or disassembly of overlying layers will be required. In addition, additional information may be obtained by using appropriate field leak tests, moisture surveys, and certain nondestructive test methods.
2. Accurate analysis of many problems will necessarily involve some selective demolition or at least partial disassembly and examination of components. Do any selective demolition to the extent necessary to confirm adequate construction assemblies and compliance with applicable codes and guide standards. The advisability of drilling through exterior walls of below-grade structures should be carefully considered.
3. For all waterproofing systems, make sure underlying substrates are acceptable with respect to strength, serviceability, and finish for application of the materials involved. Use sound, hard, dense substrates that are not sensitive to moisture deterioration for below-grade and planter applications. If at all possible, the structural plane for horizontal members should be adequately sloped in order to achieve sufficient drainage after construction.
4. Consider and fully evaluate the effect that differing ground water conditions have had on existing waterproofing systems or will have on the waterproofing system intended for use. Prior to any comprehensive renovation, evaluate potential upgrade options related to waterproofing performance. Since the new waterproofing will most likely be in place for the remaining life of the building, there will be no more opportune time than during the anticipated replacement to obtain these benefits. Include considerations for renovating or adding to existing subgrade drainage systems; where these systems were not originally provided consider potential benefits of dewatering practices.
5. Always follow good waterproofing techniques and practices in accordance with recognized waterproofing industry standards, as well as material manufacturer's requirements for the systems being installed. Make sure that membranes have been placed properly in accordance with the discussion previously provided in the text of this chapter. For below-grade vertical waterproofing, in most cases, it will be advantageous to fully adhere the membrane to the structural deck with no intermediate layers in between. Notwithstanding recommendations from some designers related to loose-laid plaza deck waterproofing, these membranes should also be fully adhered where adequate substrates exists.
6. Evaluate the existing building in conjunction with performance capabilities of materials proposed for use with respect to accommodation of movement arising from thermal expansion and contraction, as well as structure dynamics. Provide expansion joints at appropriate locations and assure that they are located at the drainage high points (Fig. 22).
7. For waterproofing located over critical or sensitive interior spaces, and particularly if waterproofing assembly methods are dependent upon field workmanship, consider the use of water flood testing to assess the level of workmanship achieved and to confirm acceptable waterproofing performance. Prior to conducting flood tests with their large live loads, always check with the building engineer regarding deck structural capacity, or else commission an independent structural assessment of the affected framing and deck by a professional engineer.
8. Utilize positive side applications of waterproofing materials whenever possible. This recommendation, of necessity, may include requirements for excavating and backfilling at problem areas, but the added expenses will usually be justified by the increased chances of successfully addressing the leakage. Negative side applications of waterproofing materials using today's technology is still risky at best and may not achieve acceptable results. Utilize negative side waterproofing only when the positive side surface is not readily accessible and only as a supplementary waterproofing application.

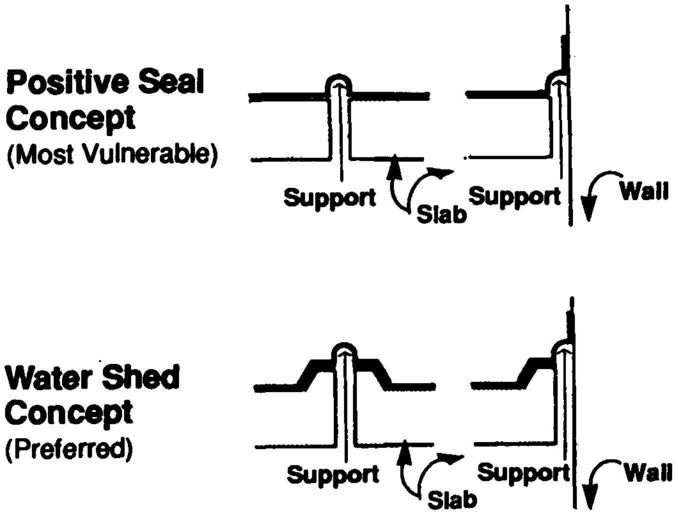


FIG. 22—Schematic expansion joint concepts at membrane level.

9. Carefully select waterproofing materials, giving proper consideration to substrate conditions and water environment, as well as past knowledge of the material characteristics and previous experience with the total system performance. Keep in mind that one type of waterproofing material will not be appropriate for all conditions encountered.
10. After installation of new or remedial waterproofing materials, always protect the membrane from possible pedestrian or vehicular traffic, other construction trades, backfilling, and installation of any separate toppings or wearing surfaces. In most cases, proprietary protection boards will be sufficient for these purposes; however, evaluate the potential for special or unusual conditions.
11. For plaza deck waterproofing, always achieve and maintain adequate drainage at the waterproofing level, as well as at the walking or wearing surface level. Utilization of special drain fixtures having multi-level openings for water entry will be required. Use proprietary drainage composites or aggregate layers with filter fabric (or both) directly on top of the membrane and protection course to assure free flow of water and consider the use of extra layers of filter fabric at drains to exclude seepage of fines and facilitate continued drainage.
12. For plaza deck waterproofing, consider the use of pavers on pedestals for all applications where it is feasible. Although initial cost of these materials will be more, they allow easy access for future maintenance and repair of the waterproofing membrane. As a second choice, use pavers on a sand bed, and only as a last resort utilize a cast-in-place topping slab. Avoid pavers set in a mortar bed because these types of assemblies tend to restrict drainage, retain moisture, cause premature joint sealant failures, and result in unsightly efflorescence.

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Manufactured Housing

by Michael F. Werner[1]

ASPECTS UNIQUE TO MANUFACTURED HOUSING[2]

The materials of construction and the basic methods of assembly for manufactured housing are nearly the same as those used in the building of single-family homes at the site. Thus, the moisture control issues for manufactured housing tend to be much the same issues as for site-built single-family dwellings. There are, however, some differences that should be considered.

Factory Assembly and Construction Methods

Factory assembly places restrictions on design and also results in benefits which contribute to differences from site-assembled structures. While the effects of these differences on the ability of the home to abate moisture migration and prevent damage due to moisture are not fully understood, it is worthwhile to identify them so that preventative measures can be sought.

Due to over-the-road height restrictions, the height of the attic cavity[3] is relatively small in comparison with attics in site-built homes. This can become a cause for restricted air movement in the attic. Figure 1 is a pictorial view showing roof covering, trusses, and insulation at the peak of the attic of a typical double-wide home. Figures 2 and 3 depict typical single-wide roof profiles. Typical double-wide roof profiles are depicted in Fig. 4. Height restrictions imposed by over-the-road restrictions of transportation are the same for single-wide and double-wide units. Once the insulation is in place, most attics tend to have little room for air movement.

Factory assembly of the open roof/ceiling structure[4] enables close attention to the quality of the application of vapor retardant and ceiling insulation. The limited access to the finished attic[5] makes re-evaluation of those same aspects at the site virtually impossible.

Tightness of construction joints, attributable to the accuracy of production cut framing and the factory-controlled application of caulking and sealing, is attained in manufactured housing. This can result in fewer air changes per hour than might be desired for purposes of water vapor dissipation. Thus, it might become necessary to provide for moisture removal.

Typical construction methods used to reduce air infiltration at the wall joints: wall to ceiling, corner wall to wall, and wall to floor; include the application of caulking or putty tape, as illustrated in Figs. 5, 6, and 7.

The minimum ceiling vapor retardant required by the HUD standard is 1 perm (dry cup method). This is equivalent to an approximate 1 mil (0.025 mm) polyethylene film. Films this thin cannot be applied without considerable stretching and tearing. Thus, the film of choice for most designers is 2 mil (0.050 mm).

The popularity of factory-applied textured surface finishes has made spray application of vapor retardant undercoatings economical. Film vapor retardants have therefore been eliminated from many ceiling designs that include factory-applied finishes. Ceiling vapor barriers are required by the HUD standard[6] whether or not the attics are ventilated.

Manufactured housing provides two basic methods of vapor control in the wall cavity: ventilated and nonventilated. Wall cavities designed to be ventilated require no vapor retardant as shown in Fig. 6. This is permitted because water vapor passing from the living space into the wall cavity can be carried away by air movement on the cold side of the insulation. Figure 7 depicts a typical nonventilated wall cavity where a vapor retarder is applied at the living space side of the cavity to reduce vapor transmission into the wall. The typical vapor retardant for walls is asphalt-impregnated paper backing

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[2] The United States Department of Housing and Urban Development (HUD) defines "manufactured home" as a structure, transportable in one or more sections, which in the traveling mode is eight body feet or more in width or 40 ft or more in length, or, when erected on site is 320 or more square feet, and which is built on a permanent chassis and designed to be used as a dwelling with or without a permanent foundation when connected to the required utilities, and includes the plumbing, heating, air-conditioning, and electrical systems contained therein.

[3] Typical height of truss at the center of the rise is 12 to 18 in. (0.3 to 0.5 m). Scissor trusses that are used for vaulted ceilings are on the order of 10 in. (0.25 m) deep. Ceiling cavities are nearly full of insulation. Higher roof profiles are achievable at considerable additional expense using hinged roof sections. These are raised at the site and closed in at the site. Due to the added cost, this method is used only to achieve aesthetic effects and not for condensation abatement.

[4] One of the benefits unique to factory assembly is that unimpaired access during the critical phase of construction enables thorough application of thermal insulation and vapor retardants as well as complete inspection of the work.

[5] No access panels are built into the ceilings of manufactured housing. Access holes are cut at the site on rare occasions that require service to the attic or limited visual inspection.

[6] See paragraph §3280.504(a) of the HUD Manufactured Home Construction and Safety Standards.

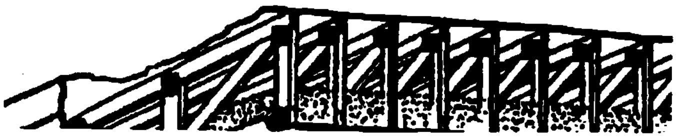

FIG. 1—Typical roof cavity.

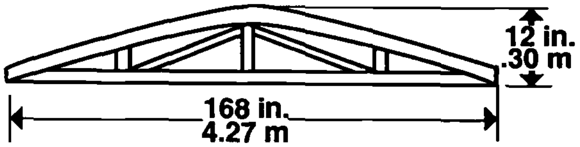

FIG. 2—Single wide with metal roof.

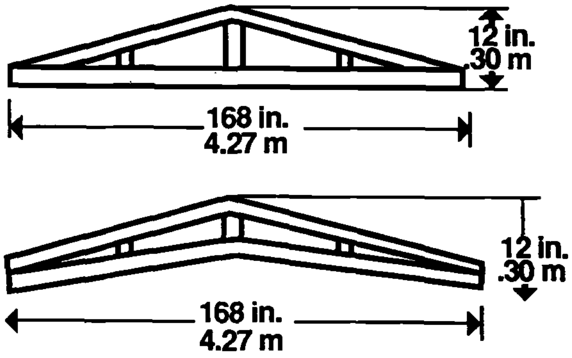

FIG. 3—Single wide with shingle roof.

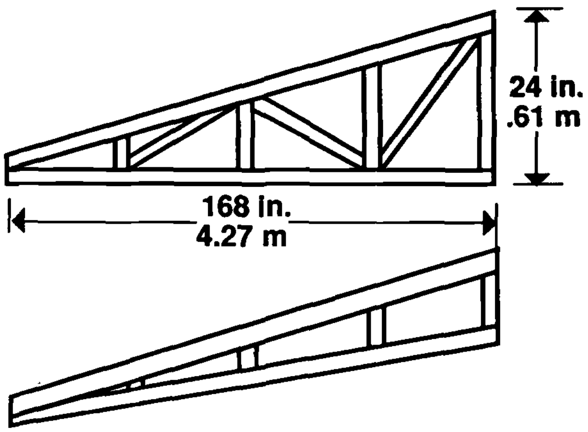

FIG. 4—Double wide (showing only one half).

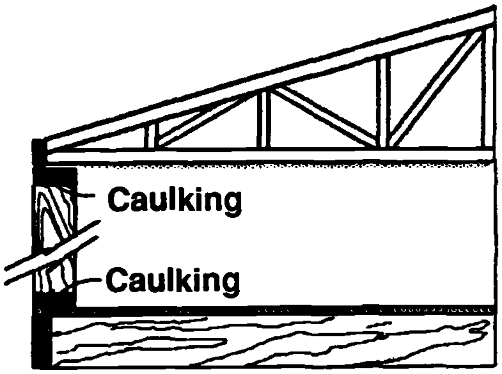

FIG. 5—Construction joints.

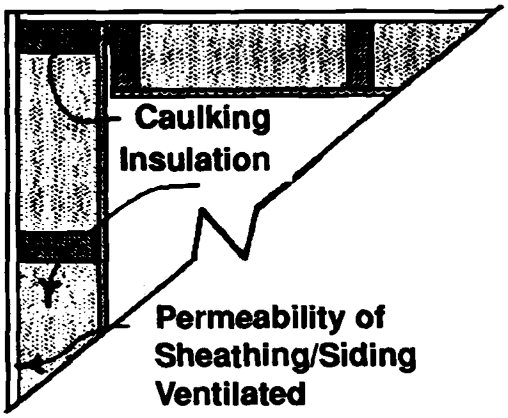

FIG. 6—Wall-ventilated cavity.

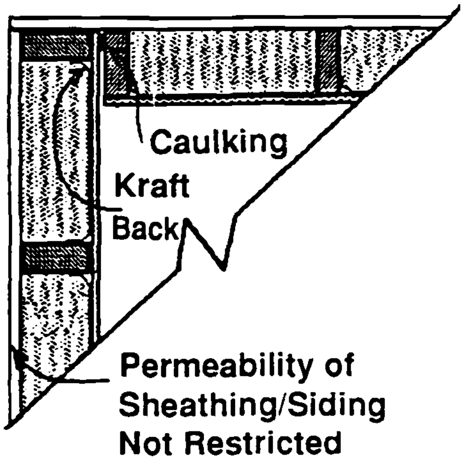

FIG. 7—Wall Kraft back insulation vapor retardant.

applied integral with the insulation batts. The paper flanges that in site-assembled construction are secured to the living side faces [1½ in. (38 mm)] of the wall studs are typically secured to the cell faces [3½ in. (88 mm)] in manufactured housing (see Fig. 3). This application troubles some designers because the lack of the conventional lap joint of paper on the 1½-in. (38-mm) stud face creates a breach in the continuity of the vapor-retardant envelope.

While Figs. 6 and 7 appear the same, there is an important difference. The designer has the option of providing a 1-perm (dry cup method) vapor retardant on the living space side of the wall in combination with sufficient ventilation to dissipate wall cavity condensation, or constructing the wall as an unventilated cavity. The unventilated cavity is required to have a combined vapor permeance (for the siding and the sheathing) of not less than 5.0 perms. Formed exterior siding such as aluminum, steel, or vinyl that is applied without caulking the joints is considered ventilated.

SITE INSTALLATION[7]

Some aspects of the site installation influence satisfactory moisture control. Effective site drainage is crucial. Significant damage has been shown to be caused by site grading that permits standing water to accumulate beneath the home. Another important installation aspect is ventilation of the crawl space. This is accomplished with screened vents as illustrated in Fig. 8. Efforts to conserve energy have caused some homeowners to close or eliminate crawl space ventilators. This has been shown to contribute to stagnant, foul air beneath the structure and is sometimes an expected cause for floor warpage attributed to water vapor. Structural damage of otherwise satisfactorily assembled and installed homes, however, can have root causes other than ventilation. Ample crawl space ventilation is usually obtained with the application of crawl space vents with a total area of (crawl space area)/150. Vents should be four or more in number and installed at or near each corner to maximize the effectiveness of cross ventilation.[8]

Manufacturer's approved installation instructions most often recommend the application of a polyethelene film ground cover. The application of film membrane ground covers in combination with effective site drainage and crawl space ventilation will assure the dryest crawl space possible for all seasons and climates and thus assure that moisture will not migrate into the home through the floor assembly.

Clothes dryer exhaust needs to be vented to the outside of the crawl space.

Where roof, ceiling, or wall assemblies are designed to be ventilated, the location of the home in relation to prevailing winds will influence the availability of ventilation air and can have an effect upon the performance of the vents.

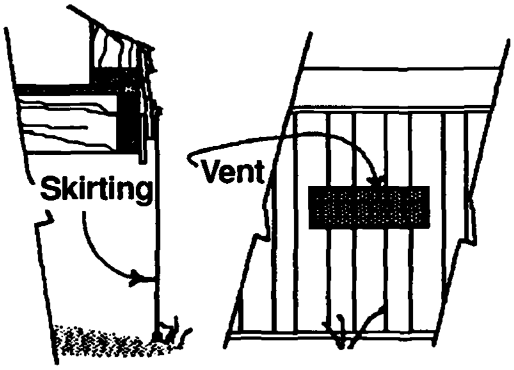

FIG. 8—Crawl space ventilation.

Mechanical Equipment

Some mechanical equipment is more prevalent in manufactured housing and can therefore require special consideration. Manufactured housing uses fuel-burning furnaces and water heaters that separate the combustion air supply from the interior atmosphere of the home.[9] This means that air for combustion and for draft hood dilution is piped in from outside the home. (Conventional residential-nonmanufactured housing uses air from inside the home.) This contributes to fewer air changes in the living space by eliminating the need for air to serve this purpose.

Several major producers of home heating equipment now offer power-driven roof vents that are connected to the return air side of the home heating system to introduce fresh air into the living space. The power system also injects fresh air into the attic. This, in combination with eave, ridge, and gable vents, accomplishes air changes in the attic that during the heating season serves to force moist attic air out of the attic. These systems have been proven successful in preventing condensation from forming in attics.[10]

Nearly all of the air conditioning equipment for manufactured housing is sold and installed in the aftermarket. While such equipment can reduce indoor humidity during the cooling season, it does not help to control moisture during the heating season.

Although some homes are offered with ducts in the attic, air duct designs are predominantly for ducts in the floor, as illustrated in Fig. 9. Floor ducts that rely on compressed floor insulation and vapor protection of the bottom board are particularly vulnerable to the formation of condensation beneath the bottom board and within the insulation during the cooling season.

Even in those situations where the insulation is not destroyed, the wetting of the insulation can cause seasonal energy waste due to increased duct heat gain and loss. It is

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[7] These aspects are the same for manufactured housing and for site-built homes on crawl space.

[8] Reference ANSI A225.1-1987 §2-6.2.1(d).

[9] Refer to HUD MHCSS §3280.709(d). Also note that the requirements for fireplace combustion air are similar [§3480.710(g)(1)(iii)], but not identical insofar as separate intake of combustion air is required, but "complete separation" is not.

[10] Home manufacturers report significant reductions in complaints attributable to attic condensation in homes that have these ventilation systems installed.

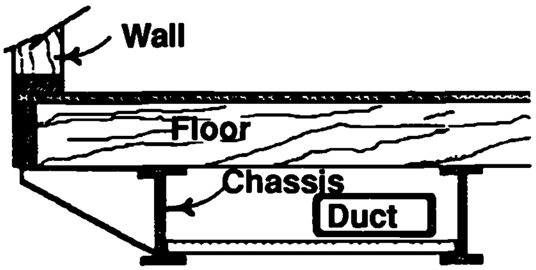

FIG. 9—Air duct in floor.

important that the duct insulation and bottom board in the area of the air duct be designed to prevent this.

Oversizing of air conditioning equipment is not uncommon. This can worsen the deterioration of insulation and increase the energy loss.

Occupancy

Manufactured housing is often thought to provide less space per occupant than other forms of housing. This is sometimes offered as an explanation for higher occupant load per unit of space and thus would make manufactured housing more susceptible to moisture production. Suffice to say, tighter-built, well-insulated construction is less tolerant of higher-than-normal occupant loads, which can result in the production of moisture that is not passively removed by ventilation and air exfiltration. While it is not illogical in those situations where higher-than-normal occupancy produces an overburden on the building to assign the problem of vapor removal to the occupants, instructing them on the opening of windows or on the virtues of turning on the exhaust fans, it is not fair. It is particularly unfair to those owners/occupants who have been sold on the importance of energy conservation and have purchased energy-saving insulation upgrades. In most situations, to rely on the opening of windows and manually turning on fans to satisfy basic ventilation needs is unrealistic and inconsistent with calls for energy conservation.

From an engineering performance point of view, the issue is whether or not sufficient air changes and vapor migration controls have been installed to reasonably assure that moisture will not accumulate and cause damage to the structure or endanger the health, comfort, or convenience of the occupants. This is as true for manufactured housing as it is for all building construction. In those situations where higher-than-normal[11] occupant density or unusual moisture loads are attributable, for example, to continuous operation of the home laundry or cooking facility, the designer should make provisions for ventilation over and above the requirements of the HUD standards.[12]

Standards and Regulations

Since June of 1976, manufactured housing has been regulated in the United States by the federal government under the HUD[13] Manufactured Home Procedural and Enforcement Regulations and the HUD[14] Manufactured Home Construction and Safety Standards. Excluded[14] are homes designed only for erection on site-built permanent foundations *and* not designed to to be moved once erected. This discussion and all others in this chapter of this manual pertain primarily to HUD-regulated homes, those homes included in the federal enforcement program.

The HUD Standards limit the vapor permeance for ceilings and walls. Current vapor performance and ventilation provisions from the HUD Standard follow in their entirety.

§ 3280.504 Condensation control (vapor barriers).

(a) *Ceilings.* Ceilings should have a vapor barrier having a permeance not greater than 1 perm (dry cup method) installed on the living space side of the roof cavity.

(b) *Exterior Walls.* (**1**) Exterior walls shall have vapor barrier not greater than 1 perm (dry cup method) installed on the living space side of the wall, or (**2**) unventilated wall cavities shall have an external covering and/or sheathing which forms the pressure envelope. The covering and/or sheathing shall have a combined permeance of not less than 5.0 perms. In the absence of test data, combined permeance may be computed using the formula:

$P_{Total} = \{1/[(1/P_1) + (1/P_2)]\}$, where P_1 and P_2 are the permeance values of the exterior sheathing in perms.

Formed exterior siding applied in sections with joints not caulked or sealed shall not be considered to restrict water vapor transmission, or (**3**) wall cavities shall be constructed so that ventilation is provided to dissipate any condensation occurring in these cavities.

§ 3280.504(b)(2) Interpretative bulletin, 1996

In unventilated wall cavities, the exterior covering and/or sheathing may have a combined permeance of less than 5.0 perms, provided that there is a vapor barrier of one perm (dry cup method) or less on the warm side of the wall, and that neither the sheathing nor the exterior covering have an individual perm rating of less than the vapor barrier installed on the warm side of the ventilated wall cavity, the combined permeance of the covering and/or sheathing shall be not less than 5.0 perms.

§ 3280.103 Light and ventilation

(c) *Bathroom and toilet compartments.* Each bathroom and toilet compartment shall be provided with artificial light and, in addition, be provided with external windows or doors having not less than 1½ sq. ft. of fully openable glazed area, except where mechanical ventilation is provided capable of producing a change of air every 12 minutes. Any mechanical ventilation system shall exhaust directly to the outside of the manufactured home.

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[11] The HUD standard does not provide limits on occupancy density. The HUD standard, in this respect, is not unusual among standards for residential construction.

[12] Paragraph 3280.103 of the HUD standard sets the minimum ventilation requirements. Openable glazing with an area of 4% of the room floor area is required in each room. Alternatively mechanical ventilation capable of changing the air every 30 min can be provided.

[13] United States Department of Housing and Urban Development.

[14] Modular homes designed and manufactured to conform to one of the nationally recognized building codes published by BOCA, ICBO, SBCC, CABO, or any state or local code are accepted as generally equivalent. Certifications of equivalence are subject to investigation by the Secretary of HUD. Reference: Paragraph 3282.12 of the HUD Procedural and Enforcement Regulations. Note that this Regulation does not prohibit manufactured homes from being installed on permanent foundations. It does exclude from the federal program those homes that once installed are not designed to be moved.

Since 1985, the HUD standard has mandated recommendations by the manufacturer to provide a ventilation improvement option available for each home produced. Although designated in the standard as a ventilation provision to improve indoor air quality and not specifically designated for condensation abatement, the consequent increased air changes usually removes moisture from the living space. Less water vapor is then available for transmission into the building assemblies where condensation could occur.

Ventilation improvement options from the HUD standard follow.

> **§ 3280.710 Venting, ventilation and combustion air.**
> (g) *Ventilation improvement options to improve indoor air quality.* (**1**) In addition to the minimum ventilation required by §3280.103 and this paragraph, each manufacturer shall make available in its approved designs and in the marketplace at least one of the following ventilation options to improve indoor air quality:
>
> (**i**) A passive ventilation system; or
> (**ii**) a mechanical ventilation system; or
> (**iii**) a combination of passive and mechanical ventilation system; or
> (**iv**) a fresh air inlet (not for combustion air) which draws its air from the exterior of the home (not the underside). The inlet shall be continuously connected from a forced air furnace to the exterior and be capable of providing at least 25 cubic feet per minute (42 M^3 per Hour) with the furnace in normal operation. The air inlet shall be listed for use with the installed forced air furnace.
>
> (**2**) The ventilation system(s) offered must improve the ventilation of the occupied living space of the manufactured home. (**3**) Ventilation improvement information sheet. Before any person enters into an agreement to sell a manufactured home to the first purchaser for purposes other than resale, the seller shall deliver a ventilation improvement information sheet to each prospective purchaser. The sheet shall include a description of the available ventilation option(s) and for mechanical systems, the rated capacity in air changes per hour or cubic feet per minute; and (**4**) The manufacturer shall provide, in its instructions, complete information for the installation of each ventilation option(s) being offered for use with its designs, including the ventilation system manufacturer's instructions.
>
> [*Editorial Note: § 3280.103 contains the minimum square foot light and ventilation provisions as a function of room size 8% and 4% respectively along with artificial light and mechanical ventilation alternates for kitchens and bathrooms. See § 3280.103 for specifics.*]

Some moisture control issues that designers might expect to find in the HUD standard are not presently addressed.

No provision is made in the current HUD standards for vapor retardation of the bottom board. Typical bottom boards consist of asphalt-treated paper. This forms the weather protection for the underside of the structure. The present standard, paragraph 3280.305(g)(4), requires that the material be evaluated according to the Beach Puncture Test. The Beach Test is required in order to afford some road durability for the bottom board to resist stone penetration. No provisions are made in the standard to control vapor migration. Control of bottom board vapor migration is important during the cooling season in hot, humid climates where the floor-cavity air-duct insulation can become subjected to deterioration due to condensation of water vapor that tends to migrate from the hot, humid crawl space toward the cold air duct and the cool living space. (Note that this issue might also be a concern for site-built homes built over crawl space.)

Minimum bottom board requirements from the HUD standard follow.

> **§ 3280.305 Structural design requirements.**
> (g) *Floors* (**4**) Bottom board material (with or without patches) shall meet or exceed the level of 48 inch-pounds of puncture resistance as tested by the Beach Puncture Test in accordance with Staest Methods for Puncture and Stiffness of Paperboard, and corrugated and Solid Fiberboard, ASTM D-781-1968 (73). The material shall be suitable for patches and the patch life shall be equivalent to the material life. Patch installation instruction shall be included in the manufactured home manufacturer's instructions.

No provision is made in the current HUD Standards to discriminate vapor control as a function of climate. See §3280.504 in the previous section. Paragraph 3280.504(b) requires the installation of a vapor barrier on the living space side of the walls. Thus, no consideration is given to the fact that in hot, humid climates the predominant vapor migration occurs from the outside of the home to the inside of the home. As water vapor moves from the outside to the inside, it is condensed on the cooler interior surfaces. While not widespread, this seasonal phenomenon does occur in the Gulf of Mexico coastal regions of the United States. In controlled experiments one manufacturer has reported preliminary successes in homes that use vapor retardants on both the inside and the outside wall surfaces.[15]

RECOMMENDATIONS FOR REMEDIAL AND PREVENTATIVE ACTIONS IN EXISTING MANUFACTURED HOUSING

Successful case-by-case remedial and preventative actions to abate continued damage from moisture in existing manufactured housing depend more than anything else upon a correct determination of cause for the symptoms observed. Simple as it might seem, it is crucial that reliable determinations are made of actual cause prior to the commencement of remedial work. In cases where the cost of repair is high, such as replacement of a floor or roof, second opinions should be sought, preferably from an independent professional.

Manufacturing Defects

Design practices that conform with the standards together with effective manufacturing quality control have minimized the production of homes with moisture problems. However, warpage of ceiling, wall, or floor surfaces, or surface water staining, particularly during and immediately after the most

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[15] Experts disagree on whether or not vapor migrates from outside to inside and thus are not in agreement on whether or not there is a benefit to be derived from installing vapor retarders on the outside of the building. The two-barrier remedy needs to be further evaluated. The traditional inside vapor retarder apparently is in need of further evaluation for effectiveness in hot, humid climates.

severe weather cycles[16], are sometimes caused by lack of continuity in the vapor envelope attributable to defective application of vapor retardant. There are other causes that show similar symptoms. More common than vapor retardant defects are roof leaks and drain and water pipe leaks. Other possible manufacturing defects that can show similar warp symptoms are wrong grade sheathing and wrong grade or broken lumber framing. Sometimes, the amount of attic ventilation called for in the design is not provided.[17] Manufacturers are generally prepared to promptly remedy warp problems that are caused by manufacturing defects.

Site Installation

Poor site drainage is a suspected leading cause for water vapor buildup in manufactured housing. Look for standing water or surface saturation beneath the home. A small adjustment to the grading immediately surrounding the home to include a small curb or berm can be an effective remedy. If the home is sited in an area for which surface drainage is not effective in maintaining a dry crawl space, more drastic measures such as general regrading, change in building elevation, or the installation of drain tiles might become necessary. If these methods are not cost effective, or if ground water (water table) problems are present, a site change might be desirable or necessary.

Mechanical Equipment

Most mechanical equipment used to improve the capacity of the building to avoid damage due to condensation works on the principle of replacing moist air with dryer air. Examples are as follows:

- bath and kitchen exhaust fans that push air from the living space to the outside
- clothes dryer exhaust duct that vents moist air from the clothes dryer to the outside
- attic ventilator that works in combination with other attic ventilators to move air from the attic and replace it with air from the outside
- combination attic/living space fresh air[18] connected to supply side of the furnace

Some manufacturers recommend in their owners manuals that dehumidifiers be used during the heating season. This, in most cases, is not only unnecessary but is likely to produce discomfort for the occupants. The use of humidifiers should be closely regulated to maintain indoor relative humidity at reasonable levels around 30%. If the health of the occupants demands more moisture in the air, special precautions are needed to protect the structure, such as the provision of additional ventilation.

Occupancy

Precautions for occupants to avoid buildup of moisture in the structure include the following: 1. Use the kitchen fan and bath fans in combination with opening of windows, especially when cooking and showering. 2. Maintain and service the power fan and vent fan systems to assure continued performance of the controls, motors, and dampers. 3. Check and empty, if necessary, the clothes dryer lint trap each time the dryer is used.

RECOMMENDATIONS FOR REMEDIAL AND PREVENTATIVE ACTIONS IN NEW MANUFACTURED HOUSING

Factory Assembly and Construction Methods

The controlled environment of the factory has made possible the application of vapor-retardant coatings integral with finishing operations. Some of these applications can significantly improve the retardancy because the application seals all cracks and joints.[19] In order to fully exploit the moisture control benefits of factory assembly and to achieve the high levels of performance possible, attention to the following production details is needed:

- storage and shelf life of materials in accordance with labels
- application rates and design film thicknesses in accordance with specifications
- continuity of vapor retarders application—no skips
- cure times and conditions of temperature and humidity—see labels
- compatibility of sealants with finishes

Where more conventional film vapor retarders are used in the ceilings or where ventilated wall assemblies[20] are used, the following items need special attention:

- continuity of vapor retarders in roof/ceiling assembly
- continuity of vapor retarders in wall assembly
- ventilation of wall assembly
- ventilation of attic cavity

Mechanical equipment designed and produced to provide air changes needs to be installed in accordance with the conditions for which it was tested and certified. Air ducts in unconditioned attics and crawl spaces designed to deliver

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[16] The most severe weather cycle for moisture load on the structure is the most prolonged period of high vapor pressure differences between the inside and outside of the home. This is dependant on climate and can occur during any season of the year. It is not likely that warp symptoms that first appear after two years' occupancy are caused by vapor retardant defects.

[17] Eave vents sometimes become closed by the application of attic insulation. Gable vent hardware is sometimes installed over siding without cutting the requisite holes through the siding to make the vents operable.

[18] More cost effective in new construction than in the after-market because some of the equipment, ducts and fan, need to be installed in the attic.

[19] Example: ceiling vapor barriers are required by the HUD standard to have a permeance not greater than 1 perm (dry cup method). See HUD Standard §3280.504(a). While a 1½ mil (3 mm) thick polyethylene film can provide 1 perm, the permeance of the aggregate ceiling assembly is effected (made more permeable) by the many fastener penetrations. Vapor retardants that are spray applied to the completed ceiling assembly seal the penetrations.

[20] See HUD MHCSS §3280.504(b)(3). The standard permits the use of exterior walls that are ventilated to dissipate condensation from the wall cavities.

comfort cooling air need to be satisfactorily insulated and vapor protected to abate condensation damage to the insulation and to other parts of the structure.

Site Installation

Some details require special attention at the site in order to assure that the factory-built home is satisfactorily resistant to moisture damage. Careful attention to installation details can guard against damage and consequent expensive remedial work.

- grading to assure adequate runoff and drainage
- ground cover under crawl space of minimum 6-mil polyethylene film or equivalent vapor retarder
- adequate ventilation of crawl space (minimum area = floor area/150; area to be distributed uniformly in no less than three of the four sides of the crawl space)
- closure of all construction joints
- closure of all penetrations in bottom board
- completion of all duct work in accordance with approved specifications

Mechanical Equipment

All mechanical equipment installed at the site needs to be installed in accordance with the instructions provided by the manufacturer. Those instructions must be prepared in accordance with the conditions of the product listing.

MNL18-EB/Feb. 1994

22

Moisture in Historic Buildings and Preservation Guidance

by Sharon C. Park[1]

MOISTURE IS THE MOST PREVALENT CAUSE OF DECAY in historic buildings. Over a long period of time, the presence of moisture will erode, rot, corrode, and otherwise deteriorate aging building materials. Moisture may come from underground sources and wick up into buildings; it may enter through cracks in deteriorated exterior materials; or it may originate in the interior of the building and migrate through materials (Fig. 1). Floods, hurricanes, tornadoes, water from fire-fighting operations, or broken and leaking interior plumbing can also greatly accelerate the flow of water into historic buildings with catastrophic results. Historic buildings must, therefore, be protected both on the outside as well as on the inside from potentially harmful moisture. Exterior surfaces must be properly maintained to prevent water infiltration, and interiors must be monitored and inspected to ensure that condensation and humidity generated on the inside are properly ventilated, managed, or eliminated. In the event of an emergency, building owners, managers, and architects should also be aware of temporary protective measures to reduce moisture damage.

This chapter identifies in checklist form the sources of moisture and typical patterns of decay for historic buildings. It outlines generally acceptable remedial treatments to guide in the control or elimination of unwanted moisture. Historic buildings, by their very nature, are irreplaceable. Their care and protection is the stewardship of their owners and communities. Even with reasonable care, historic buildings will decay if the source of moisture is not properly diagnosed and treated (Fig. 2). Moisture is notorious for traveling some distance from the source. Without understanding how moisture enters and moves through a building, it is difficult to identify the true source or multiple sources of moisture. It does little to merely repair or replace the obviously deteriorated materials without eliminating the moisture source. In some cases, improper remedial efforts to control moisture, such as sealing exteriors with waterproof coatings, can accelerate the deterioration of fragile historic materials. It is, therefore, important to investigate carefully and to monitor areas of decay (Fig. 3), evaluate options for the control or elimination of the sources of moisture, and undertake remedial treatments within a preservation context.

A methodology for action specific to historic buildings involves:

1. Researching existing drawings or earlier studies of the building.
2. Undertaking a condition assessment of the historic resource.
3. Monitoring moisture levels in materials.
4. Identifying structural and material assembly systems to understand how moisture moves and dissipates through materials.
5. Evaluating the various sources of moisture affecting the resource.
6. Undertaking corrective action within a preservation context.

Whenever historic buildings are to be restored, preserved, or rehabilitated, a team of professionals familiar with the issues involved should be assembled. If the problems involve materials deterioration from moisture damage, the following individuals should be consulted: a preservation architect, an engineer familiar with nondestructive testing and techniques for evaluating moisture damage in historic buildings, a contractor or crafts person familiar with sound repair or restoration treatments, and a maintenance supervisor who will see to it that good cyclical maintenance is undertaken once repairs have been made.

Most acceptable repair treatments are traditional and conservative and employ historic materials and techniques. This makes the treatments "reversible" in most cases—an important preservation objective. As relatively new techniques and synthetic materials are successfully utilized and their performance tested, there is a growing acceptance for their limited use in historic buildings. Many treatments developed for new buildings and quick commercial "cures" for moisture problems *may not be compatible* with historic building materials and could cause additional damage. Cautions against some of these treatments are given under treatments to avoid.

ASTM standards are an important component of good repair or replacement specifications. Specific ASTM standards, for example, concerning stainless steel anchors or lime-based mortar mixes, are not listed in this chapter, as each building presents unique circumstances and must be evaluated accordingly. A treatment or ASTM standard for one building may be completely inappropriate for another. While a number of remedial treatments may be listed under the various components of a building, the reader should be aware that *careful evaluation must be made by qualified professionals before any treatments are selected.*

Because moisture is a complex subject, this chapter breaks

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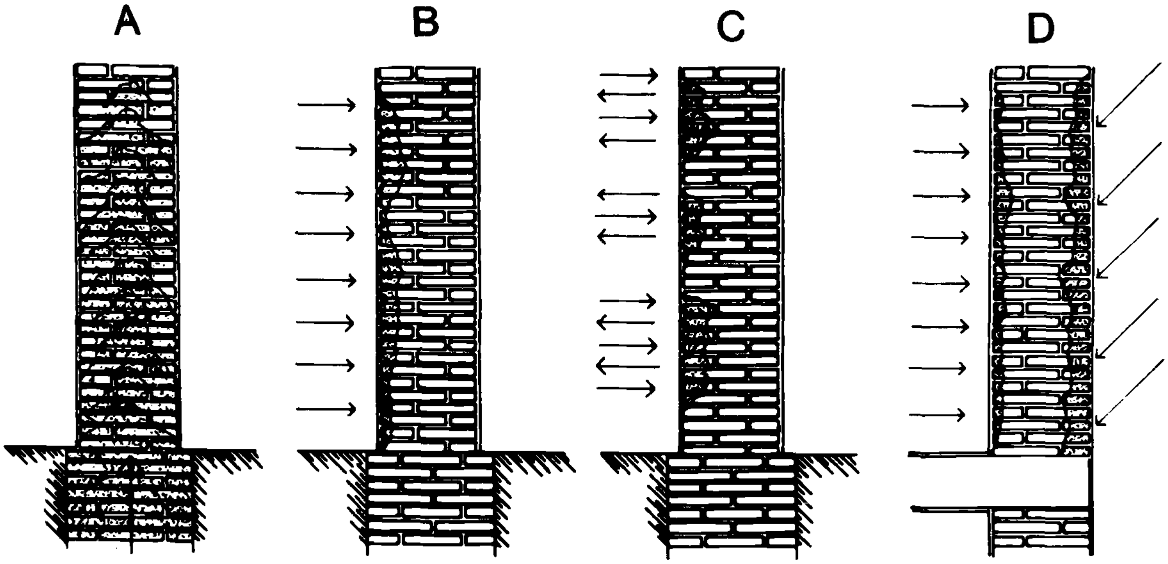

FIG. 1—Moisture can penetrate historic buildings from a number of directions. Moisture can rise through the wall from below the foundation and is known as rising damp (a); outside moisture and humidity can penetrate absorptive wall surfaces (b); vapor can move in and out of building materials (c); moisture can travel into materials either with exterior driving rain or interior humidity or condensation (d). Wall Section Sketches, NPS files.

buildings into different components, from exterior to interior. Buildings are systems and work as systems, but our diagnostic tools and abilities are limited by an approach that looks at components before it looks at systems. In most cases, the final resting place for moisture—where it is usually most apparent—may be far from its source. In order to trace moisture back to its initial source, those investigating moisture damage in historic buildings should have some sense of historical building methods and materials and must be aware of how the building components function within the overall structural system.

Some of the information presented in this chapter is adapted from previously published bulletins or reports by the National Park Service (NPS). A list of publications in found at the end of this chapter.

HISTORIC PRESERVATION GUIDANCE

The principal document outlining the National Park Service's policy on historic preservation is the Secretary of the Interior's "Standards for the Treatment of Historic Properties." These standards were developed as a response to the National Historic Preservation Act of 1966, which established a national historic preservation program to encourage the protection of historic and cultural resources. The Secretary of the Interior's "Standards" provide general objectives and principles which prescribe the scope and appropriateness of treatment work for historic resources listed in the National Register of Historic Places or eligible for such listing. The best known standards are the "Standards for Rehabilitation." "Rehabilitation" is understood to be the process of returning a property to a state of utility through repair or alteration while making possible an efficient contemporary use. According to these standards, significant historic materials, finishes, and features should be retained whenever possible. It is, therefore, important to protect and preserve the historic materials of a building while undertaking maintenance, repairs, or major rehabilitation projects.

The "Standards for Rehabilitation" (see Appendix A) call for the protection and retention of historic materials and the preservation of the historic character of the resource. This is best accomplished through a rigorous program of cyclical maintenance. If historic buildings are inspected on a regular basis, problems can be controlled before extensive damage or deterioration takes place. If materials have deteriorated, as they so often do from excess moisture, they should be repaired or replaced in kind, if at all possible. Any changes, alterations, or mitigating treatments should be carefully evaluated to prevent additional damage to the historic building or site. Before any work is undertaken, ask the question "Will these treatments or changes alter the historic character of the building or change the performance of the materials in such a way that additional damage may be caused?" If the answer is "yes," look for other options.

HISTORIC EXTERIORS

The historic site and the building's exterior—foundation walls, exterior walls, openings, and roof—are constantly exposed to the elements. Moisture, ultraviolet rays, wind, and hail all accelerate deterioration. One of the challenges of preservation is to keep a building weather-tight while still allowing the historic materials to expand and contract naturally. As building materials expand and contract, openings for moisture penetration will undoubtedly occur. Only routine inspections and cyclical maintenance can slow down this nat-

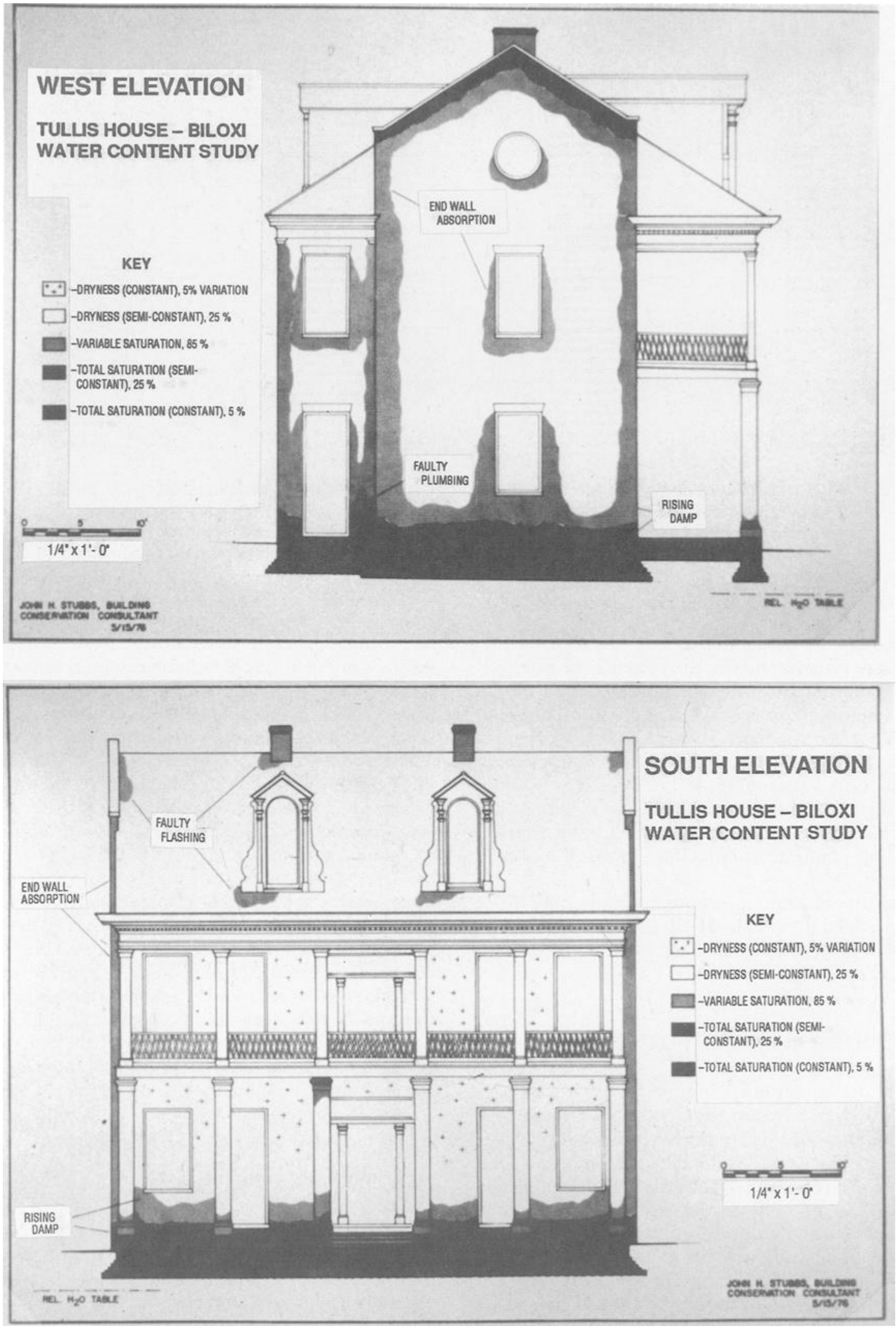

FIG. 2—Historic buildings plagued with moisture problems will benefit from systematic investigation, monitoring, and documentation to determine the type of moisture, its source, and the level of damage in order to select the best method for repair. Drawings courtesy: John H. Stubbs, NPS files.

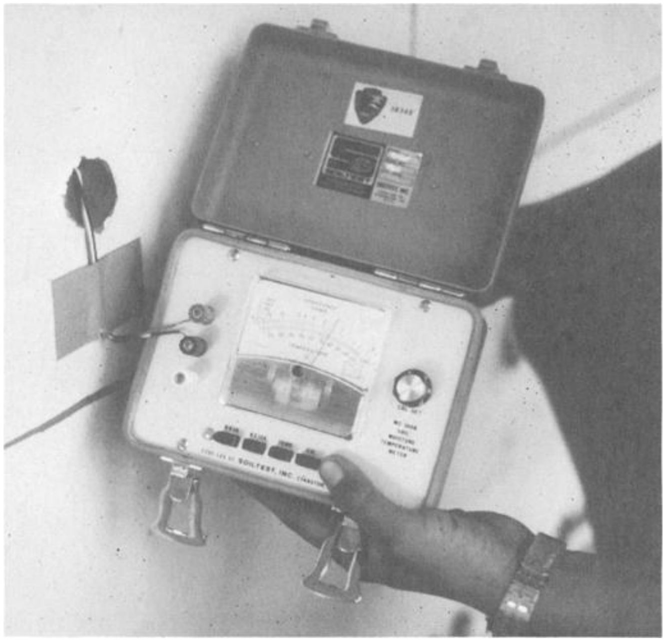

FIG. 3—Moisture meters are a useful tool in monitoring water content in historic building materials. Varying probe lengths can be inserted into small core holes to track the level of moisture. For long-term monitoring, probes are left in the wall and the meter is attached for recording. Photo: NPS files.

ural process of deterioration. As most historic exterior materials are still available, in-kind replacement of deteriorated materials should be a first consideration. Waterproofing historic building materials with coatings, claddings, and sealers generally should be avoided; these treatments can trap moisture in a building and may cause or accelerate decay. *Standard specifications for moisture protection of modern materials and construction assemblies are rarely applicable to historic buildings without some modification.* For example, compositions of new mortar for repointing should match the historic in permeability, among other properties, which may be different than that of a standard ready-mix compound.

Historic Building Site

The relationship between a building and its site establishes a context within which historic character is defined. The site, including landscape features, should be considered an integral part of any rehabilitation or maintenance work. Over time, site conditions can change and these may exacerbate moisture problems to historic buildings. Grades can shift, thereby allowing moisture to pond at foundations. Adjacent new construction can alter water tables or subsurface drainage patterns. Alterations to plantings around buildings or shifts in grade levels can cause damp earth to contact foundation materials above the dampcourse layers. Installation of modern underground automatic lawn sprinkler systems can add to unwanted moisture conditions.

Many historic buildings that have been improperly maintained can be successfully rehabilitated with good common sense and aggressive maintenance (Fig. 4). Keeping the site clear of vegetative threats and repairing the exterior envelope can go a long way to preventing problems. Generally gutters and downspouts will need repair or replacement, and the site should have drainage away from the foundation walls. Properties plagued with ground moisture problems will generally require more thorough evaluation and remedial work. Precautions should be taken if large earthmoving equipment is brought on site to avoid crushing subsurface drains located close to grade. Whenever historic sites are to be excavated, if archeological resources or special landscape features are present they should be preserved.

Evidence of Moisture: Site

- Poor site drainage
- Ponding moisture
- Foundation dampness
- Moss or other moisture-holding vegetation

Sources of Moisture: Site

- High water table
- Improper surface grading and run-off from downspouts
- Underground lawn sprinklers
- Adjacent new construction that has altered water tables or drainage patterns
- Overgrown site vegetation damaging building exteriors or foundations

Remedial Treatments: Site

- Regrade site to correct problem
- Remove or relocate nonsignificant plantings too close to foundations
- Add vapor barriers over ground surfaces in crawl spaces
- Repair damaged drainage boots

Treatments to Avoid: Site

- Extensive site paving (alters drainage patterns)
- Planting shrubbery/trees at foundation (roots cause cracks, hold moisture)
- Regrading to expose basement/foundation walls (alters historic relationships to site)

Foundations

Eighteenth and nineteenth century foundations were generally constructed of brick, rubble stones, or cut masonry, although some rustic log and frame buildings were constructed with wooden sill plates directly on the ground. Early buildings may or may not have had spread footings which tended to stabilize foundations in moist conditions. Foundations were either continuous, forming a basement or cellar wall, or were piers supporting structural sills. Ventilation grills in foundation walls were prevalent in the 18th century. These allowed air to circulate under the first floor wooden framing joist. By the end of the 19th century, concrete, concrete block, and reinforced concrete were used for structural piers. The use of a reinforced concrete slab as a unit foundation was employed by a number of architects, notably Frank Lloyd Wright, at the turn of the century. Twentieth century buildings, particularly mid-century highrises, have reinforced concrete foundations similar to those constructed today. Because footings are generally hidden and owners may not have original drawings for their buildings, it may be nec-

FIG. 4—Historic buildings on overgrown sites will deteriorate rapidly as moisture penetrates through damaged exteriors. In this view, vines have attached themselves to the house, keeping moisture in contact with deteriorating surfaces; gutters have been pulled off the porch; missing downspouts have caused mortar to erode; and broken glass allows driving rain to penetrate the interior. Photo: NPS files.

essary to research old building records or archives to determine if any records exist regarding the construction of the building. For late nineteenth and early twentieth century buildings, particularly, there are often early photographs documenting construction that can be found in historical collections. If foundations are to be excavated, care should be taken to ensure that archeological resources are properly protected (Fig. 5).

Because foundations have always been affected primarily by ground moisture, either rising damp or the lateral transmission of groundwater through walls, historically builders paid special attention to foundation details. Foundation walls were constructed of dense materials using clay or hydraulic lime mortars to prevent the capillary rise of moisture in the walls. Granite or dense limestone was often used up to the water table line. These shaped water tables helped divert rainwater from the building foundation. In the nineteenth century, impervious layers of material, such as slate, were often laid in the foundation wall just above grade to further impede moisture from rising above the water table. Grades were usually sloped away from foundations; gravel or porous materials were often used around the foundation for improved drainage; and plantings, particularly those with large root systems, were rarely placed near foundations.

The presence of moisture in the foundation wall can usually be detected by visual inspection. Moisture content of foundation materials can also be monitored and calculated using resistance moisture meters, with direct readings or through laboratory analysis, or with carbide meters evaluating core samples removed from the building. It is important to determine the absorptive rate and permeability of specific materials, as well as their moisture content in order to evaluate potential moisture problems.

If there is a basement, a damp or musty smell indicates poor ventilation and generally moisture migration through the foundation wall or basement floor. Moisture meters which probe the surface of the material can record the level and amount of moisture. Fungal growth in absorptive materials may also be present when the moisture content of materials, such as wood fibers, exceeds 20%. Damp foundation walls can be seriously weakened and moisture and fungal rot can travel to adjacent wooden sill plates, joists, flooring, skirting boards, and structural wall framing.

Remedial treatments for foundation moisture will vary depending on whether the damp is from below the footing or from lateral ground moisture. Most persistent ground moisture is improved with the installation of footing drains and waterproofing of exterior below grade foundation walls. This will do little to resolve a rising damp problem, which may require a physical damp course.

FIG. 5—In regrading to alleviate poor site drainage or excavating a foundation, archeological evidence may appear. Care should be taken to identify, record, and preserve important historic evidence. Photo: Milwaukee County Historical Society, NPS files.

Evidence of Moisture Decay: Foundation

- Damp or decayed materials
- Masonry efflorescence
- Rising damp tide marks about 2 to 3 ft (0.60 to 0.91 m) above grade
- Spalling surfaces below the water table
- Material erosion
- Mold or mildew

Sources of Moisture: Foundation

- Excessive ground moisture; high water tables; hydrostatic pressure
- Ineffective gutters and downspouts; broken drain boots
- Broken subsurface drains or abandoned cisterns
- Absence of footing drains
- Improper surface grading and runoff
- Moisture buildup in crawl space or basement (inadequate ventilation)
- Rising damp (ineffective dampcourse barriers)
- Moisture-holding lichens, algae, or plant materials
- Penetration through cracked building materials; deteriorated joints

Remedial Treatments; Foundations

- Remove or control unwanted groundwater (redirect drainage patterns)
- Install footing drains, foundation gravel, or sump pumps
- Repair/replace in-kind decayed materials
- Repair or consider physical dampcoursing (slate, lead, etc.) (Fig. 6)
- Improve cross ventilation in basements or crawl space (natural or mechanical)
- Dehumidify basements
- Waterproof *exterior* surface of foundation wall *below grade* only
- Repoint deteriorated mortar (match historic cement: lime:sand/aggregate mix, color, and appearance)

Treatments to Avoid: Foundations

- Waterproof coatings above grade (trap moisture)
- Parging unfinished damp walls (forces ground moisture further up the wall)
- New basement slab without a sump pump or drainage (alters hydrostatic pressure)
- Chemical dampcourse injections (consider *only* if all other remedial treatments fail) (Fig. 7)
- Replacement materials/patches with differing coefficients of expansion and contraction
- Creating large dry moats to accelerate foundation drying (incompatible new design feature)
- Adding vapor barrier over excessively damp crawl space (will exacerbate rising damp in foundations)

Exterior Wall Surfaces

Wall surfaces may be constructed of almost any material: wood, masonry, adobe, terra cotta, cast iron, concrete, carrara glass, plate glass, enamelized metal panels, or stucco. The two principal classes or materials in historic buildings are masonry and wood. Exterior materials were sometimes left in a natural state, such as brick or stone, or they were painted for protection from the elements, such as wood. Some materials were painted purely for decorative effect.

Exterior surfaces were carefully detailed to protect from moisture deterioration. Masonry mortars were lime-based, which allowed expansion and contraction within the masonry joints without causing cracks to open up. In repair work, the use of too hard or dense a mortar (too much cement in proportion to lime) for repointing may cause shrinkage and hairline cracks, which will then allow moisture to penetrate the wall. One of the deficiencies found in early 20th century construction was the lack of adequate expansion joints in masonry construction. This deficiency can be corrected with the careful installation of expansion joints during rehabilitation work. Wooden structures, mostly of frame construction (both balloon frame and stick built) often used cladding such as clapboards over a wooden structural frame. This created a cavity that was an important feature in dealing with moisture in buildings. It acted as a ventilation/condensation chamber between the outside and inside of the building. Any

FIG. 6—Moisture rising through foundations is often difficult to treat. In some cases the insertion of a physical barrier may help stop capillary action. This wooden replacement column, only 15 years old, was showing rapid decay (dark stains) as a result of moisture at the stone base. To arrest further deterioration, lead sheets were inserted to prevent rising damp. Photo: Bryan Blundell.

moisture migrating either in or out of the building, or condensation from temperature and humidity changes within the cavity, or the collection of moisture from hidden leaks, could dissipate without rotting or corroding materials within the wall. This cavity is frequently lost, as modern replacement sidings are installed with tight-fitting insulation. The poor performance of paint retention on wooden siding after insulation of the cavity wall is often a direct result of trapped condensation or moisture being held against the back of the painted wooden elements.

FIG. 7—Not all methods of dealing with rising damp are successful. Chemicals injected through the exterior walls to create a waterproof barrier can be visually disfiguring and often are not effective in curing rising damp. These treatments should be considered only as a last resort and injection should be from the interior to avoid disfiguring the building exterior. Photo: NPS Files.

Maintenance of exterior wall surfaces is important. Deteriorated materials should be repaired until such time as they need replacement. The removal of molds, mildews, and moisture-holding vegetation is a good first step in maintenance. The monitoring of all joints and areas where moisture can penetrate is an important annual ritual of cyclical maintenance. Painted exteriors, particularly for wooden surfaces, must be renewed periodically to keep the protective surfaces intact. As previously mentioned, exteriors must be maintained to keep moisture out to the extent possible, but must not be sealed with modern coatings that prohibit the natural migration of moisture or the movement of materials. Modern flashing and caulking can improve perimeter protection around exterior openings and if carefully installed will not detract from the historic resource.

Evidence of Moisture Decay: Exterior Walls

- Paint: blistered or failed paint to the bare substrate
- Wood: rotted, cracked, split, or punky, spongy material
- Bricks: cracked, pushed out of alignment, spalled, eroded
- Masonry/stucco: cracked, settled, eroded, spalled, delaminated (Fig. 8)
- Terra cotta: cracked, crazed finish, spalled
- Concrete: spalled due to corrosion of internal reinforcement, freeze/thaw spalling
- Rust stains from metal anchors, angles, nails, and wire lath
- Efflorescence from salts migrating along with moisture in masonry walls
- Building elements pulling away from attachments (porches, balconies, cornices)

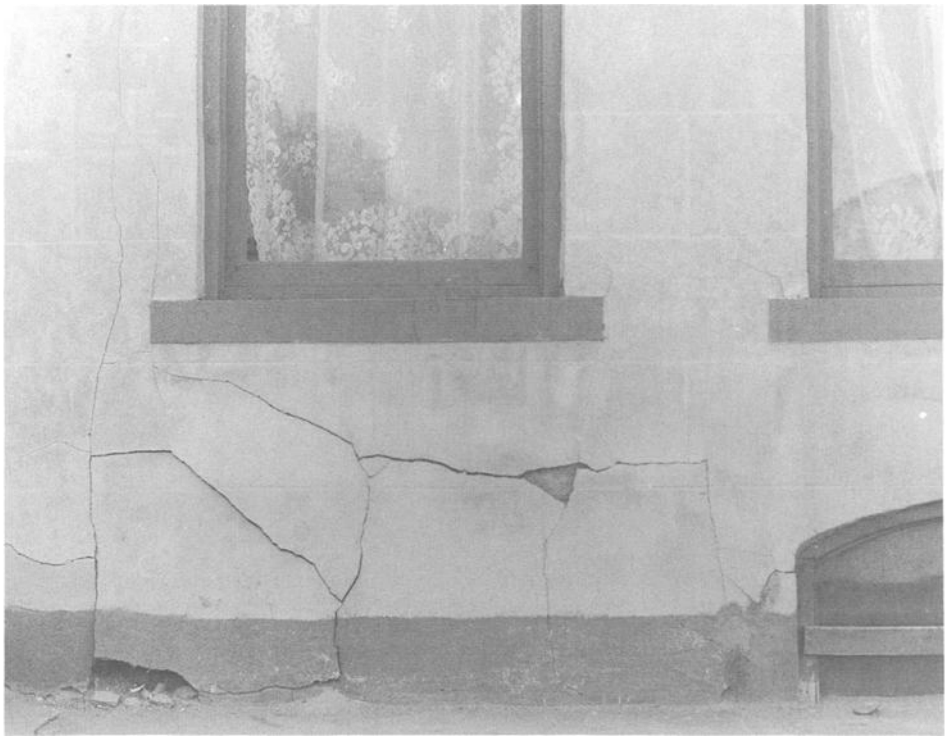

FIG. 8—Any obvious cracks should be evaluated and repaired. Moisture has entered these cracks, caused either by impact, foundation settlement, or stucco shrinkage from the modern top coat of stucco. Moisture has exacerbated the separation of the top coat of stucco from the darker historic substrate below. Damaged areas must be removed, and new stucco, formulated to be compatible with the historic substrate in strength and composition, should be reapplied. Note how the stucco has been scored to resemble cut ashlar stone. Photo: NPS files.

- Presence of moss, lichens, or other growths fed by excess moisture

Sources of Moisture: Exterior Walls

- Eroded mortar joints in brick and masonry
- Cracks in masonry, concrete, stucco (settlement, freeze/thaw) (Fig. 9)
- Open or uncaulked joints between wall surface and openings
- Deteriorated downspouts (external or internal)
- Migration through porous or deteriorated materials
- Trapped moisture behind walls (from condensation in insulated cavities or broken pipes)
- Broken or sagging gutters dripping moisture onto walls
- Most climbing vegetation (vines, ivy) growing on exterior walls
- Watering systems for foundation plantings, sprinklers, irrigation systems

Remedial Treatments: Exterior Walls

- Repair or replace in-kind deteriorated materials or features
- Repoint deteriorated mortar joints with new mortar formulated to match the historic mortar in composition, color, and visual qualities
- Replace or repair cracked masonry units; reset if necessary to correct a settlement problem
- Caulk perimeter joints around openings, if appropriate
- Repair all anchorage systems before replacing repaired features
- Remove efflorescence with water wash or poultices; determine source of moisture to avoid recurrence
- If consolidants or coatings are necessary, they should be vapor permeable and not alter the historic appearance of the materials
- Ventilate the interior of the building to reduce moisture that is transmitted through the exterior walls
- Ventilate exterior siding if frame walls have been packed with insulation
- Properly prepare surfaces if they are to be repainted; remove mildew prior to repainting
- Replace deteriorated flashings at joints where features meet the wall
- Remove vegetative threats

Treatments to Avoid: Exterior Walls

- Power washing exteriors (force may drive moisture into the building)
- Waterproof coatings (these tend to trap moisture within walls) (Fig. 10)
- Water-repellent coatings (use only after testing—may discolor materials or trap salts)
- Modern caulking and sealants on vertical masonry wall surfaces (should be properly repointed instead)
- Cement mortars or synthetic patches (may erode weaker historic materials) (Fig. 11).

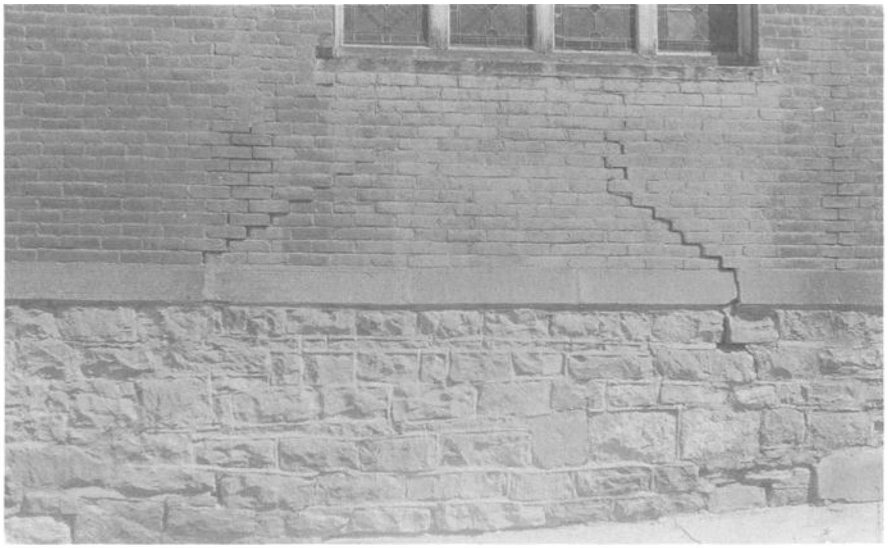

FIG. 9—Settlement cracks in historic masonary are a common source for moisture penetration, particularly from driving rain. Structural analysis should be undertaken to ensure that the cause for settlement has been corrected before repointing is undertaken. Repointing of historic materials should match the composition strength, color, and texture of the original mortar; in this case there may be two formulas, one for the stone and the other for the brick portion of the wall. Photo: NPS Files.

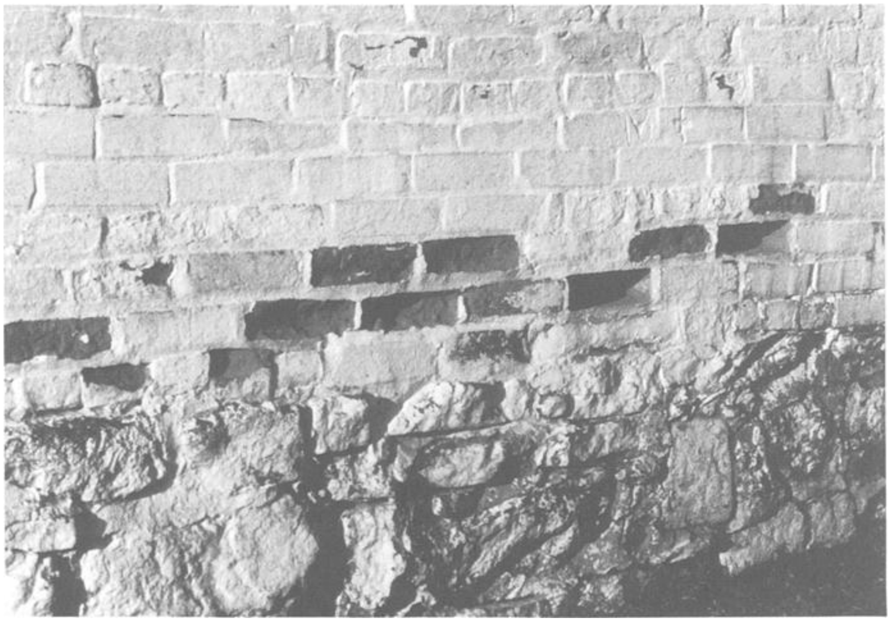

FIG. 10—Moisture naturally migrates through most historic materials. When vapor-impermeable or waterproof coatings are applied to exterior materials, moisture and salts can become trapped behind this impervious film. In this case, Freeze-thaw spalling of the historic masonry is evident where trapped moisture was unable to escape. Photo: NPS files.

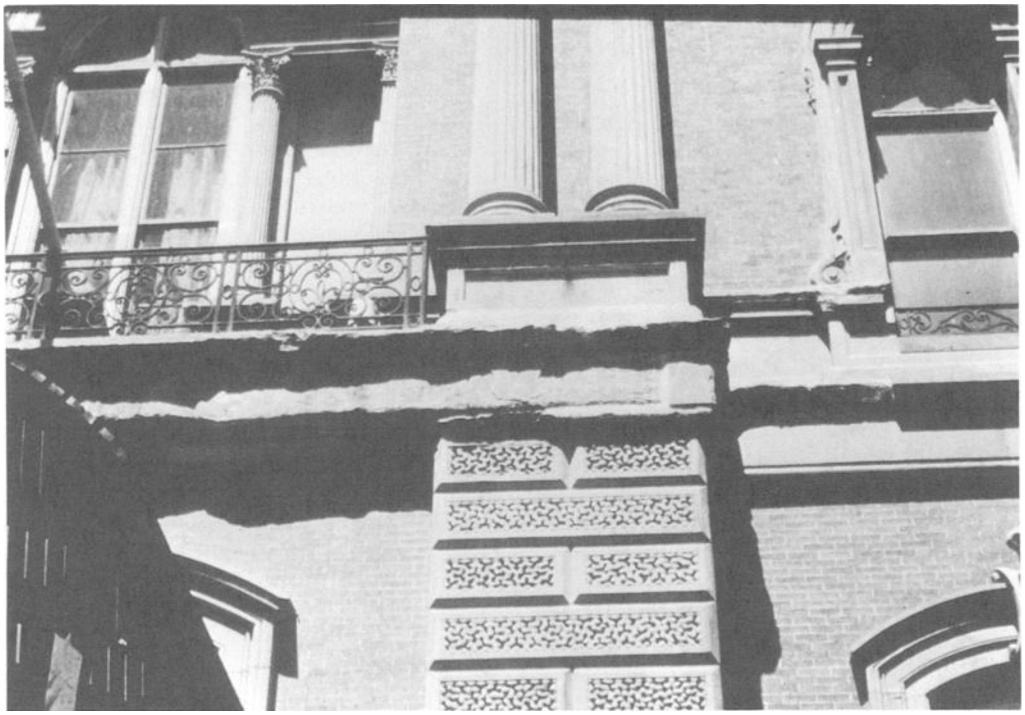

FIG. 11—Some repair treatments will result in damage more serious than the original deterioration. Synthetic patching compounds were used to repair deteriorated sandstone, only to fail within a few seasons. Moisture trapped behind the synthetic waterproof patches deteriorated sound stone and the patches failed. Deteriorated features should be replaced with the original materials to the extent possible. If substitute materials are used, they should work within the expansion, contraction, and permeability properties of the original materials. Photo: NPS files.

Windows/Doors

Windows and doors are identified as special exterior features because moisture problems are often a result of leaks from poor perimeter joints, improperly sloped sills and thresholds, or deteriorated materials. Historic windows, doors, and storefront assemblies were constructed of wood, rolled steel, bronze, Monel, aluminum, and glass (Fig. 12). Residential windows were typically casements or double-hung units; Eighteenth and early nineteenth century windows tended to be smaller and have multiple pane configurations. Later nineteenth and twentieth century assemblies used larger glass sizes and were often of an industrial, institutional, or commercial scale with metal frames and specialized glass (wire, plate, ornamental). Because many windows are inadequately maintained and, as a result, deteriorate, they are often replaced with modern thermal units that do not match the historic detailing of the originals. Moisture can generally be controlled with good perimeter closure, elimination of cracks in glazing or joint compound, and repair of deteriorated materials.

Evidence of Moisture Decay: Windows/Doors

- Blistered, peeling paint
- Rust or corrosion of metal; rotted, cracked, or punky, spongy wood
- Cupped, cracked, delaminated, spalled window sills
- Dry, pulled away, or cracked glazing putty
- Broken glass; deteriorated sash, deteriorated frames
- Water-stained areas around window perimeter
- Missing mortar or sealants around window perimeters

Sources of Moisture: Windows/Doors

- Driving rain penetrating window surrounds, cracks in units, broken glass
- Snow buildup on sills, ledges, thresholds
- Moisture settlement on deteriorated exterior muntins, stiles, and rails
- Moisture penetration through exterior cracks, missing putty
- Moisture migration around windows from interior condensation

Remedial Treatments: Windows/Doors

- Repair windows/doors whenever possible (fillers, splicing new sections, new glass)
- Replace deteriorated units with historically matching
- Reset sills and ledges for positive slope
- Fill perimeter joints to close cracks (repoint, caulking, sealant, lead wool)
- Upgrade with storm windows (sensitively designed units with venting capacity)

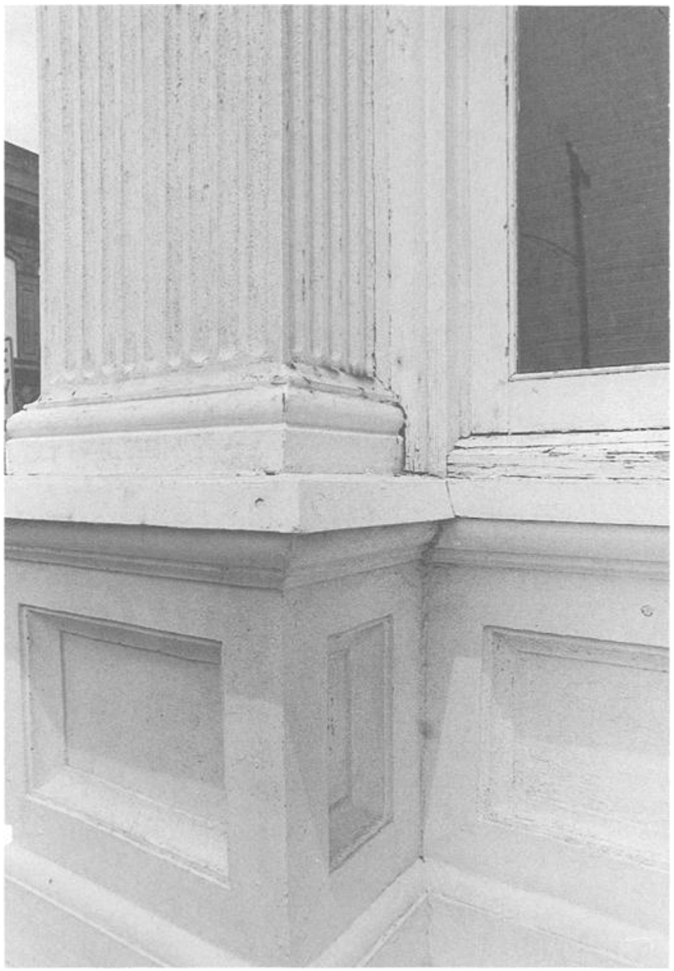

FIG. 12—Window and door openings penetrate the exterior wall and are a common source of moisture entry into a building. In this case, a wooden window and frame are in need of repainting, and the joint between the window and the cast iron pilaster is in need of caulking. Cyclical maintenance is a critical component of preserving historic buildings. Photo: NPS Files.

Treatments to Avoid: Windows/Doors

- Replacing with modern thermal glazed units (design/detailing should match historic)
- Unvented/fixed storm sash (can trap moisture condensation)
- Panning over (covering with aluminum) deteriorated jambs, frames, and sills

Roofs

Determining the source of a roof leak is often difficult because moisture can travel long distances along rafters, vent pipes, or electrical conduits before it drips onto ceilings below. Moisture from condensation can also form in attics or on the underside of roofing, causing moisture damage to sheathing boards without any apparent deterioration on the exterior roofing surfaces. Roofs and their accompanying gutter and downspout systems should be inspected at least twice a year to determine if materials are in good condition.

Roofs can be flat or sloped. Traditional roofing materials include wooden shingles, slates, clay or metal tile, standing or flat seamed metal, copper, and lead-coated copper. Such roofs last from a minimum of 20 years (wooden shingles) to over 100 years (clay tiles and slate). The existing roof on a historic building may not be the original roof. If the roof is to be replaced due to age or damage, careful research may be necessary to accurately record the configuration of the original roof. Historically, roofs were well ventilated from the underside, and the historic roofing materials had a long life. When attics are converted to useable space, the natural ventilation of the underside of the roofs has been lost. This creates a situation where moisture may condense on roof sheathing, thereby accelerating deterioration.

Depending on the historic roofing materials, the roof may or may not have been painted. Wooden shingles were sometimes painted; tin roofs were almost always painted to avoid corrosion. Slate and clay tile remained in their natural color and in the case of slate were often configured in a polychromatic design. In the 20th century, concrete shingles and a variety of synthetic shingles have been developed, and many are now considered historic in their own right.

Roof inspections should only be done by someone familiar with this work. Most roofs should not be walked on during an inspection, as roofing units may crack under the concentrated weight of the inspector. It is also dangerous. Roofs are critically dependent on their flashing systems, the continued ventilation of the attic spaces, and the condition of the roof framing and sheathing. These areas should be inspected on a regular basis. Inspections of the attic areas during a heavy rain may give a good indication if leaks in the roof are present. Roof leaks should be repaired immediately as the building will deteriorate rapidly once the weathertightness of a roof is gone (Fig. 13).

Evidence of Moisture Decay: Roofs

- Missing or slipped roofing units: tiles, slates, shingles, parapet caps
- Cupped, cracked, or broken units
- White stains (gypsum) or delaminated areas of slate
- Rusted, pitted, or deteriorated metal roofing or flashing (chimneys, valleys, gables, parapets)
- Broken or sagging gutters
- Galvanic corrosion from incompatible metal components on the roof
- Freeze-thaw spalling of tile, slate, or other roofing materials

Sources of Moisture: Roofs

- Driving rain
- Ice dams, snow buildup
- Condensation on the underside of the roof (unventilated attics, excessive insulation)
- Slow leaks from pinholes in flashing, inadequately lapped roofing, broken solder joints or deteriorated materials
- Moss or tree debris holding moisture onto the roof
- Blocked gutters and downspouts as a result of poor maintenance, ice dams, or icicles
- Emergency storm damage

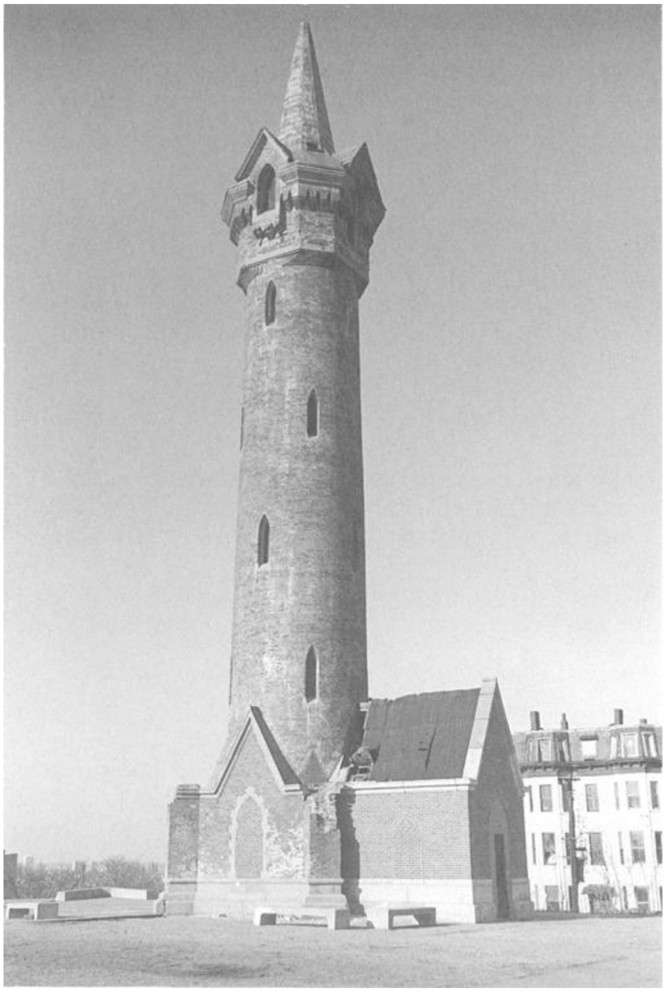

FIG. 13—Rapid deterioration of a historic building occurs when the roof is not maintained. In this unoccupied observatory tower, the temporary roof over the entrance has failed, allowing moisture free access to the interior. Note the efflorescence caused by this moisture and the loss of masonry at the side buttress. Photo: courtesy SPNEA, NPS files.

Remedial Treatments: Roofs

- Monitor attics during a rain to try to locate areas of leaking
- Reanchor slipped roofing or coping units before further damage occurs
- Replace missing roofing units or parapet materials in kind
- Repair or replace deteriorated flashings, crickets, vent collars, and parapets
- Undertake emergency repairs quickly (install tarpaulins or roof felts)
- Ventilate attics
- Install ventilating channels between insulation and sheathing
- Keep roof free of debris (trim overhanging trees, brush away pine needles)
- Clean/repair gutters and downspouts
- Protect eaves and parapets from snow buildup and ice dams in colder climates
- During reroofing consider reinforcements at intersections (membranes, flexible flashing)

Treatments to Avoid: Roofs

- Applying tar or other sealants to metal, tile, or slate roofing (traps moisture, unsightly)
- Insulating rafters without ventilation channels and vapor barriers (condensation)
- Installing roofing felts directly under unventilated wooden shingles (shortens life)
- Interweaving roofing felts with shakes (traps moisture and accelerates deterioration)
- Sealing gable vents to reduce energy costs (leaves humidity and condensation in attic)
- Installing vapor impermeable membranes completely under roofing units (traps moisture condensation)
- Installing poorly designed modern grills or ventilator hoods (incompatible design)

HISTORIC INTERIORS

Historic interiors, for the purpose of this checklist, constitute the *structural systems*, the *mechanical systems*, including HVAC and plumbing, and the *interior finishes* found within the building. Because historic interiors often have a high degree of craftsmanship associated with the interior finishes, such finishes are not easily reproduced. It is, therefore, important that damage or potential damage from moisture be identified early to minimize costly repairs. Moisture damage to historic interiors can come from moisture that has migrated from the ground to the structural framing or through the exterior envelope. Interior moisture that has not been properly controlled, such as condensation from humidified interiors, or excess moisture from accidental damage from burst plumbing pipes or from putting out a fire can also do enormous damage.

The type and use of a historic building may determine the type of interior finishes found within its envelope. For example, if the building is an industrial warehouse, it may have a simple unadorned brick interior with exposed wooden post and beam timbers. Because of the openness of the industrial interior, moisture damage is generally easy to visually detect and monitor. More formal buildings, such as municipal buildings, may have a variety of interior finishes, from elegant marble and wooden-panelled interiors to relatively functional plastered office spaces. Finished spaces are less easily monitored for moisture damage.

Structural Systems

Structural systems may be hidden or exposed. Differing approaches will, therefore, be needed for evaluating moisture damage. Exposed systems may include cast iron frames, heavy timber post and beam warehouse construction, concrete, or fireproof brick skew-back construction. Materials deterioration will be evident from visual inspection. Structural systems that have received a cladding or a finished surface may conceal moisture damage for some time. There are a number of nondestructive tests to ensure the structural stability of historic materials. Devices such as optical fiber boroscopes can be inserted into small cavities to observe hidden structural conditions, and small video camera attachments can be used to record these conditions behind walls, down piping, and into chases. There are building conservators, nondestructive testing companies, engineers, and specialized contractors who are familiar with these investigative techniques.

Structural deterioration will most likely occur if moisture has penetrated the exterior envelope or is rising from the ground. This has been previously outlined under exterior walls and foundations. Wooden members will show deterioration before other materials. For wooden structural members, dry rot caused by a fungal spore (Fig. 14) or damage from wood-boring insects, such as carpenter ants and termites, attracted to moist wood can accelerate damage to wooden structural members. Structural steel elements generally have a slower decay rate from moisture damage. For metal anchors buried behind exposed wall surfaces, such as those used to structurally support exterior terra cotta elements, serious damage may not be readily evident. Rusting streaks from corroding anchors or cracked or spalling elements will hint at a structural failure. The loss of structural stability may be seen in falling ceilings, caved-in floors, vertical elements pulling away from horizontal elements, or bowed walls. A structural engineer familiar with historic construction methods should assess and identify structural damage and recommend appropriate remedial treatments.

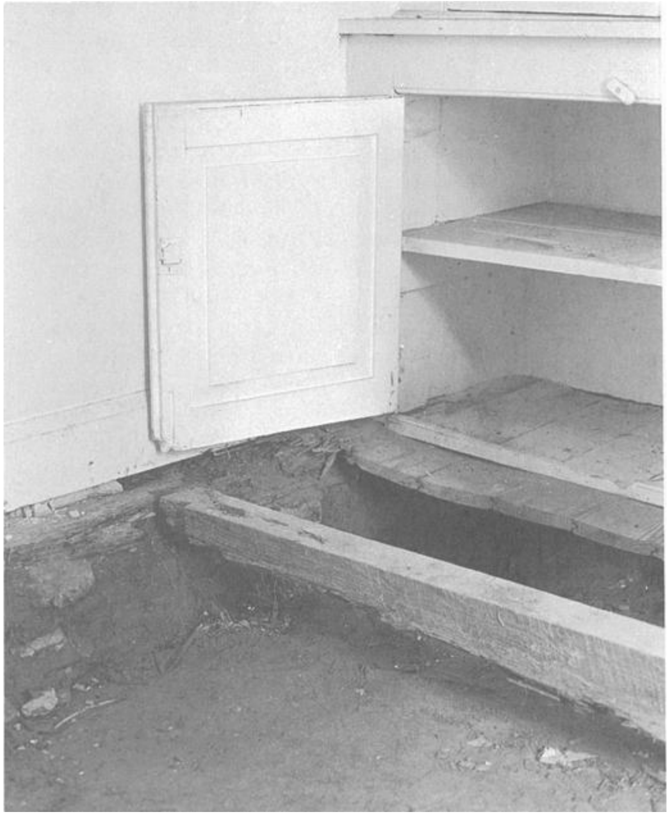

FIG. 14—Moisture can cause dry rot, a type of fungus, to structurally weaken framing members. These floor joists have been in contact with wet foundations just above a damp crawl space. The new replacement joist should be isolated from these moist conditions, perhaps by excavating the crawl space to a deeper depth, by adding a vapor barrier over the dirt layer, and by increasing the natural ventilation in the crawl space. Photo: NPS files.

Evidence of Moisture Decay: Structural Systems

- Sagging structural elements
- Settlement cracks in load-bearing walls
- Separation of building elements (chimneys, porches)
- Spalling and erosion of materials
- Corrosion of metal structural elements
- Insect or fungal damage in wooden elements

Sources of Moisture: Structural System

- Moist foundations (wooden joists or sill plates in ground contact)
- Migration of moisture through external walls
- Condensation on structural elements
- Moisture contact of damp insulation on structural members
- Melting frost in attics or in walls from winter conditions
- Ice dam in gutters

Remedial Treatments: Structural Systems

- Investigate to determine source of moisture
- Repair deteriorated elements; eliminate source of moisture
- Remove insect-damaged or fungal contaminated elements; treat areas to avoid recurrence
- Reinforce weakened elements (sistering of joists, epoxy repairs)
- Mothball or undertake emergency bracing or stabilization of weakened systems

Treatments to Avoid: Structural Systems

- Removing historic materials that can be reinforced and retained in place
- Using ferrous metal anchors or synthetic materials inappropriately (rusting, stress cracks)
- Cosmetically covering deterioration without removing moisture source
- Installing a new rigid structural system without appropriate connections to allow movement with historic materials (will cause cracking)

Mechanical Systems

The introduction of mechanical systems in historic buildings has done much to make them more comfortable, but the change in interior climate can do much to generate moisture within the building. As a result of energy retrofit to tighten the exterior envelopes and to reduce air exchanges, interior condensation can be a major contributor to moisture deterioration in historic buildings. New climate control systems for historic buildings, particularly museum structures, may exacerbate moisture migration within the building due to the introduction of humidity above the 50% rate of relative humidity. Condensation at the dew point within a wall can cause structural deterioration depending on its location within the wall and the rate of dissipation of moisture (Fig. 15). The greater the differential between interior and exterior temperature and humidity levels, the greater the potential for

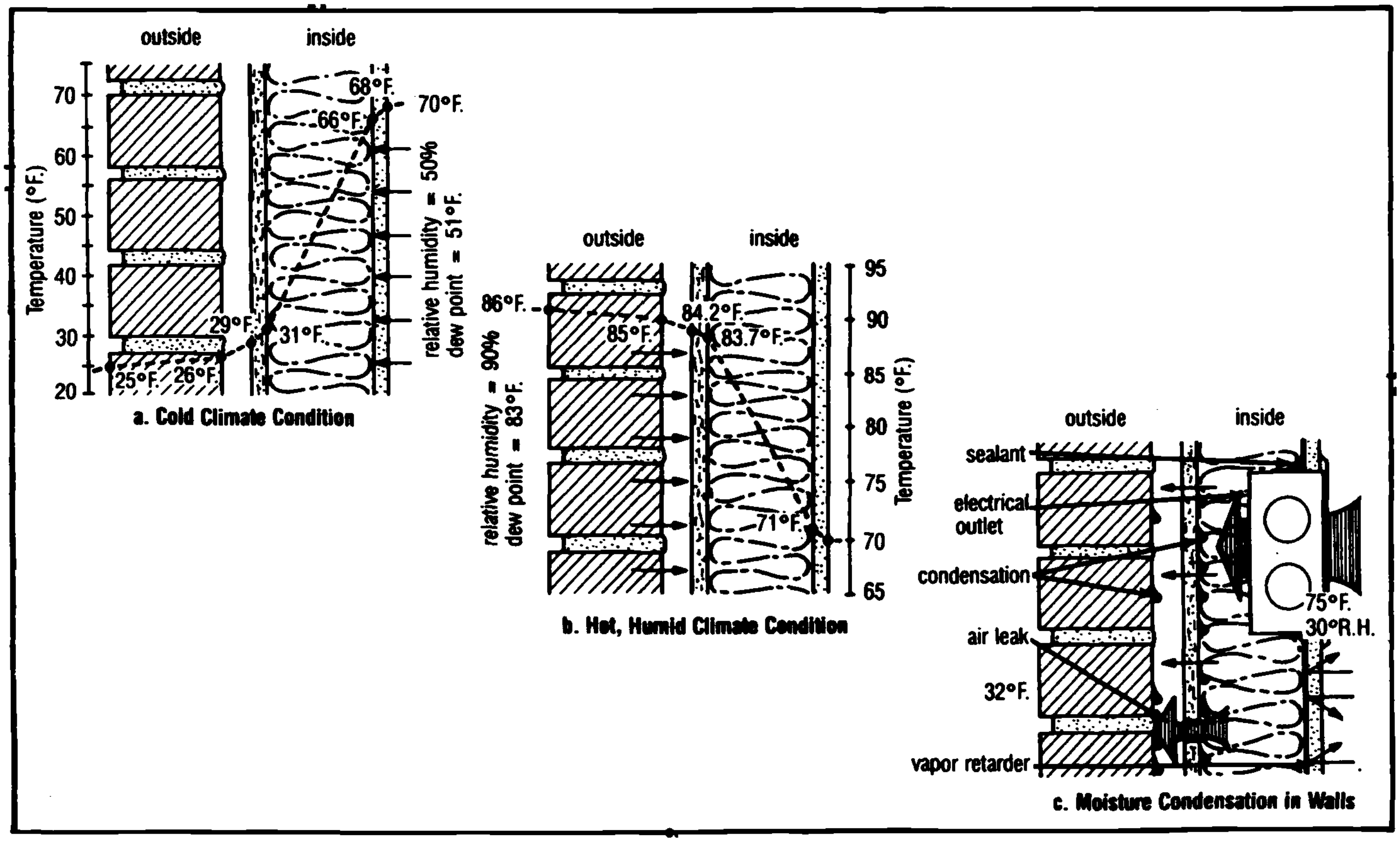

FIG. 15—Mechanical heating and cooling systems change the interior climate of a building. Moisture in the air will dissipate from the warmer area of a building to a colder area, often resulting in condensation on surfaces or moisture within the wall. Dew point condensation within historic walls with modern wall insulation can be particularly damaging if the insulation becomes wet. Even with vapor retarders, moisture can still penetrate through openings into wall surfaces. Sketch: NPS files: taken from NPS publication of *Preservation Briefs 24: Heating, Ventilating, and Cooling Historic Buildings; Problems and Recommended Approaches.*

condensation to form within building walls deteriorating wooden and metal elements. In cold climates, freeze-thaw damage to masonry exteriors can also occur, thereby undermining the structural integrity of the wall surface. As many historic buildings combine plumbing with heating systems, all plumbing lines should be checked as part of the search for undetected sources of moisture damage to historic interiors.

Evidence of Moisture Damage: Mechanical Systems

- Bubbling interior plaster, particularly around forced air registers
- Stained or deteriorated windows and window sills from condensation
- Peeling exterior paint on insulated frame buildings
- Bleeding or weeping moisture at insulated frame exteriors, particularly at sill plates
- Wet floors from leaks around condensate pans of fan coil units and radiators
- Efflorescence or moisture patches under window or through-wall air conditioning units

Sources of Moisture: Mechanical Systems

- Overly humid interiors from poorly designed or malfunctioning climate control system
- Air conditioners set too cold for summer use
- Improperly maintained drainage and condensate lines
- Condensate forming on uninsulated sheet metal a/c ductwork
- Leaking piped water supplies for hydronic heating or fan coil systems
- Dew point condensation forming within walls or on interior surfaces

Remedial Treatments: Mechanical Systems

- Modify temperature and humidity levels
- Increase ventilation in building
- Maintain equipment and monitors
- Remove dampened insulation or other materials holding moisture
- Ventilate and dry out damage before repairs are made

Treatments to Avoid: Mechanical Systems

- Installing insulation in unvented walls (insulate attic and crawl space instead)
- Installing through-wall or window air conditioners if condensate will wet wall
- Reducing ventilation as part of an energy retrofit (closing grills)

- Installing new piping without adequate safeguards (use liners, pans, moister detectors)

Interior Finishes

Water can stain or irretrievably damage delicate historic wallpapers, decorative finishes, or their substrates, such as plaster. Most interior moisture damage will be from slow roof of plumbing leaks (Fig. 16), but catastrophic damage can result from hurricanes, storms, or firefighting (Fig. 17). Whenever there is the slightest appearance of moisture on an interior surface, a visual inspection should be undertaken immediately to trace the source of the leak. In many cases, the leak will be from a breached exterior joint, such as roof flashing, perimeter caulking around windows, or eroded mortar joints over window heads or at sill ledges. Refer back to the exterior checklist for recommendations on these repair treatments. Once the source of the leak had been detected and corrected, the interior finished surfaces cannot be successfully treated until subsurfaces are fully dried out. This may require several months. For major leaks in external walls, it may take one month per inch (2.5 cm) of wall thickness before surfaces can be replastered—eight months of drying time for an 8-in. (20-cm) solid masonry wall. For moisture-damaged material, this slow drying is preferred to avoid warping and cracking of fragile historic materials, notably the wooden elements.

Evidence of Moisture Damage: Interior Finishes

- Bubbling plaster or damp spots on walls and ceilings
- Buckling of floor boards, particularly around radiators or windows
- Stains on walls and ceilings
- Loss of key connection between plaster and lath
- Peeling paint; delaminating surfaces

Sources of Moisture Damage: Interior Finishes

- Leaking plumbing, fancoil, or fire sprinkler lines
- External wall leaks (see section on exterior walls and under Windows/Doors)
- Rising damp for first floor walls
- Roof leaks, fire suppression, or other emergency damage
- Unvented interior moisture from cooking, bathing, climate control systems
- Floor washing with large quantities of water

Remedial Treatments for Moisture: Interior Finishes

- Identify sources of moisture and control or eliminate them (see section on repairs of exteriors and under Mechanical Systems)
- Repair or replace deteriorated materials
- Ventilate interiors to help dissipate excessive moisture and dry out damaged interiors
- Use sump pumps or dehumidifiers in basement areas

FIG. 16—Moisture damage on the interior may be a direct result of an exterior problem. In this case, the corner leak at the roof suggests that the internal downspout drain has become blocked. The use of a video camera, specially designed to look into drains, may help determine the condition of this internal drain. The exterior mortar of the masonry should also be inspected. Photo: NPS files.

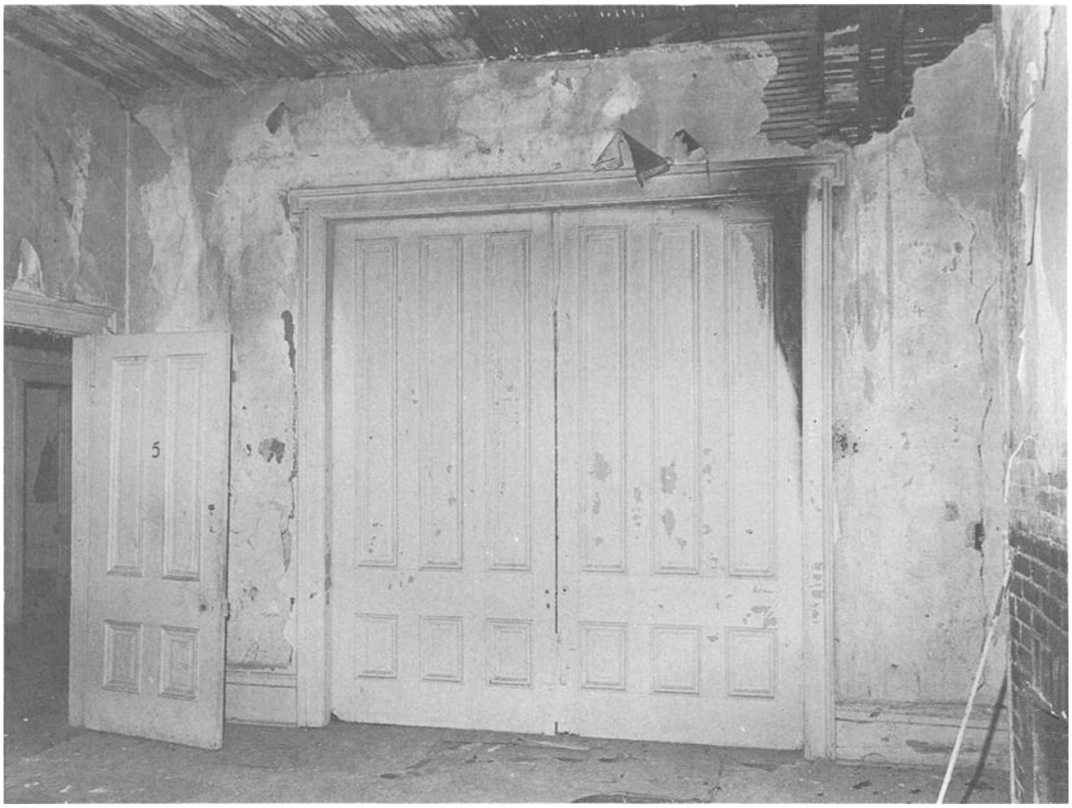

FIG. 17—The damage to this historic plaster was in part the result of moisture used to put out a serious fire. Once plaster interiors are saturated with water, they must be slowly and thoroughly dried out before effective repairs can be made. For plastered walls, this drying out process may take several months and the movement of air may be more beneficial than the use of heat. Rapid drying with heat often causes wooden elements to crack on the surface, still leaving moisture in the walls behind. Once dried, these lath walls will take fresh plaster, and they should not be covered with modern drywall. Photo: NPS Files.

Treatments to Avoid: Interior Finishes

- Undertaking wholesale removal of damaged interiors if repair is possible
- Applying vinyl, varnish, or other waterproof coatings over chronic dampness
- Rapid drying out of water-damaged interiors with heaters (will warp, crack, deteriorate finishes)

CONCLUSION

There are no shortcuts to curing moisture problems in historic buildings. It is important that a systematic approach be taken to ensure that the source of the moisture has been properly identified so that an effective cure can be implemented. In the case of historic buildings, however, modern waterproofing treatments and other techniques for stemming the flow of moisture through the building may be damaging. As a result, careful monitoring, an understanding of how the building was originally constructed, and how these materials interact with one another will be invaluable in devising a suitable remedial treatment that will preserve the resource in the long run. The National Park Service has a number of publications that contain guidance regarding appropriate preservation treatments. Some of these publications are listed in Appendix B. A free catalogue is available by calling Preservation Assistance Division at (202)343-9578.

Appendix A

Secretary of the Interior's "Standards for Rehabilitation"

1. A property shall be used as it was historically or be given a new use that requires minimal change to its distinctive materials, features, spaces, and spatial relationships.
2. The historic character of a property shall be retained and preserved. The removal of distinctive materials or alterations of features, spaces, and spatial relationships that characterize a property shall be avoided.
3. Each property shall be recognized as a physical record of its time, place, and use. Changes that create a false sense of historical development, such as adding conjectural features or elements from other historic properties, shall not be undertaken.
4. Changes or a property that have acquired historical significance in their own right shall be retained and preserved.

5. Distinctive materials, features, finishes, and construction techniques or examples of craftsmanship that characterize a property shall be preserved.
6. Deteriorated historic features shall be repaired rather than replaced. Where the severity of deterioration requires replacement of a distinctive feature, the new feature shall match the old in design, color, texture, and, where possible, materials. Replacement of missing features shall be substantiated by documentary and physical evidence.
7. Chemical or physical treatments that cause damage to historic materials shall not be used. Treatments, if appropriate, shall be undertaken using the gentlest means possible.
8. Archeological resources shall be protected and preserved in place. If such resources must be disturbed, mitigation measures shall be undertaken.
9. New additions, exterior alterations, or related new construction shall not destroy historic materials, features, and spatial relationships that characterize the property. The new work shall be differentiated from the old and shall be compatible with the historic materials, features, size, scale and proportion, and massing to protect the integrity of the property and its environment.
10. New additions and adjacent or related new construction shall be undertaken in such a manner that, if removed in the future, the essential form and integrity of the historic property and its environment would be unimpaired.

Appendix B

National Park Service Publication Sources

The National Park Service, Preservation Assistance Division has a number of bulletins relating to the preservation of historic properties. Following is a listing of some publications that describe remedial approaches to moisture damage. Most are available from the Government Printing Office. Some publications, however, are out of print, but are available in microfiche or as reproduced copies from the National Technical Information Service. The addresses are listed below.

A free catalogue of National Park Service publications is available from:

Preservation Assistance Division
National Park Service
P.O. Box 37127
Washington, D.C. 20013-7127
Tel. (202) 343-9578

Superintendent of Documents
Government Printing Office
Washington, D.C. 20402-9325
Tel. (202) 783-3238

National Technical Information Service (NTIS)
5285 Port Royal Road
Springfield, VA 22161
Tel. (703) 487-4600

National Park Service Publications Articles and bulletins with information on moisture in historic buildings:

A Glossary of Historic Masonry Deterioration Problems and Preservation Treatments. Anne E. Grimmer. 1984. Government Printing Office stock number 024-005-00870-5. $2.50 per copy.

Metals in America's Historic Buildings: Uses and Preservation Treatments. Margot Gayle and David W. Look, AIA. 1980. Original out of print (168 pages; 180 photos); duplicated copies available from NTIS order number PB90-206269. $23.00 for paper; $8.00 microfiche.

Moisture Problems in Historic Masonry Walls: Diagnosis and Treatment. Baird M. Smith, AIA. 1984. Government Printing Office stock number: 024-005-00872-1. $1.25 per copy.

Preservation Briefs. These 4 to 16-page publications help owners of historic buildings recognize and resolve common preservation and repair problems. While general in nature, some of the briefs deal with moisture-related damage. Individual briefs cost $1.00 and are available from the Government Printing Office.

- *Preservation Briefs 1: The Cleaning and Waterproof Coating of Masonry Buildings,* Robert C. Mack, AIA, 1975, GPO No. 024-005-00877-2.
- *Preservation Briefs 2: Repointing Mortar Joints in Historic Brick Buildings,* Robert C. Mack, AIA, 1980, GPO No. 024-005-00878-1.
- *Preservation Briefs 7: The Preservation of Historic Glazed Architectural Terra-Cotta,* de Teel Patterson Tiller, 1979, GPO No. 024-005-00883-7.
- *Preservation Briefs 10: Exterior Paint Problems on Historic Woodwork,* Kay D. Weeks and David W. Look, AIA, 1982, GPO No. 024-005-00885-3.
- *Preservation Briefs 13: The Repair and Thermal Upgrading of Historic Steel Windows,* Sharon C. Park, AIA, 1984, GPO No. 024-005-00868-3.
- *Preservation Briefs 15: Preservation of Historic Concrete; Problems and General Approaches,* William B. Coney, 1987, GPO No. 024-005-01027-1.
- *Preservation Briefs 16: The Use of Substitute Materials on Historic Buildings Exteriors,* Sharon C. Park, AIA, 1988, GPO No. 024-005-01037-8.
- *Preservation Briefs 19: The Repair and Replacement of Historic Wooden Shingle Roofs,* Sharon C. Park, AIA, 1989, GPO No. 024-005-01053-0.
- *Preservation Briefs 21: Repairing Historic Flat Plaster—Walls and Ceilings,* Marylee MacDonald, 1989, GPO No. 024-005-01055-6.
- *Preservation Briefs 22: The Preservation and Repair of Historic Stucco,* Anne E. Grimmer, 1990, GPO No. 024-005-01066-1.
- *Preservation Briefs 23: Preserving Historic Ornamental Plaster,* David Flaharty, 1990, GPO No. 024-005-01067-0.
- *Preservation Briefs 24: Heating, Ventilating, and Cooling Historic Buildings: Problems and Recommended Approaches,* Sharon C. Park, AIA, 1990, GPO No. 024-005-01090-4.
- *Preservation Briefs 26: The Preservation and Repair of Historic Log Buildings,* Bruce D. Bomberger, 1991, GPO No. 024-055-01087-4.
- *Preservation Briefs 27: The Maintenance and Repair of Architectural Cast Iron,* John G. Waite, AIA/Historical Overview by Margot Gayle, 1991, GPO No. 024-005-01088-2.
- *Preservation Briefs 29: The Repair, Replacement, and Maintenance of Historic Slate Roofs,* Jeffrey S. Levine, 1992, GPO No. 024-005-01109-9.
- *Preservation Briefs 30: The Preservation and Repair of Historic Clay Tile Roofs,* Anne E. Grimmer and Paul K. Williams, 1992, GPO No. 024-005-01110-2.

- *Preservation Briefs 31: Mothballing Historic Buildings,* Sharon C. Park, AIA, 1993, GPO No. 024-005-01120-0.
- *Preservation Briefs 33: The Preservation and Repair of Stained and Leaded Glass,* Neal A. Vogel and Rolf Achilles, 1993, GPO No. 024-005-01122-6.

Secretary of the Interior's Standards for Rehabilitation with Guidelines for Rehabilitating Historic Buildings, rev. 1990, Government Printing Office stock number: 024-005-01061-1, $2.00 per copy.

The Secretary of the Interior's Standards and Illustrated Guidelines for Rehabilitating Historic Buildings, 1992, GPO No. 024-005-01091-2, $8.00 per copy.

Part 4: Implementation

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Contract Documents and Moisture Control

by Richard B. Mundle[1]

CONSTRUCTION PROJECTS ARE NORMALLY EXECUTED by means of a written formal contract. While the extent of detail may vary according to the complexity of the work, the documents must describe the services to be performed accurately and unambiguously. Most construction projects consist of contract clauses, drawings, and specifications. The contract clauses cover the administrative operations of the contract. The technical description of the work is provided in the drawings and specifications.

In general, drawings depict the layout of the work, indicate the materials to be used, and the arrangement of those materials. The specification describes the materials, their properties, quality, and methods of installation. Together, the drawings and specifications form the definition of the project. When there are conflicts between the drawings and specifications, most contracts state that the specifications will take precedence over the drawings. For this reason, it is important that the specifications accurately reflect the intentions of the project designer.

As construction specifications have become more complex over time, a systematic order has evolved in their preparation. The Construction Specifications Institute (CSI) has developed a format for the specification as a whole and for the individual sections which comprise the total specification [*1*]. This format is followed in all major commercial and government specification systems and results in specifications which are consistent in the presentation of material descriptions and the methods of installation. The format consists of 16 divisions, each with a varying number of sections. The extent and detail of the construction documents vary depending on the size and complexity of the work. The documents for a large building may consist of hundreds of drawings and many hundreds of pages of specifications. A small building may require only a dozen or less drawings and 20 to 50 pages of specifications. A major rehabilitation project may require almost as many or as many drawings as a new building, but a minor repair job or the installation of a minor moisture control measure may only require a small sketch and a one-page written contract. However large or small, the documents must always be in writing, must be concise, unambiguous, spell out the specific tasks and performance levels to be accomplished by the contractor, and the amount and method of payment. This chapter discusses rehabilitation or addition projects of a size that do require more than a simple contract, but are small enough that a professional specification writer is generally not needed. The chapter also discusses the overall organization of the contract documents for large new construction.

ORGANIZATION OF SPECIFICATIONS

Divisions

Each of the 16 divisions covers a major trade or building component or a group of related components or products. For example, all electrical work is specified in Division 16, while all masonry is specified in Division 4. A useful tool to find where a particular material may be specified is CSI's Masterformat list of keywords. Each item listed is followed by the preferred specification location. Most professionals writing construction specifications and most systems of guide specifications follow Masterformat's recommendations [*1*].

Division 1—General Requirements. This division includes all those provisions applying to all other divisions, such as alternatives, regulatory requirements, references, submittals, quality control, project administration, and the list of drawings.

Division 2—Site Work. This includes demolition, dewatering, excavation, earthwork, paving, as well as landscaping. With regard to moisture control, grading for proper surface run-off and subsurface drainage are of importance and are specified in this division.

Division 3—Concrete. The title of this division is self explanatory. It includes both in situ and precast concrete. The provision of an underslab vapor retarder is generally specified in this division. Also included is insulating concrete.

Division 4—Masonry. Includes concrete, brick, and stone masonry, mortar and grout. Also included here is parging for moisture control.

Division 5—Metals. Structural steel, joists, steel deck, cold-formed metal framing, miscellaneous metals, and expansion joints. Proper protection against moisture-induced corrosion is specified in Division 9.

Division 6—Wood and Plastics. Includes rough and finish carpentry, framing and decking, and cabinetry. With regard to moisture control, wood species, drying (kiln dried or air dried), and treatment for all wood products used in the construction are important and are specified here.

Division 7—Thermal and Moisture Protection. This is the division in which most moisture and water protection items

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[1] Engineering Field Activity, Chesapeake Naval Facilities Engineering Command, Washington, DC. The opinions expressed in this paper are his own and do not necessarily reflect those of any government agency.

and materials are specified, including damp and waterproofing, roofing, siding, flashing, and most vapor retarders. The individual sections of this division will be discussed in greater detail below.

Division 8—Doors and Windows. The division title is self explanatory. It includes all types of windows (aluminum, steel, wood, and plastics) and metal curtain walls. From a moisture control point of view, the most important issues relating to doors and windows are rain water penetration, air leakage, treatment and finishes to prevent rot in wood and corrosion in metals, and flashing. The specification of proper type and class of windows and doors for the particular application is understood. Thus, a type of window specified for the upper floors of a high-rise building in a region with frequent rainstorms will be drastically different from that for a one-story residence in a dry climate, and even in a single building it may be appropriate to specify a higher performing window for the upper floors because these windows are exposed to higher wind velocities.

Division 9—Finishes. Includes lathing, plaster, stucco, drywall, floor finishes, including carpet, acoustical treatments, ceilings, coatings and paints, veneers and wall coverings. Both exterior and interior finishes can be crucial for moisture control. Current guide specifications do not generally require a specific water vapor transmission rate (perms), although proper moisture control may require either a low-permeance finish (essentially impermeable to water vapor) or a high-permeance finish (highly permeable to water vapor). There is no reason that the perm rating of a paint, for example, should not be specified. However, the specifier must be aware that only few manufacturers provide such ratings in their product literature and that the determination of the actual values installed on a building may be highly dependent on application procedures, thickness, and number of coatings (for paints). In addition, actual installed values are difficult to determine.

Division 10—Specialties. This division covers a large array of miscellaneous items, most having no impact on moisture problems. Included are bathroom accessories, signage, lockers, hospital drapes, fire extinguisher cabinets, etc. Also included are wall and door vents, which can become involved in moisture control strategies.

Division 11—Equipment. This division includes vault doors, library equipment, waste compactors, to food service and laboratory equipment. Fume hoods are specified in this division and could have an effect on ventilation and air movements related to moisture control.

Division 12—Furnishings. Includes casework, cabinetry, furniture, and window treatments. In general this division is not involved in products relating to moisture control. However, curtains and permanent furnishings that restrict airflow to the indoor face of exterior walls in cold climates can cause moisture problems, but such problems are the result of improper design and can not be overcome by specifications.

Division 13—Special Construction. The contents of this division range from air-supported structures to pre-engineered buildings and swimming pools. Of interest are swimming and therapeutic pools, saunas and steam rooms, cold storage rooms. The division also includes solar collectors and energy monitoring and control systems.

Division 14—Conveying Systems. As the title implies, this division is devoted to systems used for moving goods and people. It includes such devices as elevators, escalators, dumbwaiters, moving sidewalks, and warehouse product conveyors, conveying belts, and cranes. None of these systems should be of concern with regard to moisture control.

Division 15—Mechanical. This division includes heating, ventilating, air conditioning, as well as plumbing. Moisture control strategies that rely on mechanical devices, heaters, dehumidifiers, system insulation, or ventilation will be specified in this division, including the necessary controls, testing, and adjustments. Also included are fire protection provisions.

Division 16—Electrical. The name of this division is self-explanatory, and the contents will not normally be involved in moisture control strategies except for electrical devices as a part of the mechanical system.

Sections

The divisions are subdivided into individual sections, each covering a specific building component, system, or trade. A section is a subdivision of the complete project specification, describing a unit of work within a construction project in the form of instructions to the contractor. CSI places each section within one of the 16 divisions and gives it a five-digit number. The section describes the basic unit of work. A section must answer three fundamental questions:

1. What interrelationship will exist between the unit of work, other work on the project, or with any portion of the project?
2. What is the product or products included in the unit of work?
3. How is the product or are the products incorporated into the work?

Scope of Sections—The scope of a section can be broad, medium, or narrow:

Broadscope: A broadscope section is quite general, encompassing numerous products of similar nature. The broadscope titles for Division 7, Thermal and Moisture Protection listed in the CSI Masterformat, are:

07100 Waterproofing: This broadscope section covers waterproofing membranes and coatings which are expected to withstand hydrostatic pressure.

07150 Dampproofing: This covers coatings which are not expected to withstand water under pressure.

07180 Water Repellents: Included here are sealers and coatings designed to shed water from building surfaces, but not intended to actively prohibit the entry of water or moisture vapor.

07190 Vapor Retarders: Usually single-purpose membranes to prevent the passage of water vapor by means of low permeance.

07195 Air Barriers: Products for the exclusion of wind or air, such as House-Wrap or TYVEK (R).

07200 Insulation: This broadscope section is one of paramount interest to the moisture investigator. It covers all types of building insulation: roof, walls, and ceilings, in all its forms: board, batt, blanket, foams, poured, foils, etc. Also usually included in this section are attachments to insulation which provide vapor retardance.

07240 Exterior Insulation and Finish Systems: Complete wall assemblies which include inside and outside finishes, structure, and insulation and vapor retardant properties.

07250 Fireproofing: Methods and products used to protect the structural integrity of the building during a fire, which are not usually of interest to a moisture investigator.

07270 Firestopping: Methods and products used to seal openings and cavities to prevent the spread of fire. This section may be of interest to a moisture investigator as it may also inhibit the expected passage of air circulation.

07300 Shingles and Roofing Tiles: Composition shingles, metal and wood shingles, and ceramic products used to cover (usually residential) roofs. Sometimes products which function as a vapor barrier are included in these sections.

07400 Manufactured Roofing and Siding: Metal and plastic fabrications which often include insulation and vapor retardant components.

07480 Exterior Wall Assemblies: This section specifies systems of convention components to form multi-story exterior wall panels. Assemblies usually include framing, insulation, substrates, and finish surfaces. This section usually specifies the installation of conventional components specified in other sections, although the components themselves may optionally be specified entirely in this section.

07500 Membrane Roofing: This very broad category covers the many and varied types of membrane roofing including fiberglass inpregnated felts, synthetic rubbers, and plastics, often making reference to roof insulation and vapor retarders.

07570 Traffic Coatings: This broadscope section covers membranes for decks to resist the abrasion of light pedestrian and vehicular traffic. This section is not intended for heavy industrial use.

07600 Flashing and Sheet Metal: A very important section for moisture investigators, but it is usually concerned with materials only. This section needs to be very carefully coordinated with the drawings to ensure that the flashing details as drawn do indeed prevent the intrusion of water.

07700 Roof Specialties and Accessories: Included here are roof ventilators and other roof attachments. The primary interest for moisture investigators is that of flashing.

07800 Skylights: This section covers skylights and roof windows. It should be carefully coordinated with the glazing section (usually 08800) and the flashing section (usually 07600). Properties such as CRF (condensation resistance factor), air and water infiltration, and U-value need careful scrutiny.

07900 Joint Sealers: Chemical compounds used to seal joints to prevent the intrusion of water. Care should be taken to ensure that these sealants and caulkings will withstand the exposure to elements such as ultraviolet and sunlight.

Mediumscope: A mediumscope section focuses on work of a more limited scope within the broadscope category. For example, the broadscope category 07200, Insulation, can be subdivided into these mediumscope section titles:

07210 Building Insulation: Covers all types of wall, ceiling, and floor insulation. Also covers different materials and forms: Loose fill (mineral wood, mineral granular, and cellulosic), batt and blanket, and board (mineral fiber, plastic foam), and sprayed insulations.

07220 Roof and Deck Insulation: Covers both flat and tapered insulation for low slope roofs.

Narrowscope: A narrowscope section becomes very specific, limited to subsets of the mediumscope section, covering a particular product. For example, using the mediumscope category of building insulation, possible narrowscope sections are:

07211 Batt and Blanket Insulation: Fiberglass and mineral fiber.

07212 Board Insulation: Plastic foam and mineral fiber boards.

07213 Foamed-in-Place Insulation: Urethanes.

07214 Loose Fill Insulation: Vermiculite, perlite, mineral wool, and cellulose.

07215 Sprayed Insulation.

As general guidance, use of many narrowscope sections should be limited to complex projects. The combination of several narrowscope sections into a mediumscope section or broadscope section may be more appropriate for smaller projects.

Organization of Sections

In the same manner as the divisions of the specification are always presented in a consistent order, CSI Masterformat has provided a standardized format for the sections themselves, known as the three-part format. Use of the format has the benefits of a consistent appearance, organization, and completeness from section to section within the specification. More importantly, a consistent format reduces the chance that major items are overlooked, and it helps suppliers, contractors, and the designer to clearly understand what is required. The three parts are:

Part 1: General
Part 2: Products
Part 3: Execution

Part 1: General

Part 1 covers general areas of concern which relate to the work and which define the general administrative and technical requirements specific to the particular section. This part lists referenced documents, interrelationships with other specification sections, product submittal requirements, testing, and other procedural matters unique to the section. As an illustration, the following articles are drawn from the *CSI Manual of Practice* [2]:

(a) Summary of work
(b) References
(c) Related Sections
(d) Definitions
(e) System Description
    (1) Design Requirements
    (2) Performance requirements
(f) Submittals
    (1) Samples

    (2) Shop Drawings
    (3) Certifications
    (4) Test Reports
(g) Quality Assurance
    (1) Qualifications
    (2) Regulatory Requirements
    (3) Mockups
    (4) Preinstallation Conference
(h) Delivery
    (1) Packing and Shipping
    (2) Acceptance at Site
    (3) Storage and Protection
(i) Site Conditions
    (1) Environmental Requirements
    (2) Existing Conditions
    (3) Field Measurements
(j) Sequencing and Scheduling
(k) Warranty
(l) Maintenance
    (1) Maintenance Service
    (2) Extra Materials

Part 2: Products

This part defines in detail the acceptable equipment, materials, mixes, and fabrications, i.e., products to be incorporated into the work. As discussed above, there are a number of ways that a product may be specified in this part. Either a manufacturer's brand or model, compliance with an industry standard, performance requirements, or a detailed description of the construction of the product may be specified. The following are examples of individual articles that may be used in Part 2:

(a) Materials
(b) Manufactured units
(c) Equipment
(d) Components
(e) Accessories
(f) Mixes
(g) Fabrication
    (1) Shop Assembly
    (2) Shop/Factory Finishing
    (3) Tolerances
(h) Source Quality Control
    (1) Tests
    (2) Inspection
    (3) Verification of Performance

Part 3: Execution

This part describes in detail the preparatory actions required before installation of the product and the manner in which the items covered in Part 2 are to be incorporated into the work, the installation itself, and actions required after product installation. In many instances the preparation and installation are crucial to the adequate performance of an otherwise acceptable material or product in service. For example, joint preparation and the temperature during installation are often critical to the performance of a sealed joint. The following articles may be included in Part 3:

(a) Examination
    (1) Verification of Existing Conditions
b) Preparation
    (1) Protection
    (2) Surface Preparation
(c) Erection or Installation or Application
    (1) Special Techniques
    (2) Interface with Other Products
    (3) Field Tolerances
(d) Field Quality Control
    (1) Field Tests
    (2) Inspection
    (3) Manufacturer's Field Service
(e) Adjusting
(f) Cleaning
(g) Demonstration
(h) Protection
(i) Schedules (Hardware Sets, Equipment)

SPECIFICATION METHODS

There are four basic specification methods commonly used:

Descriptive

A detailed description defining the required properties and dimensions of materials and products and their methods of installation without reference to a proprietary product or manufacturer. This method requires extensive research on available products in order that common features and attributes of products can be identified and specified. Care should be taken to ensure that multiple products which meet the specified requirements are, in fact, available. Testing and submittal requirements to ensure that the desired materials and properties are met need to be specified.

Performance

Specifies only the final result to be required and gives standards by which this performance can be verified, giving the contractor latitude to be creative, yet achieve the desired results. This method may be used for complete assemblies such as wall panels or for individual components such as refrigeration equipment. Performance specifying should not be so restrictive that the requirements can be met by only one manufacturer. In a pure performance specification, any material or installation method is allowable if it will provide the desired result. Although this is in principle a desirable method, the difficulty arises at the interface of components and products. Since the details, materials, etc., are not specified, the interfaces need to be carefully identified.

Reference Standard

Specifies that materials or methods meet the requirements of widely accepted industry or government standards. The physical description of the materials and the requirements for installation are not repeated in the specification, though they may be modified somewhat. Industry standards are available to cover both the material properties and proper installation methods. Use of these widely accepted standards reduces the specifier's need to write at length and has the advantage of being familiar to product suppliers and installers, reducing potential misunderstandings. It is imperative that the specification writer be familiar with the content of the standards referenced.

Proprietary

Specifies the materials or product by manufacturer or brand name and model, often leaving the methods of installation to the recommendation of the manufacturer. In situations where substitutions are to be allowed, it is necessary to specify the criteria which will be used to determine the equality of the substituted product. The use of proprietary specifications has the advantage of close control of product selection, but it limits competition. As a general rule, proprietary standards should be avoided (government contracts allow for them only with stringent safeguards), but they may be necessary where compatibility of materials is critical. This is often the case in moisture control projects.

In any particular building construction specification, a combination of the above methods is sometimes used. If this is the case for any particular product, great care must be given to avoid redundancies, conflicts, and ambiguities. For instance, it may be impossible to meet a specified performance requirement if the material, shape, and size of a component also are specified. The supplier then may not be able to meet the letter of the specification but is forced to choose between meeting the performance requirement or the specified material requirement. Needless to say that such ambiguities can be costly in terms of construction delays or legal disputes and should be avoided.

Nevertheless, in many sections a combination of these types is used. For example, pure performance specifications are rare since completely reliable evaluation and test methods are not available for all performance characteristics or the required performance levels are not accurately established, while empirical data (experience) suggest that a certain metal gage or a certain minimal dimension provided adequate performance in service. Also, no building part or trade functions in a vacuum, but is attached to and functions in conjunction with other parts. Unless the physical characteristics (and not just its performance) are known, it may be impossible to establish the performance parameters for adjoining parts.

USING SPECIFICATIONS IN MOISTURE INVESTIGATIONS

In the process of investigating the causes of moisture problems, often clues can be found in the original building specifications. Knowing where to look is sometimes an art in itself. While most moisture-related products, components, and systems related to moisture control are located in Division 7, some are specified elsewhere. For example, vapor retarders are sometimes found in Division 3 Concrete when used under a concrete slab and in Division 9 when the vapor retarder is also a finish such as vinyl fabric wall covering or water vapor resistant paint. (Vinyl fabric, we sometimes forget, is a fairly good vapor retarder in addition to its aesthetic use. This is also true of some oil-based or epoxy-based paints.) There are other sources of moisture problems which lurk in sections of the specification not normally associated with moisture protection. A sample listing follows:

03300 Concrete: Some items relating to moisture problems in this section are vapor retarders placed under concrete slabs and the insulating values specified for insulating concrete.

04200 Masonry: In this section will be specified the allowable absorption of masonry units and parging to provide moisture protection to masonry walls.

08500 Metal Windows, 08600 Wood and Plastic Windows, 08650 Special Windows: In these sections, window performance factors such as condensation resistance factor are specified. Also included are discussions of flashing methods.

08710 Hardware: Weatherstripping is the only subject in this section with relevance to moisture.

08800 Glazing: Use of sealed insulating glazing is covered in this section.

09250 Gypsum Wall Board: The types of gypsum board specified can have an effect on moisture transmission. Some boards are moisture resistant and some incorporate a foil backing which functions as a vapor retarder.

09900 Painting: In this section, consideration should be given to the permeability of coatings specified.

09950 Vinyl Wall Covering: This section covers wall-decorating materials which can act as a vapor retarder.

10200 Louvers and Vents: This section covers metal louvers used in walls and doors. Mechanisms to prevent the entry of moisture should be included.

15250 Mechanical Insulation: This section covers insulation used on piping and ductwork and will have an impact on possible condensation problems.

15400 Plumbing: This section covers all the expected plumbing fixtures encountered in construction, as well as roof and floor drains. The amount of water vapor introduced by these fixtures is of concern.

15500 Heating, Ventilating, and Air Conditioning: In this section the performance characteristics and capacities of mechanical equipment are specified. Parameters to consider are supply and leaving temperature of transfer medium, volume of delivered air, wet and dry bulb temperatures of entering and leaving air, etc.

15810 Humidifiers: Equipment installed in the HVAC system to introduce moisture into the air. Factors to consider are the capacity in pounds per hour and the required relative humidity.

15820 Dehumidifiers: Equipment installed in the HVAC system to remove moisture from the air. Here, also, some factors to consider are the capacity for moisture removal in pounds per hour and the required relative humidity.

WRITING SPECIFICATIONS

The question of when to use a professional specification writer is a difficult one to answer. If you are an engineer or architect, you will probably feel comfortable writing your own specifications, perhaps with the collaboration of the other discipline professionals. If you are not a design professional, it may be wise to obtain the services of an engineer, architect, or a specification writer. Specification writers are generally either engineers or architects who have made a speciality of preparing construction specifications. They keep up on new product developments and are a good source of advice on the performance of these products.

A small remedial project may require only a few materials to be specified. Probably anyone understanding these products will be able to write the specification for such a contract. When the project becomes more complex and requires the expertise of a number of disciplines, specifications should probably be written by the professionals involved or a professional specification writer.

Each specification decision has an impact on the future performance of the building. Careful thought before choosing material types and properties is necessary to ensure that the desired performance will be achieved. It is also important to be able to realize the implications that one choice will have upon another. Incompatibilities between materials can often cause problems such as chemical breakdown, corrosion, and differential expansion. These can all lead to entry points for moisture.

Building envelope openings present the major opportunity for moisture intrusion. Doors, windows, vents, louvers, and roof hatches each may allow the entry of moisture if proper flashing precautions are not taken. It is necessary to check the specification carefully to determine the materials to be used for flashing and caulking and the installation methods to be used. The drawings should be checked to ensure that the location and design of the flashing of such components will, in fact, deter the entry of water.

Sometimes the installation methods themselves can be a source of moisture infiltration. For example, when insulation is mechanically fastened to a metal roof deck, each penetration is a potential entry point for water in the event of a roof membrane failure. This water can travel along the flutes of the deck for great distances and cause damage far from the source of the roof leak.

A specification can be thought of as a handy catalog of the materials and equipment which are (or should be) in the building under investigation. Is adequate bathroom ventilation provided? What is the CFM capacity of the bathroom fan? Are there humidifiers or dehumidifiers provided in the HVAC system? What type of waterproofing is provided on basement walls? Answers to these questions can be found in the specifications and can lead to determination of the cause of moisture problems.

Automated Specifications Systems

With the advent of personal computers and word processing programs, much of the work of writing a specification can be simplified. A number of systems have been developed to produce accurate construction specifications. These systems have the advantage of a large library of carefully researched specification sections to be used as a manuscript for editing the final specification. These sections have been prepared by professional specification writers and have usually undergone extensive review by architects and engineers to ensure accuracy. Although sections have not been developed for every conceivable product, sections have been developed for most items normally encountered in construction. Using these sections as a basis for a final construction specification greatly simplifies the writing process and ensures consistency in format.

Some of the currently available specification systems available are:

Masterspec: This product, produced by the American Institute of Architects, has long been used by architects and engineers. The sections tend to favor specification by manufacturer, brand name, or model. A version of this system was produced for the General Services Administration, which relies more heavily on reference standard specifying [*3*].

SPEC-TEXT: This product is produced by the Construction Specifications Institute using the resources of the chapter members of the Institute to write the sections. The sections are written to allow specification by either reference standards or brand name [*4*].

SPECSINTACT: This system was originally developed for NASA's construction program. It is now also used by the Naval Facilities Engineering Command and the Army Corps of Engineers and is the official specification processing system for the three agencies. Nearly all of the sections rely on reference standards for specifying products since government regulations generally do not allow specification by brand name. It is distributed by the National Institute for Building Sciences as part of the Construction Criteria Base (CCB), a very complete database of construction-related documentation issued by governmental and private organizations. The CCB is distributed by the National Institute of Building Sciences on CD-ROMS for use on IBM compatible computers [*5,6*].

VAPOR RETARDERS

The use or misuse of vapor retarders is of paramount importance when dealing with moisture. Although the CSI Masterformat contains a suggested section for specifying vapor retarders, it should be realized that this section is intended for specifying a material such as polyethylene sheet, which acts solely as a vapor retarder, with no other function except that, if effectively installed, i.e., without tears, holes, and well sealed to adjoining walls, ceilings, or other constructions, also acts as an air barrier.

In fact, there are many other specification sections which either explicitly or implicitly specify a vapor retarder. Waterproofing and dampproofing also perform as vapor barriers. Membrane roofing specifications often include the requirement for a vapor retarder, as do sections dealing with roof insulation. The specification section dealing with gypsum wallboard may require moisture-resistant wallboard or a foil backing, both of which function effectively as vapor retarders. The specification for a concrete slab may specify a polyethylene sheet as a vapor retarder. Paints and wall coverings may effectively act as vapor retarder although not chosen for such properties. The selection of insulation may include types of foam board insulation which are impervious to moisture absorption or transmission or are covered with foil or kraft paper, which act as moisture barriers.

The point is that vapor retarders can exist (and at the wrong places) where the specifier did not intend that they should exist. A complete investigation of moisture problems should include a review of the specification to find where vapor retarders have been required. When writing specifications for new construction or remedial work, careful thought should be exercised when specifying materials to avoid the inclusion of unwanted vapor retarders.

DRAWINGS

It should be noted that the specification is only a part of the contract documents, existing to complement the drawings. The specifier should be alert to conflicts between what is shown on the drawings and the specified requirements. All items shown on the drawings should have a corresponding specification, and all items specified must be located on the drawings. Critical details, such as flashing, must be examined to ensure that the desired deterrent to moisture penetration can be achieved with the specified materials. A consistency of terminology is important; the drawings and specifications must refer to the same item of work in the same words. Also important from the specifier's viewpoint is the possible inclusion of "specifications" on drawings. Often designers indicate material specifications or standards in notes on the drawings or include installation requirements. The specifier has to be alert to ensure that the drawings and their notes do not introduce conflicts with the specifications.

CONCLUSIONS

The specifications are perhaps the most important part of the contract documents. In cases of conflict, the specifications will supercede the drawings. The performance of building products is dependent both on proper specification of the required product characteristics and the accurate description of the correct installation methods to be used. Modern buildings are complex constructions, and the interrelationships between its parts are in large measure determined by a correct, concise, and technically accurate specification.

REFERENCES

[*1*] CSI Masterformat, The Construction Specifications Institute, Alexandria, VA 22314.
[*2*] *CSI Manual of Practice*, The Construction Specifications Institute, Alexandria, VA 22314.
[*3*] MASTERSPEC, The American Institute of Architects, Washington, DC.
[*4*] SPEC-TEXT, Construction Specifications Institute, Alexandria, VA, 22314.
[*5*] SPECSINTACT, National Aeronautics and Space Administration, (distributed by The National Institute of Building Sciences, Washington, DC).
[*6*] Construction Criteria Base (CCB), The National Institute for Building Sciences, 1201 L Street NW, Washington, DC 20005.

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Rosenfeld, W., *The Practical Specifier*, AIA, McGraw Hill, New York, 1985.
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Simmons, H. L., *The Specification Writer's Book of Checklists and Forms*, John Wiley and Sons, New York, 1986.

24

Applicable Guidelines, Standards, and Codes

by Wayne P. Ellis[1]

STANDARD TERMINOLOGY IN MOISTURE CONTROL

There is no standard terminology of moisture control in building design, operation, and maintenance. The terms associated with the various states of water (e.g., water, moisture, water vapor, humidity, hygroscopicity, rising damp, dampness, dryness, condensation, permeance, permeability, diffusion, wetness, barrier, retarder, waterproofing) are often used incorrectly, giving rise to confusion, ambiguity, and misunderstanding.

In the broadest sense, a standard is simply an agreed-upon way of doing something repetitively. In this sense, familiar examples of such standards are musical notation, the procedures of arithmetic, and the grammar and syntax of language. In the narrower sense (in the buildings field), technical standards are documented agreements that define properties, processes, dimensions, materials, relationships, concepts, test methods, terminology, guidelines, and practices.

The terms *guideline*, *standard*, and *code* are sometimes misconstrued. Each of these concepts has a related, but different, meaning. For clarification, the discussions in this chapter adhere to the following definitions. A *guideline*[2] is a written statement or outline of policy, practice, or conduct. There are at least three consensus definitions of the term *standard*[3] (1) a concept that has been established by authority, custom, or agreement to serve as a model or rule in the measurement of quality or the establishment of a practice or procedure; (2) a document established by consensus and approved by a recognized body that provides for common and repeated use, rules, guidelines, or characteristics for activities or their results aimed at the achievement of the optimum degree of order in a given context;[4] and (3) a prescribed set of rules, conditions, or requirements concerned with the definition of terms; classification of components; delineation of procedures; specification of dimensions, materials, performance, design, or operations; measurement of quality and quantity in describing materials, products, systems, services, or practices; or descriptions of fit and measurement of size.[5]

A *code* (in the law) is a collection of laws (regulations, ordinances, or statutory requirements) adopted by governmental (legislative) authority.[2] Codes are further classified as model codes, building codes, energy codes, fire codes, plumbing codes, mechanical codes, and electrical codes.

Standards concepts can represent the consensus of a single group (a company standard or construction project standard) of a trade group or technical discipline (an industry standard), of a professional or technical society (a professional standard), or of a national or international standards-developing organization in which all interests are represented (a full-consensus standard).

Note further that in ASTM, for example, a standard is a document that has been developed and established within the consensus principles of the Society and meets the approval requirements of ASTM procedures and regulations.[6] Other consensus organizations have similarly defined their standards documents. ASTM also categorizes its standards as *classifications, guides, practices, specifications, terminology*, and *test methods*.

Information Sources

A detailed list of sources is found in the bibliography and footnotes to this chapter (the bibliography is arranged in chronological order). A further search for moisture-control information standards was made in several databases: the Construction Criteria Base (CCB) of the National Institute of Building Sciences (NIBS), the HUD User Database of the U.S. Department of Housing and Urban Development (HUD), the National Technical Information Service (NTIS) Bibliographic Database, the Airbase of the Air Infiltration and Ventilation Centre (AIVC), and the DIALOG information retrieval service. Other general sources were: the *1990 Annual Book of ASTM Standards*, the *Directory and Index of Standards of the Standards Council of Canada* (SCC), and the *Standards Catalogue of the British Standards Institution*.

Although the principal guidelines, standards, and codes relating to moisture control are cited in this chapter, the list is not intended to be complete. Within the past decade, much field study and research has been conducted on moisture problems in buildings. Valuable guidance has been developed in this way, but much of it is recorded in technical papers, symposia, and articles in the technical press. Textbook treatment is still in preparation. It is unfortunate there

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[1] Standards consultant (deceased), 754 Bob-Bea Lane, Harleysville, PA 19438-1603.

[2] ASTM E 631-92a, Terminology of Building Constructions.

[3] ASTM E 1316-92, Terminology for Nondestructive Examination.

[4] ISO/IEC Guide 2, "General Terms and Their Definitions . . .," International Organization for Standards, Geneva, 1989.

[5] Circular A-119, U.S. Government Office of Management and Budget. Washington, DC, October 1982.

[6] Regulations Governing ASTM Technical Committees, June 1992.

is not yet a comprehensive manual that identifies all moisture-control standards documentation.

Building Envelope Moisture Control

The primary focus of moisture control is on the building envelope, whether the moisture to be controlled originates from outside or inside the building. The building envelope is defined as the outer elements of a building, both above and below ground, that divide the external from the internal environments[2]. This chapter will categorize the standards identified according to these building elements, i.e., the roof, walls, floors, and foundations (earth-coupled spaces). Three elements of the envelope—thermal insulation, storm doors and windows, and vapor retarders—form the most significant means of energy conservation.

The basic mechanisms of moisture movement through the envelope are leakage or permeation of liquid water, diffusion of water vapor, and entrainment of moisture within *air leakage*. Control or reduction of *air leakage* has received much attention in energy conservation research and practice because of potentially significant heat savings. A study of houses in the Southwest showed that holes in the envelope accounted for a 30% loss in energy and also that 59% of the energy used could be attributed to cracks and openings.[7] Control of air infiltration or leakage for energy conservation also benefits moisture control, but it is a secondary consideration.

In a 1984 review,[8] it was found that twelve countries had adopted standards of building airtightness and ventilation requirements. Achenbach et al.[9] described and discussed envelope condensation control.

In the U.S. Department of Energy, *Energy Performance Standards*,[10] the building envelope is viewed as a controlled membrane rather than an immutable barrier. "The desired goal of the energy design of the building envelope shall be to produce a controlled membrane that allows or prevents heat, light, *and moisture* flow to achieve a balance between internal and external loads" (Sec. 5.2.1.3). Moisture migration guidelines are detailed (Sec. 5.3.7).

Applicable Guidelines

Relatively few uncontested, reliable guidelines have been developed for control of moisture problems in buildings. A principal reason is that not enough understanding exists to translate the results of numerous laboratory and field tests into universal design guidelines.[11] One widely referenced work is the *ASHRAE Handbook of Fundamentals*,[12] in which chapters prepared by ASHRAE Technical Committees 4.4 on Thermal Insulation and Moisture Retarders and 4.3 on Ventilation Requirements and Infiltration provide moisture control guidance. ASHRAE Standards 90A-1980[13] and 90.1-1989[14] provide guidelines for energy conservation including control of air infiltration, but moisture control is not specifically addressed.

Other guidelines exist in technical publications,[15] but many are based on the ASHRAE guidelines and upon published results of prolific research in the field of energy conservation. The preceding chapter on moisture control in building design specifications treats implementation of accepted guidelines into the building construction process. Such specifications are a form of guidelines (guide specifications) and a form of standard (when incorporated into a building construction contract). Any redundancy between these chapters serves to emphasize the importance of materials and techniques for moisture control.

ASTM Standard Guidelines

In the field of moisture control, general guidelines are several ASTM standard practices directed to quality in construction:

C 755: Practice for Selection of Vapor Barriers for Thermal Insulations. Outlines factors to be considered, describes design principles and procedures for vapor retarder selection, and defines water vapor transmission values appropriate for established criteria. Emphasis is placed on the control of moisture penetration by choice of the most suitable components of the system.

C 898: Guide for Use of High Solids Content, Cold Liquid-Applied Elastomeric Waterproofing Membrane with Separate Wearing Course. Describes the use of a waterproofing system for building decks subject to hydrostatic pressure and provides information and guidelines for consideration of the designer, as well as guide specifications, for the use of purchaser and seller in contract documents.

C 962: Guide for Use of Elastomeric Joint Sealants. Describes the use of single- and multi-component, cold-applied, chemically curing elastomeric joint sealants for moisture control applications in buildings and related areas such as plazas, decks, and pavements for vehicular or pedestrian use, and

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[7] Miller, D. R., "Energy Conservation Opportunities in the Building Envelope . . .," *Proceedings*, Thermal Performance of the Exterior Envelopes of Buildings. ASHRAE/DOE-ORNL Conference, 3–5 Dec. 1979.

[8] Jackman, P. A., "Review of Building Airtightness and Ventilation Standards," *Implementation and Effectiveness of Air Infiltration Standards in Buildings. Proceedings*, 5th AIC Conference at Reno, Nevada, Air Infiltration Centre, Bracknell, UK, 1984.

[9] Achenbach, P., Reese, and Trechsel, H. R., "Evaluation of Current Guidelines of Good Practice for Condensation Control in Insulated Building Envelopes," *Thermal Performance of the Exterior Envelope of Buildings II*, ASHRAE SP38, ASHRAE, Atlanta, 1983.

[10] 54 FR *(Federal Register)* Washington, DC, 30 Jan. 1989, p. 4554.

[11] *National Program Plan for the Thermal Performance of Building Envelope Systems*, "Moisture Control in Buildings," Building Thermal Envelope Coordinating Council, National Institute of Building Sciences, Washington, DC, 1988.

[12] Chapter 20, "Thermal Insulation and Vapor Retarders—Fundamentals," Chapter 21, "Applications," Chapter 22, "Thermal and Water Vapor Transmission Data," Chapter 23, "Infiltration and Ventilation," *1989 ASHRAE Handbook of Fundamentals*, Atlanta, 1989.

[13] ASHRAE Standard 90A-1980: Energy Conservation in New Building Design.

[14] ASHRAE Standard 90.1-1989: Energy Efficient Design of New Buildings Except Low-Rise Residential Buildings.

[15] See bibliography.

types of construction other than highway and airfield pavements and bridges.

C 981: Guide for Design of Built-Up Bituminous Membrane Waterproofing Systems for Building Decks. Describes the design and installation of waterproofing systems for plaza deck and promenade construction over occupied spaces of buildings where covered by a separate wearing course.

E 241: Practices for Increasing Durability of Building Constructions Against Water-Induced Damage. Presents design and construction practices intended to limit deterioration problems involving combinations of building materials. Involves three principal factors in performance durability: time, moisture, and temperature. Discusses vapor retarder placement, air infiltration, moisture exhaust systems, roof drainage systems, and wall penetrations.

E 936: Practice for Roof System Assemblies Employing Steel Deck Preformed Roof Insulation and Bituminous Built-up Roofing. Performance requirements for the design, components, construction, and service expectations of new roof system assemblies. The appendix contains commentary on water vapor retarders and on moisture evaluation.

Industry Guidelines

APA[16] Design/Construction Guide; Residential and Commercial. Treats vapor retarder design for ground surfaces and crawl spaces.

FMS[17] Loss-Prevention Data for Insulated Steel Deck (Roofing). Design of vapor retarder installation.

GA[18] 216: Application and Finish of Gypsum Board.

GA 600: Fire-Retardant Design Manual. Includes design and application of water-vapor retarders.

SPI[19] AY 102: Protective Coatings. Good discussion of vapor retarder and breather coatings.

Applicable Standards

Most of the consensus standards applicable to moisture control in buildings are standard test methods for measuring the resistance to penetration by water or permeation by water vapor of various building materials and systems. Other standards are specifications (and related tests) for materials and systems that provide moisture control in service.

Engineering Design Standards

Typical of standard specifications requiring measures for moisture control are those appearing in Division 7[20] of construction specifications of engineering organizations and government departments and agencies. One example, that of the *Department of Energy Construction Specifications*[21] details waterproofing, dampproofing, vapor and air retarders, building insulation and its protection, exterior insulation and finish systems (EIFS), roofing and flashing, sealants and joints.

ROOFING MATERIALS AND SYSTEMS

ASTM Standards

There are many ASTM standards concerned with roofing and waterproofing promulgated by Committee D-8 on Roofing, Waterproofing, and Bituminous Materials. Most are concerned with materials and their testing, not with design guidelines. Exceptions are the standards described below.

D 466: Method of Testing Films Deposited from Bituminous Emulsions. (Resistance to water action.) A test to determine the ability of the dried film to retain its adhesion and to resist re-emulsification after immersion in water. The test specimen [4 by 4 in. (10.16 by 10.16 cm)], dried at room temperature, is subjected to a 1-in. (2.54 cm) column of water for 24 h.

D 2164: Methods of Testing Structural Insulating Roof Deck. (Resistance to cyclic exposure.) The strength of specimens after six complete cycles of accelerated aging (water immersion, steam spray, low temperature, dry heat, steam spray, and dry heat) is compared to that of specimens evaluated in the "as received" condition. The loss in strength after aging is assumed to be the measure of loss in strength after many years of service under extreme weathering conditions.

See also ASTM C 981 and E 936, and FMS guidelines (page 5). The NRCA *Roofing and Waterproofing Manual*[22] is a comprehensive treatment of roofing system design and application. Bibliography reference Griffin, C. W., 1970, contains an excellent bibliography of earlier roofing literature.

WALLS, FENESTRATION, MATERIALS, AND SYSTEMS

ASTM Standards

C 209: Methods of Testing Insulating Board (Cellulosic Fiber), Structural and Decorative. Included are test methods for

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[16] American Plywood Association, P.O. Box 11700, Tacoma, WA 98411.

[17] Factory Mutual System, 1151 Boston-Providence Turnpike, P.O. Box 9102, Norwood, MA 02062.

[18] Gypsum Association, 810 First St. NE, Suite 510, Washington, DC 20002.

[19] Society of the Plastics Industry, 1275 K Street NW, Suite 400, Washington, DC 20005.

[20] Construction Specifications Institute (CSI); 601 Madison St., Alexandria, VA 22314. MASTERFORMAT® numbering system, Division 7: Thermal and Moisture Protection.

[21] General Design Criteria (Buildings), U.S. Dept. of Energy, Washington, DC.

[22] *Roofing and Waterproofing Manual*, 3rd ed., National Roofing Contractors Association, Carol Stream, IL. 1990.

water absorption (immersion), water vapor transmission (ASTM E 96), and water vapor content (gravimetric).

C 240: Test Method for Cellular Glass Insulating Block. Included is a test method for water absorption by immersion under isothermal conditions.

C 553: Specification for Mineral Fiber Blanket and Thermal Insulation for Commercial and Industrial Applications. Test for moisture adsorption (by weight and by volume) exposes an oven-dried specimen within a humidity test chamber at 120 ± 3°F (48.8 ± 16.1°C) and 95 ± 3% RH for 96 h.

C 677: Practice for Use of a Standard Reference Sheet for the Measurement of the Time-Averaged Vapor Pressure in a Controlled Humidity Space. Describes the use of a standardized polyester reference film for determining the time-averaged vapor pressure and relative humidity in a test space, essential factors in water vapor transmission testing.

C 739: Specification for Cellulosic Fiber (Wood-base) Loose-Fill Thermal Insulation. Composition and physical requirements include water vapor absorption (by weight) following exposure of a specimen conditioned under standard conditions to 90 ± 5% RH for 24 h.

C 1134: Test Method for Water Retention of Rigid Thermal Insulations Following Partial Immersion. Determines the amount of water retained (including surface water) by rigid block and board thermal insulations used in building construction applications. Specimens are partially immersed in liquid water for prescribed time intervals under isothermal conditions. Determination of moisture accumulation in thermal insulations due to complete immersion, water vapor transmission, internal condensation, freeze-thaw cycling, or a combination of these effects requires different test procedures. Describes other limitations of this test method.

C 1136: Specification for Flexible, Low Permeance Vapor Retarders for Thermal Insulation. Physical properties and test methods for flexible vapor retarder materials (having a permeance of 0.10 perm or lower) for thermal insulation materials at ambient temperatures of −20 to 150°F (−28.8 to 65.5°C).

D 822: Practice for Conducting Tests on Paint and Related Coatings and Materials Using Filtered Open-Flame Carbon-Arc Light and Water Exposure Apparatus. Evaluation of the behavior of films exposed in apparatus that produces ultraviolet radiation, high temperatures, and water condensation on the films. Used to make an early-materials comparison of the exterior exposure quality of paints.

D 870: Practice for Testing Water Resistance of Coatings Using Water Immersion. Evaluation of organic coatings applied to steel panels after partial immersion in water at standard temperature, followed by examination for blistering, wrinkling or roughening, disintegration, changes in color, or other effects.

D 1499: Operating Light-and Water-Exposure Apparatus (Carbon-Arc Type) for Exposure of Plastics. Evaluation of the resistance of plastic material to deterioration of its electrical, mechanical, and optical properties when exposed in light- and water-exposure apparatus.

D 1653: Test Method for Water Vapor Transmission of Organic Coating Films. Gravimetric determination of the amount of moisture passing through a free film, or supported film, of organic coating, using a standard metal test cell incorporating a wet cup procedure similar to ASTM E 96.

D 2247: Practice for Testing Water Resistance of Coatings in 100% Relative Humidity. Evaluation of coated metal specimens exposed at 100% relative humidity and a temperature of 100 ± 2°F (37.7 ± −16.6°C) with condensation on the specimens at all times. Examination covers degradation such as gloss, rusting, blistering, hardness, and adhesion.

D 4099: Specification for Poly(Vinyl Chloride) (PVC) Prime Windows. Materials properties and performance characteristics, including air infiltration and water penetration.

D 4585: Practice for Testing the Water Resistance of Coatings Using Controlled Condensation. Test to evaluate degradation of coatings by water exposure, conducted on metal or wood specimens with the coating facing inside the chamber. Condensation is produced by exposing one surface of a coated specimen to a heated, saturated mixture of air and water vapor, while the reverse side of the specimen is exposed to the cooling effect of room temperature air.

E 96: Test Methods for Water Vapor Transmission of Materials. Gravimetric determination of water vapor transmission of specimens not over 1.25 in. (3.17 cm) thick. Two basic methods, the desiccant method and the water method are provided for the measurement of permeance. Well-detailed procedure and rationale.

E 283: Test Method for Rate of Air Leakage Through Exterior Windows, Curtain Walls, and Doors. Determination of resistance to air infiltration resulting from air pressure differences, with constant temperature and humidity across the specimen.

E 331: Test Method for Water Penetration of Exterior Windows, Curtain Walls, and Doors by Uniform Static Air Pressure Difference. Determination of resistance to water penetration when water is applied to the outdoor face simultaneously with a static air pressure at the outdoor face higher than the pressure at the indoor face.

E 398: Test Method for Water Vapor Transmission Rate of Sheet Materials Using a Rapid Technique for Dynamic Measurement. The specimen is mounted between two chambers, one of known relative humidity and the other of dry air. After conditioning, the response of an electrical sensor capable of detecting water vapor accumulation is recorded. A curve showing the relationship between the response of the sensor and reference water vapor transmission (WVT) values determined by methods E 96 is used to relate sensor response to WVT.

E 514: Test Method for Water Permeance of Masonry. A test wall is sealed into one face of a chamber within which is provided water spray (and drain pipes) for a 4-h period, while increasing the internal air pressure to simulate wind-driven rain exposure.

E 546: Test Method for Frost Point of Sealed Insulating Glass Units. Laboratory procedure for determining the frost point within the air space(s) of sealed insulating glass units and criteria for determining whether that point is above or below a given or specified temperature.

E 547: Test Method for Water Penetration of Exterior Windows, Curtain Walls, and Doors by Cyclic Static Air Pressure Differential. Evaluation of the resistance to water penetration when water is applied to the outdoor face simultaneously with a cyclic static air pressure at the outdoor face higher than the pressure at the indoor face.

E 576: Test Method for Dew/Frost Point of Sealed Insulating Glass Units in the Vertical Position. Field or laboratory procedure for determining the frost point within the air space(s) of sealed insulating glass units and criteria for determining whether that point is below or above a given or specified temperature.

E 741: Test Method for Measuring Air Leakage Rate by Tracer Dilution. The method entails introducing a small amount of tracer gas into a structure, thoroughly mixing it, and measuring the rate of change (decay) in tracer concentration.

E 773: Test Methods for Seal Durability of Sealed Insulating Glass Units. Testing the performance of preassembled permanently sealed insulating glass units against accelerated weathering and fogging.

E 779: Method for Determining Air Leakage Rate by Fan Pressurization. Mechanical pressurization and depressurization of a building and measurements of the resulting airflow rates at given indoor-outdoor static pressure differences.

E 783: Method for Field Measurement of Air Leakage Through Installed Exterior Windows and Doors. Evaluation of the resistance of installed exterior windows and doors to air leakage resulting from static air pressure differences.

E 1017: Performance Specification for Exterior Residential Window Assemblies. Establishes acceptance criteria, including air infiltration and water penetration resistance.

E 1105: Test Method for Field Determination of Water Penetration of Installed Exterior Windows, Curtain Walls, and Doors by Uniform Cyclic Static Air Pressure Difference. Evaluation of the resistance to water penetration when water is applied to the outdoor face simultaneously with a static air pressure at the indoor face lower than the static air pressure at the outdoor face.

F 372: Test Method for Water Vapor Transmission of Flexible Barrier Materials Using an Infrared Detection Technique. A rapid procedure in which a dry chamber is separated by the barrier material under test from a wet chamber of known temperature and humidity. The time for a given increase in water vapor concentration of the dry chamber is measured by monitoring the differential between two bands in the infrared spectral region; one in which water molecules absorb and the other where they do not. This information then is used to calculate the water vapor movement through the known area of barrier material.

F 1249: Test Method for Water Vapor Transmission Rate Through Plastic Film and Sheeting Using a Modulated Infrared Sensor. A dry chamber is separated by the barrier material under test from a wet chamber of known temperature and humidity. The two chambers make up a diffusion cell in which the test film is sealed. The cell is placed in a test station where the dry chamber and the top of the test film are swept with dry air. Water vapor diffusing through the film mixes with the air and is carried into a pressure-modulated infrared sensor. This sensor measures the fraction of infrared energy absorbed by the water vapor and produces an electric signal, the amplitude of which is proportional to water vapor concentration. The amplitude of the electric signal produced by the test film is then compared to the signal produced by measurement of a calibration film of known transmission rate. This information then is used to calculate the rate at which moisture is transmitted through the material being tested.

G 53: Practice for Operating Light-and Water Exposure Apparatus (Fluorescent UV-Condensation Type) for Exposure of Non-Metallic Materials. Use of this apparatus is intended to simulate deterioration caused by water as rain or dew and the ultraviolet energy in sunlight.

British Standards

BS[23] 4315: Methods of Test for Resistance to Air and Water Penetration. Part 1: Air infiltration of windows, resistance to water penetration of windows under static pressure, and resistance to water penetration of gasket-glazing systems under dynamic conditions. *Part 2:* Resistance to water penetration of permeable walling constructions without open joints under static air pressure.

BS 5368: Methods of Testing Windows. Part 1: Air Permeability Test. To assess the property of a closed window to let air pass when it is subjected to a differential pressure. *Part 2: Watertightness Test Under Static Pressure.* To assess the watertightness quality of a window. *Part 3: Wind Resistance Tests.* To assess the resistance under positive and negative pressures for all windows, including door height windows.

BS 6375: Performance of Windows. Part 1 Classification for Weathertightness. Establishes terms of exposure categories

[23] British Standards Institution, Linford Wood, Milton Keynes, MK14 6LE, England.

related to test pressure levels for air permeability, watertightness, and wind resistance.

Industry Standards

ANSI/AAMA[24] 101-85: Aluminum Prime Windows; Aluminum Sliding Glass Doors

ANSI/NWMA[25] I.S. 2-80: Wood Window Units (Improved Performance Rating Only). ANSI/NWMA I. S. 3-83: Wood Sliding Patio Doors UL[26] 1784-1990: Air Leakage Tests of Door Assemblies

Other Standards and Guidelines

CID[27] A-A-272: Caulking Compounds

HUD UM-80: Spray-Applied Cellulosic Thermal Insulation

HUD-FHA[28] Minimum Property Standards (MPS) for Housing[29] is invoked for housing in which mortgage financing has federal government guarantees. Although titled as a standard, it has the nature of a building code. It requires that all buildings be constructed in compliance with the CABO Model Energy Code[30] (with certain exceptions). All windows and sliding glass doors must be tested for air infiltration, water penetration, and physical loading.

Insulation in contact with the ground must be installed so as not to be adversely affected by soil, vermin, and *water*. Vapor retarders and base course must be provided for all interior concrete slabs to which a finish flooring is applied. Section 607-2.1 requires that alternate waterproofing membranes comply with ASTM E 154 (a mistaken reference as pointed out by Hans,[31] since E 154 is not a specification but a guideline for test methods). Polyethylene sheeting (2 to 6 mils thick) is recommended for water-vapor flow control in walls and ceilings to protect against condensation.

The HUD standards for manufactured homes (mobile homes) require installation of condensation control in ceilings and exterior walls by use of vapor retarders (vapor barriers) not exceeding one perm in water-vapor transmission.

FLOORS, FOUNDATIONS, EARTH-COUPLED SPACES

ASTM Standards

C 836: Specification for High Solids Content, Cold Liquid-Applied Elastomeric Waterproofing Membrane for Use With Separate Wearing Course. Required properties and test methods for membrane for waterproofing building decks subject to hydrostatic pressure. Includes testing for adhesion-in-peel after immersion in deionized water for seven days, using the procedures of Method C 794.

C 957: Specification for High Solids Content, Cold Liquid-Applied Elastomeric Waterproofing Membrane with Integral Wearing Surface. Required properties and test methods for membrane for water-proofing building decks not subject to hydrostatic pressure. Includes testing for adhesion-in-peel after immersion in deionized water for 7 days, using the procedures of Method C 794.

D 529: Accelerated Weathering Test of Bituminous Materials. Thin films of bitumen are uniformly applied to aluminum panels or to weather surfaces of fabricated materials such as bituminous roofing. A choice of two test cycles is given, along with options for determining the period of exposure and evaluating results.

E 154: Methods of Testing Materials for Use as Vapor Barriers Under Concrete Slabs and as Ground Cover in Crawl Spaces. The series of test methods evaluating membrane materials, primarily plastic films and other flexible sheets, includes water vapor transmission (WVT) as received, and after wetting and drying and long-time soaking. Specimens are exposed to cycles of water immersion and oven drying, then measured for WVT by the procedures of Methods E 96.

Table 1 is a consolidated list of cited ASTM standards dealing with moisture in building materials and systems.

APPLICABLE CODES

The principal codes concerned with regulation of buildings design are model building codes, addressing primarily issues of health and safety, and national and state energy codes, addressing conservation of energy in buildings. The three model building code organizations in the United States are BOCA (the Building Officials and Code Administrators International[32], ICBO (the International Conference of Building Officials[33], and SBCCI (the Southern Building Code Congress International[30]. Their codes have a common standard

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[24] American National Standards Institute/American Architectural Manufacturers Association, 2700 River Road, Suite 118, Des Plaines, IL 60018.

[25] National Woodwork Manufacturers Association, 1400 E. Tuohy Avenue, Des Plaines, IL 60018.

[26] Underwriters' Laboratories Inc., 333 Pfingsten Road, Northbrook, IL 60062.

[27] Commercial Item Description, U.S. General Services Administration, Washington, DC.

[28] Federal Housing Administration, within HUD, U.S. Dept. of Housing and Urban Development, Washington, DC.

[29] U.S. Department of Housing and Urban Development (HUD), Office of Housing, *Minimum Property Standards, One- and Two-Family Dwellings*, Washington, DC, 1984 ed., currently under revision by FHA.

[30] 900 Montclair Rd., Birmingham, AL 35213.

[31] Hans, G. E., "Coordination of Performance Standards on Moisture Control in Buildings," *Moisture Migration in Buildings, ASTM STP 779*, M. Lieff and H. R. Trechsel, Eds., Philadelphia, 1982.

[32] 4051 West Flossmoor Rd., Country Club Hills, IL 60477-5795.

[33] 5360 S. Workman Mill Rd., Whittier, CA 90601.

TABLE 1—Condensed list of ASTM standards dealing with moisture in building materials and systems.

C 209:	Methods of Testing Insulating Board (Cellulosic Fiber), Structural and Decorative
C 240:	Methods of Testing Cellular Glass Insulating Block
C 553:	Specification for Mineral Fiber Blanket and Thermal Insulation for Commercial and Industrial Applications
C 677:	Practice for the Use of a Standard Reference Sheet for the Measurement of the Time-Averaged Vapor Pressure in a Controlled Humidity Space
C 739:	Specification for Cellulosic Fiber (Wood-base) Loose-Fill Thermal Insulation
C 755:	Practice for Selection of Vapor Barriers for Thermal Insulations
C 836:	Specification for High-Solids Content, Cold Liquid-Applied Elastomeric Waterproofing Membrane for Use With Separate Wearing Course
C 898:	Guide for Use of High Solids Content, Cold Liquid-Applied Elastomeric Waterproofing Membrane with Separate Wearing Course
C 957:	Specification for High Solids Content, Cold Liquid-Applied Elastomeric Waterproofing Membrane with Integral Wearing Surface
C 962:	Guide for Use of Elastomeric Joint Sealants
C 981:	Guide for Design of Built-Up Bituminous Membrane Waterproofing Systems for Building Decks
C 1134:	Test Method for Water Retention of Rigid Thermal Insulations Following Partial Immersion
C 1136:	Specification for Flexible, Low Permeance Vapor Retarders for Thermal Insulation
D 466:	Method of Testing Films Deposited from Bituminous Emulsions
D 529:	Test Method for Accelerated Weathering Test Conditions and Procedures for Bituminous Materials (Carbon-Arc Method)
D 570:	Test Method for Water Absorption of Plastics
D 822:	Practice for Conducting Tests on Paint and Related Coatings and Materials Using Filtered Open-Flame Carbon-Arc Light and Water Exposure Apparatus
D 870:	Practice for Testing Water Resistance of Coatings Using Water Immersion
D 1499:	Practice for Operating Light- and Water-Exposure Apparatus (Carbon-Arc Type) for Exposure of Plastics
D 1653:	Test Method for Water Vapor Transmission of Organic Coating Films
D 2164:	Methods of Testing Structural Insulating Roof Deck
D 2247:	Practice for Testing Water Resistance of Coatings in 100% Relative Humidity
D 4099:	Specification for Poly(Vinyl Chloride) (PVC) Prime Windows
D 4585:	Practice for Testing the Water Resistance of Coatings Using Controlled Condensation
E 96:	Test Methods for Water Vapor Transmission of Materials
E 154:	Methods of Testing Materials for Use as Vapor Barriers under Concrete Slabs and as Ground Cover in Crawl Spaces
E 241:	Practices for Increasing Durability of Building Constructions Against Water-Induced Damage
E 283:	Test Method for Rate of Air Leakage Through Exterior Windows, Curtain Walls, and Doors
E 331:	Test Method for Water Penetration of Exterior Windows, Curtain Walls, and Doors by Uniform Static Air Pressure Difference
E 398:	Test Method for Water Vapor Transmission Rate of Sheet Materials Using a Rapid Technique for Dynamic Measurement
E 514:	Test Method for Water Permeability of Masonry
E 546:	Test Method for Frost Point of Sealed Insulating Glass Units
E 547:	Test Method for Water Penetration of Exterior Windows, Curtain Walls, and Doors by Cyclic Static Air Pressure Differential
E 576:	Test Method for Dew/Frost Point of Sealed Insulating Glass Units in Vertical Position
E 741:	Test Method for Measuring Air Leakage Rate by Tracer Gas Dilution
E 773:	Test Methods for Seal Durability of Sealed Insulating Glass Units
E 779:	Test Method for Determining Air Leakage Rate by Fan Pressurization
E 783:	Method for Field Measurement of Air Leakage Through Installed Exterior Windows and Doors
E 936:	Practice for Roof System Assemblies Employing Steel Deck Preformed Roof Insulation and Bituminous Built-up Roofing
E 1017:	Performance Specifications for Exterior Residential Window Assemblies
E 1105:	Test Method for Field Determination of Water Penetration of Installed Exterior Windows, Curtain Walls, and Doors by Uniform of Cyclic Static Air Pressure Difference
F 372:	Test Method for Water Vapor Transmission of Flexible Barrier Materials Using an Infrared Detection Technique
F 1249:	Test Method for Water Vapor Transmission Rate Through Plastic Film and Sheeting Using a Modulated Infrared Sensor
G 53:	Practice for Operating Light- and Water-Exposure Apparatus (Fluorescent UV-Condensation Type) for Exposure of Nonmetallic Materials

format, although the content is not identical; taking into account the regional jurisdictions in which they are adopted.

Model Building Codes

These codes do not cover in detail the control of moisture in buildings, except to warn against possible damage from water-vapor condensation. Ignored is the fact that the transfer of moisture in buildings may result in increased heat transfer and energy requirements.[34] One reference to moisture control, but related to fire control, is "Any material which is subject to an increase in flamespread rating or smoke developed rating beyond the limits herein established through the effects of age, *moisture*, or other atmospheric conditions, shall not be permitted.[35]"

The ICBO Uniform Mechanical Code, providing "complete requirements for the installation and maintenance of heating, ventilating, cooling and refrigeration systems" mentions moisture control only as a footnote in Table 10-D, Insulation of Ducts: "Vapor barriers shall be installed on conditioned-air-supply ducts in spaces vented to the outside in geographic areas where the average July, August, and September mean dew point temperature exceeds 60°F."

All three model codes embody requirements for proper drainage of surface water or weather-protection. Typical requirements are:

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[34] Hollingsworth, M., Session Summary: "Moisture Effects," *Thermal Insulation, Materials, and Systems for Energy Conservation in the '80s, ASTM STP 789*, F. A. Govan, D. M. Greason, and J. D. McAllister, Eds., ASTM, Philadelphia, 1983.

[35] Sec. 719.1, 1985 *Standard Building Code*. Southern Building Code Congress International (SBCCI), 900 Montclair Road, Birmingham, AL 35213.

> . . . sufficient slope or camber [of roof decks] to assure adequate drainage after the long-time deflection from dead load; control drainage of surface water around buildings; weather-resistant barriers shall be installed [under exterior lath] . . . the weep screed required allows trapped water to drain to the building exterior: the barrier to terminate on the screed attachment; install flashing and counter-flashing to make weatherproof; weather-exposed areas outside balconies, etc. shall be sealed underneath and waterproofed; provide adequate drainage as necessary to prevent entrance of water at openings and projections through veneered walls; proper flashings shall be installed [parapet walls] in such a manner as to prevent moisture entering the wall through joints in the coping, through moisture-permeable materials, at intersections with the roof plane, or at parapet wall penetrations; install waterproofing for below-ground (hydrostatic pressure) conditions, and dampproofing above grade from below the lowest slab to six inches above grade.

The CABO One and Two Family Dwelling Code (1986) requires flashing:

> To minimize chance of water leakage in the interface between wall covering and juncture of other materials, flashing is required to be properly installed. (The 1989 version contains more details of flashing requirements).

Energy Codes

The CABO (Council of American Building Officials[36] Model Energy Code (MEC) is a source document for many locally mandated energy codes applicable to new residential construction.[37] The MEC has been adopted by the model building code organizations: BOCA, ICBO, and SBCCI. ASHRAE Standard 90 generally is the basis for current energy codes.[38] Although model energy codes give some recognition to moisture control as an energy conservation measure, they are concerned primarily with heat losses, rather than moisture control. The treatment of moisture control in indoor air quality codes still is developing. The 1990 amendments to the CABO MEC now caution: "The design shall not create conditions of accelerated deterioration from moisture condensation. In all frame walls and floors and ceilings not ventilated to allow moisture to escape, an approved vapor retarder having a maximum perm rating of 1.0, when tested in accordance with ASHRAE Standard RS-23[39] . . . shall be used on the warm-in-winter side of the thermal insulation."

Conclusions

More than twenty sources of guidelines, standards, and codes have been cited in this chapter. There is no single information source, index, database, or compendium in which the designer or practitioner may find all standards, codes, and guidelines dealing with moisture control in buildings. Obviously such a resource would be widely used providing that it could be available in electronic form, and periodically updated.

Although there is no dearth of publications (books, symposia proceedings, research reports) describing problems, and remedial action, for moisture movement and its control in buildings, very few results have been transformed into formal standards—guidelines, codes, or consensus standards.

Practically all of the literature is concerned with design of *new* construction, with only slight attention paid to remedial measures needed for problems in existing buildings. While this manual does assemble the significant current information on moisture problems and their control, new research and new experience eventually will make this work outdated. A logical route to make available timely guidance to new and revised design and construction information would be the development of a rational system of buildings-moisture-control standards adopted on ASTM principles; especially because such standards must be updated periodically. The work of standards development is best accomplished by participation of all interests, including but not limited to the experts. In this way, the moisture performance of buildings may be optimized, the stock of buildings preserved, and their service to the owner and user maximized.

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[36] 5203 Leesburg Pike, Suite 708, Falls Church, VA 22041.

[37] Johnson, A. W., "Complying with the CABO Model Energy Code," *RSI (Roofing, Siding, Insulation)*, May 1989.

[38] See also the earlier mention of the HUD Minimum Property Standards, Footnote 28.

[39] ASTM E 96-92, *Test Methods for Water Vapor Transmission of Materials*.

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Legal Considerations and Dispute Resolution: The Water-Related Construction Failure

25

by Bruce W. Ficken[a]

LEGAL CONSIDERATIONS

Introduction

Water causes more construction failures than any other agent. Whether from leaks, air, floods, failed plumbing, or fire hoses, water very often is the culprit where, for example, mold and mildew occurs, adhesive fails, insulation fails to maintain its ability to insulate, or concrete begins to spall and crack. Exactly how water affects buildings and materials is explained elsewhere in this book. The subject of this chapter is the rules applicable to resolving construction-related failures, with particular emphasis on those caused by water. The chapter concludes with a detailed case study analysis of a several-week arbitration arising out of a 16-story hotel riddled with mold and mildew.

The Construction Failure Defined

A construction failure occurs any time that construction fails to perform as intended or required. Thus, not only is a construction failure the bridge that collapses or the structured support system that fails, it is also the paint that prematurely peels, the roof that leaks, or the glue that fails to bond. Every construction failure raises key issues and considerations that must be understood for the contractor, architect, specification writer, or owner to protect itself.

Unfortunately, whether a construction problem involves a construction failure is not always easily recognized. Take, for example, a catastrophic fire causing significant loss of life and property. If the reason for the loss is the failure of the design or construction of the building to function appropriately once the fire started, the controversy involves the resolution of a construction failure.

Or, for example, while the nature of a contractor's claim against an owner may be delays and disruptions to his work, if those delays were caused by the failure of some element of the construction (like a water infiltration problem during construction), the essential nature of the controversy is a construction failure.

The following discussion sets forth the sources of liability in construction failure cases for contractors, design professionals, and owners.

The Parameters of Exposure: Contractor

Compliance with Plans and Specifications

In every jurisdiction, the contractor is required to perform construction fully in accordance with the contract documents, usually consisting of at least plans and specifications[1] Thus, if the contractor fails to construct in accordance with applicable contract documents, he is responsible for resulting damages.[2] Conversely, a contractor's compliance with plans and specifications is universally recognized as a contractor's defense against liability in construction failure cases. This well-established principle of law is commonly referred to as the "*Spearin* doctrine."[3] Under *Spearin*, if a contractor is "bound to build according to plans and specifications prepared by the owner, the contractor will not be responsible for the consequences of defects in the plans and specifications."[4]

In situations involving water infiltration, those attempting to blame the contractor will typically look for water leaks in the exterior skin of the building or the plumbing systems and attempt to attribute the leaks to the contractor's failure to comply with applicable plans and specifications. In this context, particular attention will be paid to the roof construction, flashing, and other window details, and whether the plumbing and HVAC systems work as specified.

It should be noted, however, that there are descriptive specifications, performance specifications, and specifications that are both performance and descriptive. A contractor who complies solely with the descriptive portion of specifications cannot utilize the defense that he complied with the specifications if his work fails to meet specified performance requirements.[5]

A good example of specifications that are both performance and descriptive are typical concrete specifications. Concrete specifications usually describe the type of aggregate, type of cement, mix ratio, pouring procedures, and so on. But these specifications also state a performance requirement usually in terms of PSI. When the concrete fails to meet specified strength requirements, it is no defense for the contractor to say he followed the descriptive provisions of the concrete specification.[6]

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[a] Pepper, Hamilton, and Scheetz, Philadelphia, PA.

[1] 13 Am. Jur. 2d § 27, "Building and Construction Contracts" (1964 & Supp. 1990); 17A C.J.S. § 494(2), "Contracts" (1963 & Supp. 1990). See, e.g., *Tate-Jones & Co. v. Union Electric Steel Co.*, 281 Pa. 448, 453, 126 A. 813, 815 (1924).

[2] See, e.g., *Parkes v. Opfermann*, 180 Pa. Super. 184, 186–88, 119 A.2d 624 (1956).

[3] *United States v. Spearin*, 248 U.S. 132 (1918). See generally 6 A.L.R. 3d 1394, 1397–1403, § 2 (1966 & Supp. 1990).

[4] *Spearin*, 248 U.S. at 136.

[5] See section B.4, *infra*.

[6] The only exception is where the contractor can prove that, under the descriptive specifications, the strength requirements were impossi-

Poor Workmanship

Often construction contract documents set forth a requirement that work be "first rate" or "of the highest standard" or of "good workmanship." However, even absent such an explicit contractual requirement, there is implied in every construction contract the obligation of the contractor to perform the contract requirements in a workmanlike manner. Thus, the contract specifications will not tell the painter how to apply the paint or the welder how to make his weld. Nevertheless, it is an implied and fully foreseeable obligation that this work will be done by competent workmen in a workmanlike manner.[7]

If, for example, a roofing specification is not explicit about roof erection procedures, it is assumed that the contractor will exercise that skill and judgment to be expected of an experienced and competent roofer and erect that roof in a skilled and workmanlike manner. Even in the absence of flashing details, it is expected that flashing will be installed in accordance with good construction practice.

Exceeding Specification Requirements

Contract specifications do not generally call for a minimum standard which the contractor is free to exceed. Rather, the contractor is to meet the contract requirements, and, if he exceeds them, he can be held liable for any damages that result from exceeding the contract requirements. This principle was recognized a century ago in *Filbert v. Philadelphia.*[8] In *Filbert,* plaintiff contractors who had built a reservoir for the City of Philadelphia were held not liable for leaks in the reservoir in their lawsuit against the city for the contract price. The court held that the contractors had complied fully with the city's plans and added that, had the contractors "thought it wise to depart from the plans, and had done so and built a better reservoir, they could have recovered nothing" from the city.[9]

For example, a contractor may believe that he is enhancing the quality of the job by thickening a deck slab. If, however, as a result, the desk collapses because the slab thickening caused its supports to fail, the contractor is liable for failing to comply with the plans and specifications.

Or, for example, if a contractor voluntarily upgrades roof shingles, the owner is entitled to those set forth in the contract specification. That the contractor has enhanced the work is no defense to his failure to follow the contract requirements. Indeed, in such a case, courts will not even consider whether the original specifications were defective since the contractor, by deviating from the plans, would have become, in effect, the guarantor of his own work.[10]

Assumed Design Responsibility

Absent contract provisions to the contrary, the contractor is not responsible for the design professional's design. It is possible, however, for specification requirements to shift design responsibility to the contractor through the subtle incorporation into the contract requirements of performance requirements. Thus, the specification for a manufacturing facility might describe a conveyor assembly and add, for example: "such that production rates will exceed X units per hour." Or, in a structural steel specification, a beam might be described along with the following language: "and will be fabricated to support loads in excess of X." Or, most pertinent here, a specification for an exterior building skin or roof might add the phrase "such that it shall be free of leaks for a period of ___ years."

Such provisions in an inappropriate context may be unprofessional and poor construction practice. Nevertheless, these types of performance specifications are enforceable unless the contractor can demonstrate that the specified performance requirement could not be reached by following the descriptive specification.

This is not to say that in every case of performance requirements the contractor assumes the risk that the desired result will ultimately prove impossible to achieve. More commonly, a contractor merely agrees to meet a performance requirement without guaranteeing the adequacy of the specification. If the result is not satisfactory, the contractor may still claim that the result required by the owner and its design professional was "impossible" to perform.

In *Foster Wheeler Corp. v. United States,*[11] for example, the United States Court of Claims reversed a decision of the Armed Services Board of Contract Appeals denying the contractor an equitable adjustment for the increased costs it incurred in attempting to comply with impossible specifications. The contract there was a fixed price supply contract which obligated the contractor to design, fabricate, and deliver two boilers which could withstand a certain level of shock intensity, measured by a "dynamic shock analysis." The court rejected the board's ruling against the contractor, finding it significant that the government had ultimately accepted a boiler that was not shock-hard as originally required, that no other boiler manufacturer had succeeded in designing such a boiler, and that the government ultimately changed the performance requirements relating to shock-hardness.[12] The court was also persuaded that the contractor had not assumed the risk of impossibility, in part because the government had the greater expertise in the subject matter of the contract and had taken the initiative in promoting a particular method of boiler design.[13]

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ble to reach. In that case, the failure is attributable to design error. See section B.4, *infra.*

[7] See, e.g., *Mann v. Clowser,* 190 Va. 887, 59 S.E.2d 78, 84–85 (1950); *Henggeler v. Jindra,* 191 Neb. 317, 214 N.W.2d 925, 926 (1974); *Pittsburgh Nat'l Bank v. Welton Becket Assocs.,* 601 F. Supp. 887, 890–92 (W.D. Pa.); 13 Am. Jur. 2d §329, *supra.*

[8] 181 Pa. at 545.

[9] *Id.* Similarly, a contractor who deviates from what he claims were otherwise defective plans and specifications proceeds at his own peril and assumes the risk of such deviation. See, e.g., *W. H. Lyman Constr. Co. v. Village of Gurnee,* 131 Ill. App. 3d 87, 475 N.E.2d 273, 281 (1985).

[10] See, e.g., *Robert G. Regan & Co. v. Fiocchi,* 44 Ill. App. 2d 336, 194 N.E.2d 665 (1963), *cert. denied,* 379 U.S. 828 (1964).

[11] 513 F.2d 588 (Ct. Cl. 1975).

[12] *Id.* at 594–98.

[13] *Id.* at 598.

The Failure to Warn of Known Defects

The contractor who knows that there is a material risk of a construction failure if he complies with applicable plans and specifications has a duty to bring these deficiencies to the attention of the owner. If there is a subsequent construction failure as a result of the specified deficiency, the contractor can be held liable for his failure to warn.[14] Similarly, a contractor has a duty to warn of defective site conditions or soil conditions if the contractor knows or should know of the defect.[15]

This does not mean, however, that a contractor has an affirmative duty to review contract documents for design deficiencies or that courts will imply a duty on the contractor's part to investigate the site beyond what is reasonable. The contractor can be held liable only if he knows or should know of the design defect or the site condition problem and says nothing.

The Parameters of Exposure: The Design Professional

Failure to Design According to Applicable Standards

In virtually every jurisdiction, design professionals, including architects and engineers, are required to follow accepted standards of practice. They are liable, therefore, for damages which may arise from failing to follow these standards.[16] Thus, for example, the architect who specifies an interior latex for exterior use has not acted according to reasonable professional standards and will be liable if and when the paint fails. Likewise, the structural engineer who exceeds accepted margins of safety in designing load bearing beams, will be deemed responsible if, as a result, the beams fail.

A leading case on architect liability is *Bloomsburg Mills, Inc. v. Sordoni Construction Co.*,[17] in which the Pennsylvania Supreme Court held:

> An architect is bound to perform with reasonable care the duties for which he contracts. His client has the right to regard him as skilled in the science of the construction of buildings, and to expect that he will use reasonable and ordinary care and diligence in the application of his professional knowledge to accomplish the purpose for which he is retained. While he does not guarantee a perfect plan or a satisfactory result, he does by his contract imply that he enjoys ordinary skill and ability in his profession and that he will exercise these attributes without neglect and with a certain exactness of performance to effectuate work properly done. . . . While an architect is not an absolute insurer of perfect plans, he is called upon to prepare plans and specifications which will give the structure so designed reasonable fitness for its intended use, and he impliedly warrants their sufficiency for that purpose. . . .[18]

Breach of Implied Warranties Attached to Contract Documents

In addition to liability for professional negligence, the design professional can be held to have essentially guaranteed that his design, as set forth in applicable plans and specifications, is free of defects. Thus, it has been held that a design professional impliedly warrants that his plans and specifications are free of defects and fit for the purpose for which they were produced.[19] According to this standard, the design professional promises that if the contractor constructs according to plans and specifications, the resulting construction will not fail.[20]

Whatever the source of the design professional's duty, Bloomsburg Mills is strong ammunition for a plaintiff owner to argue that his design professional breached an implied contractual warranty if the construction fails due to an alleged design defect. Under such an approach, the plaintiff need not prove the architect's failure to exercise reasonable care if he can show the inadequacy of the plans and specifications for their intended purpose.

As it relates to moisture-related construction failures, this doctrine that the design professional warrants the fitness of its plans and specifications can be used to create a myriad of design obligations. Under this doctrine, it can be argued that if the finished construction is built in accordance with plans and specifications, it:

1. Will not leak.
2. Will not allow the accumulation of water where the building may be adversely affected.
3. Will not be unduly affected by predictable influx of moisture in the physical construction.
4. Will expel water which enters the construction predictably.
5. Will not utilize materials which tend to entrap excessive amounts of water under predictable circumstances.

In short, under this theory of liability, if a building with a moisture problem is properly maintained and the contractor can establish that he constructed in accordance with the applicable plans and specifications, the mere fact that the finished construction failed may cause the design professional to bear full responsibility for the moisture related failure.

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[14] See, e.g., *Mann*, 59 S.E.2d at 85 (the contractor has a duty to make a full and fair disclosure of the consequences of changes in the contract which the contractor knows or should know might cause structural defects from the nature of the undertaking or his experience).

[15] See, e.g., *Rippy v. Phipps*, 475 P.2d 646, 647–48 (Colo. Ct. App. 1970) (a contractor proceeded with construction of a dam and reservoir without advising the owner of soil conditions that it had discovered which it knew or should have known would make the site unsuitable for the dam and reservoir).

[16] See, e.g., *Bloomsburg Mills, Inc. v. Sordoni Constr. Co.*, 401 Pa. 358, 164 A.2d 201 (1960).

[17] *Id.*

[18] *Id.* at 361–62 (citations omitted). The source of the architect's duty—whether in tort or implied by contract—is discussed in section C.2, *infra*.

[19] See *Bloomsburg Mills*, 401 Pa. at 361–62. See *Federal Mogul Corp. v. Universal Constr. Co.*, 376 So. 2d 716 (Ala. Civ. App.), *writ denied*, 376 So. 2d 726 (Ala. 1979) (architects impliedly warrant that their plans and specifications for construction of a building are sufficient to make the structure fit for its intended purpose). *But see Castaldo v. Pittsburgh-Des Moines Steel Co.*, 376 A.2d 88 (Del. 1977) (an architect cannot be held liable in the absence of negligence and purchasers of architectural services can expect only reasonable care and competence); *Audlane Lumber & Builders Supply, Inc. v. D.E. Britt & Assocs.*, 168 So. 2d 333 (Fla. Dist. Ct. App. 1964), *cert. denied*, 173 So. 2d 146 (Fla. 1965).

[20] See also *Hill v. Polar Pantries*, 219 S.C. 263, 64 S.E.2d 885).

Inspection of the Work

The design professional is responsible for any damages that result from the breach of any contractual undertaking or the negligent performance of professional duties (including nondesigning activities) which he undertakes. Thus, if the architect, by contract or otherwise, inspects the work and fails to discover defects in the work which he should have discovered, the architect may be liable, along with the contractor, when the construction subsequently fails.[21]

Court decisions based on the architect's duty to inspect caused the American Institute of Architects ("AIA") to revise its standard form contracts to include a duty of "observation" rather than "inspection."[22] The AIA intended thereby to limit the architect's exposure to liability for defects in the contractor's work. And, to the extent that a duty to "observe" may be considered a less rigorous undertaking than a duty to "inspect," the architect is somewhat protected by this contractual qualification in the AIA standard form documents. Nonetheless, this distinction is not likely to protect the "observing" design professional from liability where he did observe or should have observed visible defects in the construction.

For example, in *First National Bank of Akron v. Cann,*[23] a United States Federal District Court, in effect, imposed a duty to inspect on the architect notwithstanding the parties' use of the term "observation" in their contract. In *Cann*, the owner bank sued both the construction manager and the architect for problems involving granite facing on the south wall of a remodeling job for the bank. The court recognized that "the scope of the architect's duty generally to observe" was "not clearly defined" in the contract documents and that "continuous on-site inspections were not required."[24] Nonetheless, the court held that such a provision "does not allow the architect to close his eyes on the construction site, refrain from engaging in any inspection procedure whatsoever, and then disclaim liability for construction defects that even the most perfunctory monitoring would have prevented."[25] Based on, *inter alia*, the nature of job, the large fees paid the architect justifying his supervisory role, and the fact that site visits should have been made, at a minimum, when the erection of the supporting steel for the granite walls was undertaken, the court held that the architect had a duty of "inspection and monitoring of a nature that would have uncovered the defective conditions."[26]

As *Cann* demonstrates, the duty of the design professional to discover defects through inspection or observation, even with the use of the AIA language, may in some cases depend more on the facts than on the contract language. Nonetheless, the contractual language serves an important purpose by qualifying the architect's role as one in which the architect is not a guarantor of the contractor's work as it progresses.

In the recent Alabama Supreme Court case of *Watson, Watson, Rutland/Architects, Inc. v. Montgomery County Board of Education,*[27] the local school board sued the architect involved in the construction of a junior high school when the roof leaked, causing property damage. The "inspection" clause of the architect's contract was, in material respects, the same as the AIA standard form, requiring "periodic visits to the site" and familiarity "with the progress and quality of the Work . . . to determine in general if the Work is proceeding in accordance with the Contract Documents."[28] In addition, the contract, again in conformance with the AIA form, provided that the architect would "not be required to make continuous on-site inspections to check the quality of the Work."[29] The architect performed inspections but did not discover any problem with the roof of the structure. After project completion, the roof leaked, and the school board sued the architect for failing to discover an obvious deviation from the plans and specifications by the contractor. The jury returned a verdict in favor of the school board. However, the Alabama Supreme Court reversed, holding that the contract required only "reasonable inspections."[30] While the court recognized that the architect had a duty "to notify the owner of a known defect," there was no evidence in *Watson* that the architect knew of the contractor's deviation or the defect in the roof.[31] The court ultimately reversed the trial court's judgment, entering judgment in favor of the architect because of the school board's failure to present expert testimony as to whether the architect should have conducted an inspection that would have discovered the defect.[32] Implicit in the court's ruling in *Watson* is the notion that the contract documents only imposed a general duty on the architect to inspect and/or to observe, not an obligation to make continuous on-site inspections or to serve some more significant purpose on behalf of the owner school board.

Based on the various sources of architectural liability, many contractors attempt to minimize their own liability by blaming the construction failure on the architect's failure to inspect and to note the defect in construction. However, the architect's failure to inspect and/or to observe a construction defect, while a source of architectural liability, is not a defense to the contractor, whose duty it is to build in accordance with plans and specifications regardless of whether the architect noted construction defects through inspection.

For example, it is not uncommon for an injured third party to sue both the contractor and the design professional, as well as the owner and other parties, when a construction failure causes personal injuries. In *Heath v. Huth Engineers, Inc.,*[33] the administratrix on behalf of the decedent's estate brought wrongful death and survival actions against the sewer authority owner, the engineering firm, and the sewer contractor for the same injury. The decedent, an employee of the contractor, was killed when the trench in which he was working collapsed. The trench was not properly braced or shored against

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[21] See, e.g., *Heath v. Huth Eng'rs, Inc.*, 279 Pa. Super. 90, 420 A.2d 758, 759 (1980) (engineering firm liable to decedent third party for, *inter alia*, negligently failing to inspect the work properly).

[22] *See* AIA Standard Form Agreement Section 2.65.

[23] 503 F. Supp. 419 (N.D. Ohio 1980), *aff'd*, 669 F.2d 415 (6th Cir. 1982).

[24] *Id.* at 436.

[25] *Id.*

[26] *Id.* at 437.

[27] 559 So. 2d 168 (Ala. 1990) [hereinafter "*Watson*"].

[28] *Id.* at 170.

[29] *Id.*

[30] *Id.* at 173.

[31] *Id* at 174.

[32] *Id.*

[33] 279 Pa. Super. 90, 420 A.2d 758.

collapse, in violation of both federal and state safety laws. Among other successful theories, the plaintiff argued that the engineer failed to supervise the work in a proper fashion and assist in safeguarding the owner against defects and deficiencies on the part of the contractor.[34] Although the issue was not even raised, it is obvious that the contractor in *Heath* could not rely on the architect's negligent failure to inspect as a defense against his own liability for defective construction. Moreover, it appears that the $205,000.00 jury verdict was, in fact, a judgment against the three defendants jointly and severally.[35]

Architect's Certificates

Contractors doing substantial projects are paid periodically according to the percentage of work complete. Often a precondition of payment is the architect's certification (that is, a sworn statement) that the work has been completed to a certain percentage "in accordance with the contract documents" or "in accordance with applicable plans and specifications." The design professional who signs such a certification arguably may be guaranteeing the quality of the contractor's work by certifying that the contractor's work conforms to the contract documents. At a minimum, the design professional who issues a certificate to the effect that the work conforms to the contract documents should exercise reasonable care in making such a representation. For example, in *General Trading Corp. v. Burnup & Sims, Inc.*,[36] the United States Court of Appeals for the Third Circuit held that the standards of reasonable care which apply to other professionals apply to an architect "to whom an owner has entrusted certification of work for progress payments."[37]

Whether an architect's duty in this regard differs to any extent from his duty to discover defects that he observed or should have observed will depend on the contract language governing the contractor's administrative and supervisory responsibilities and his certification responsibilities. The AIA standard form provides that "[t]he Architect's certification for payment shall constitute a representation to the Owner, based on the Architect's observations at the site . . ., that the Work has progressed to the point indicated and that, to the best of the Architect's knowledge, information and belief, quality of the Work is in accordance with the Contract Documents."[38] Insofar as this provision incorporates by reference the AIA "inspection" provision requiring on-site "observations," it is unlikely that the architect's certification duty is meant to expand the architect's duty to observe construction defects, apart from the percentage of the work completed. Indeed, while the AIA form describes the issuance of the architect's certificate as a representation that the contractor is due payment in the amount certified, the same paragraph states that the architect does not represent that he has made exhaustive on-site inspections to check the quality or quantity of the work or that he has reviewed the "construction means, methods, techniques, sequences, or procedures."[39]

Thus, while an architect may be liable for "overcertification" in terms of the percentage of the work completed,[40] he only promises that to the best of his knowledge, information, and belief, the quality of the work conforms to the contract documents. Such a standard does not appear different than the previously discussed duty of observation.

The Parameters of Exposure: Owner Responsibility

In any construction failure dispute, the owner is likely to argue that it hired a design professional to design and a contractor to construct, so that if anything goes wrong with the job, it must be the responsibility of one or the other. That perspective ignores the sources of owner liability in construction failure cases.[41] A construction failure can result from the owner's failure to maintain a project. Thus, an owner cannot complain of leaks in his building if the leaks result from the owner's failure, for example, to caulk joints or repair roof shingles. Similarly, if an owner modifies existing construction in a way that causes the construction failure, the owner may be responsible.[42] For example, the owner that removes structural bracing cannot blame the contractor or design professional for the deck collapse that results.

THE CASE STUDY: CLAIM ANALYSIS DISPUTE RESOLUTION AND TRIAL

Introduction and Review

A construction failure is an event in which the physical construction does not do what it was supposed to do. The rules that govern the resolution of these disputes are usually fairly straightforward. Absent contract provisions to the contrary, the contractor has fulfilled his obligations for construction when he has provided the scope of his work fully in accordance with the contract documents. A contractor may also be liable under the rather narrow circumstances of (1) failing to warn of a known defect, (2) the explicit assumption of design responsibility, or (3) contract terms wherein the contractor

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[34] See *id.* at 759.

[35] *See id. See also Palmer v. Brown*, 127 Cal. App. 2d 44, 273 P.2d 306, 317 (1954) (contractor and architect may be concurrently negligent for owner's damages in case where architect undertook duty to supervise the work).

[36] 523 F.2d 98 (3d Cir. 1975).

[37] *Id.* at 101.

[38] AIA Standard Form Section 2.6.10.

[39] *Id.*

[40] *See, e.g., Browning v. Maurice P. Levien & Co.*, 44 N.C. App. 701, 262 S.E.2d 355, 358 (1980) (surety's architect, whose duties included inspection of the construction at the time of each progress payment, could be held liable to the owner for negligent overcertification of payments).

[41] *See, e.g., Jarcho Bros., Inc. v. State*, 179 Misc. 795, 39 N.Y.S.2d 867 (1943) (duty to disclose superior knowledge of material matters regarding the contract, which were unknown to or not readily available to the contractor); *Housing Auth. of Dallas v. Hubbell*, 325 S.W.2d 880 (Tex. Civ. App. 1959) (duty to cooperate); *Natkin & Co. v. George A. Fuller Co.*, 347 F. Supp. 17 (W.D. Mo. 1972) (duty not to impede, hinder or interfere with the work); *Bates & Rogers Constr. Corp. v. North Shore Sanitary Dist.*, 92 Ill. App.3d 90, 414 N.E.2d 1274 (1980) (owner impliedly warrants that the plans and specifications it furnishes for the job will enable the contractor to perform the work successfully).

[42] *See, e.g., Cincinnati Riverfront Coliseum v. McNulty Co.*, 28 Ohio St. 3d 333, 504 N.E.2d 415, 419 (1986) (issue of fact for jury as to whether the city's modifications and alterations in the design of a walkway or alleged defects in design caused deterioration of walkway and damages incurred by owner coliseum).

warrants the performance characteristics of the work. But even in those exceptional cases, the "rules of the road" are not complicated and usually quite predictable.

The designer, whether an architect or engineer, has a duty to exercise reasonable care in designing the project (including the depiction of the work in the plans and the description of the work in the specifications). In most jurisdictions, the designer warrants, at least to the party with whom he contracted, that his design will work (that is, that the construction will appear and perform as intended).

However, application of these rules to an actual construction failure can be another matter altogether. Liability in a construction failure case is determined by inference. The issue is always: from the failure, the accounts of the failure, and the construction documentation during construction, what can be inferred regarding whether the contractor complied with the applicable plans and specifications? If the evidence supports the view that the contractor complied with plans and specifications, poor design usually can be inferred to the same extent. Thus, fact gathering and effective presentation of the evidence regarding a construction failure often determines the outcome of these disputes. This chapter is a practical guide for contractors, design professionals, and construction owners through the litigation of a typical construction failure, emphasizing the critical issues which often are the difference between winning and losing.

For uniformity of reference, this chapter uses the following case study as an example of a significant construction failure dispute involving water. The facts and events cited are based on an actual construction failure dispute that was litigated through trial before three arbitrators sitting in South Carolina.[43]

The Case Study: Mold and Mildew Contamination

In 1984, Our Way Development ("owner") purchased an ocean-front site in Turtle Beach, South Carolina. Shortly thereafter the developer hired Martian Design ("architect") to design a 16-story, ocean-front hotel complete with parking garage, pools, restaurants, conference rooms, and 300 guest rooms.

The owner specified several design elements including accessible balconies for each guest room, but also wanted the lowest construction cost design that could be utilized consistent with this hotel competing as a first class facility in Turtle Beach.

Martian was hired pursuant to a contractual requirement to provide "observation" of construction only on an "as needed" basis as requested by the owner. Design revisions and shop drawing review were similarly to be done "as requested."

Thereafter the architect designed a 16-story hotel with enclosed corridors and balconies serviced by glass sliding doors for each guest room. As initially designed, the exterior of the structure was to be stucco clad. Of particular relevance here was the design of the HVAC systems, which specified through-the-wall heating and cooling units for each guest room, and centralized HVAC systems for the corridors and lower floors of the hotel (common areas).

During the summer of 1985, the project was let for bid to a select list of contractors. Almost solely for reasons of its low bid, Maverick Construction ("contractor") was awarded the contract for general construction. Maverick's price was further reduced after the owner approved post-tension concrete floors as a substitute for metal deck under poured-in-place concrete. The owner further approved substitution of EIFS exterior skin in lieu of standard masonry and stucco cladding.

The architect was not consulted regarding either cost-cutting substitutions and provided no input into the two changes.

The project was constructed during the period September 1985 through August 1986. In January 1986 the contractor approached the owner for an extension of time due to various delays, including design changes, adverse weather, and delays in issuance of building permits. According to the contractor, an extension was necessary so that the exterior could be closed in and weather-proofed prior to installation of interior dry wall partitions. The owner, however, anxious to see its hotel open, refused any extension, and the contractor went ahead with dry wall erection before the building was weather tight.

In March and again in April the building was inundated with heavy rains. Much of the interior dry wall erected through Floor 13 (out of 16) was saturated. Of great concern to all was that by April, mold and mildew started to appear throughout several areas of installed dry wall.

At that point the architect recommended that all dry wall be demolished and replaced. However, the contractor, the insured for this damage, as well as the owner (still anxious to get his hotel open), all opted for a less severe remedy. It was decided that while some drywall would be replaced, much of the drywall that exhibited only minor discoloration would be painted with a "water proof" coating, designed to seal in any residual moisture, as well as any mold and mildew.

These repairs were expedited, the hotel was completed, and in October of 1986 the hotel was opened for business.

Almost immediately, mold and mildew began to appear on lampshades and bed linens, etc. However, by early Summer 1987, mold and mildew spotting started to appear behind the vinyl wallpaper. As the summer wore on, it was clear that the major problem was the mold and mildew behind the vinyl wallpaper at the room partitions. Unfortunately, as it appeared the problem was widespread, there was a real possibility that every interior partition in the hotel would have to be replaced.

At that point the owner hired a distinguished outside consultant, A.B.C. & Associates (the "owner's consultant") to evaluate the problems experienced at the hotel. Several weeks of investigations followed, including extensive testing for water leaks. That testing confirmed that the building leaked extensively, and the owner's consultant ordered an engineering review effort of the exterior building skin. Meanwhile, and only as a temporary measure, most of the interior partition wallpaper in the hotel was replaced.

In the summer of 1987, A.B.C. and Associates issued their "preliminary" report. It documented extensive water leaking in the building, but specifically declined to access responsibility between the contractor and the architect.

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[43] The names of the participants have been changed as a courtesy to the losing parties and experts.

During the winter of 1987–88, the owner replaced the entire exterior skin of the building, presumably to correct the leak problem. However, extensive leak testing of the new building skin was not done.

Also during the winter of 1987–88, the owner's consultant did extensive observation of the building's HVAC systems. There was a centralized system to condition air in the lobby, restaurant, and other public areas at the lower floors. Similarly, the corridors were centrally controlled, but each guest room had its own individually controlled through-the-wall heating and air-conditioning unit. For reasons that will be more fully developed below, the owner's consultant concluded that while poor construction by the contractor also contributed to the mold and mildew condition, most of the problem was caused by the infiltration of moist air because defects in the design of the HVAC systems resulted in the building's operation under severe negative pressure.

Accordingly, in the Spring of 1988 the owner demanded arbitration against the contractor and architect. Unfortunately for the owner, however, because of a prohibition on consolidated arbitrations in the owner-architect agreement, the arbitrations were not consolidated. And because the owner's consultant insisted that the HVAC design was the primary cause of the mold and mildew problem, the owner proceeded first with its arbitration against the architect.

Preparation of the Claim or Defense

Establishing Goals

In construction failure disputes, the contentions of the parties are usually quite predictable. The owner contends that he hired an architect to design and a contractor to construct, and one of the two must be responsible for the failure. The contractor contends that the failure resulted from poor design, while the architect contends that the contractor failed to comply with the applicable contract documents. Typically, both the contractor and designer may also contend that the failure resulted from or was aggravated by the owner's lack of maintenance (as in the case of construction completed for some time) or directives of the owner regarding design or construction.

Investigating the Facts

Given the contentions of the parties, the issues to be investigated are almost always the same: Was the design adequate? Did the contractor comply with plans and specifications?

Investigation of these issues involves at least the following sub-issues:

1. Design issues
   a. Is there anything on the face of the design that is obviously deficient (for example, incorrect structural calculations or math errors in the HVAC requirements analysis)?
   b. Did the physical construction failure manifest a design error (e.g., a buckled beam or imploded glass)?
   c. Has this design performed appropriately elsewhere under similar circumstances?
   d. Following the failure, has the project been repaired or rebuilt according to the original plans and specifications? If so, how is the new construction functioning? If not so rebuilt, why was the design changed?
2. Construction issues
   a. Did the construction failure physically manifest poor workmanship or a deviation from applicable contract requirements?
   b. What is the written record (i.e., inspection reports, punch lists, job conference reports, correspondence) of the contractor's performance? Is there any contemporaneous documentation of the uncorrected deviations from the contract documents?

With these questions in mind, several steps are appropriate when the owner, contractor, or Designer learns of a construction failure.

First, appropriate counsel should be contacted for direction regarding an immediate investigation. A party involved with a construction failure should have the ability to make an appropriate investigation that is not necessarily subject to pre-trial disclosure by its adversaries in subsequent litigation. Unfortunately, such investigations are probably discoverable unless protected by the attorney-client or attorney work product privilege. Obviously, those privileges cannot exist if counsel has not been retained or is not overseeing the investigation.

Second, where applicable, insurance carriers should be placed on notice and all insurance contract procedures followed.

Third, the designer should put his appropriate consultants on notice of the failure and that he intends to hold those parties liable if it appears that their work contributed to the failure.

Fourth, a site investigation, as thorough as possible, should be made, recording in detail all physical observations. It is important at this preliminary investigative stage not to record any opinions regarding the probable cause of failure. Invariably, experts will be hired to formulate their own opinions and conclusions. Under those circumstances, a report in the owner's, Designer's, or contractor's files which (even if favorable) is inconsistent with the theory of the failure subsequently developed by that party's expert can undermine the expert's credibility and jeopardize the party's chances of prevailing on the issue of liability.

Fifth, when possible, anything that appears to be relevant demonstrative evidence should be gathered. This usually means taking photographs, but it can also involve, for example, gathering pieces of a failed waterproof membrane, samples of failed concrete, or the saturated insulation under a leaking roof.

Sixth, the available job correspondence should be gathered and organized, with particular emphasis on the part of the construction that failed. Obviously, if the dispute involves a roof collapse, the inspection reports, punch lists, and job conference reports which relate to the construction of the roof are the relevant records.

Seventh, the individuals who participated in the design, construction, acceptance, or maintenance of the failed construction should be located and interviewed. This is usually done through counsel. Of course, the contractor or designer accused of faulty construction or poor design cannot expect voluntary interviews from the employees of the owner and other potential adversaries. Nor will the contractor volunteer its own employees for pre-litigation interrogation. Nevertheless, most projects also involve third parties (such as state and local inspecting agencies, subcontractors, suppliers, and ex-employees of one's adversaries) who, if cooperative, can provide important and objective information regarding the events of design or construction.

Eighth, with the foregoing information gathered and reviewed, the party, its counsel, and experts must, if possible, construct a theory of the case which is consistent with all of the objective evidence. For example, if the dispute involves the delaminating of wall covering, one possible theory supporting a contention of defective design may be that the covering system is defective because it delaminates in high humidity conditions. However, that theory cannot support a finding of liability for the particular failure in issue unless it can also be demonstrated that conditions of high humidity existed at the construction site.

Or, for example, an owner may contend that the cracking and settling of a concrete slab resulted from insufficient thickness. This contention can be difficult to sustain, however, if there is no correlation between slab thickness and the point where the slab failed. Similarly, if an owner claims that shoddy workmanship caused a construction failure, it will be important for the owner to correlate specific workmen who performed deficiently to particular areas of the failed construction.

The Case Study

The factual investigation that preceded arbitration was similarly slanted in favor of the owner, who had total control over the site. Specifically, the owner allowed the architect limited site access and only under the watchful eye of the owner's consultant.

Thus, the owner was able to document first-hand several facts and phenomenon, which supported its "negative pressure" theory. Among them were the following:

1. During all seasons, opening the individual room balcony doors resulted in a rush of air inward.
2. At times, at the lower floors, doors connected to the building exterior were difficult to open because of inward air pressure.
3. The mildew contamination was pervasive throughout the building, particularly near the HVAC through-the-wall units.
4. There was some lesser mildew damages in upper floors where the negative pressure was theoretically lowest.
5. The HVAC through-the-wall units introduced less outside air into the room than the bathroom fans exhausted.

All of these factors, the owner argued, demonstrated conclusively that the mold and mildew was caused by the operation of a poorly designed HVAC system.

The architect, of course, contended that leaks due to faulty construction caused the mold and mildew problem. And, to rebut the foregoing factors, the architect was able to show:

1. The influx of air through balcony doors was explainable in any room that fronts on the Atlantic Ocean.
2. The severe negative pressure at the lower floors could be tied to the hotel's failure to operate the return air system in the kitchen at the very times that the owner's consultant was making its investigations. That, not the operation of the through-the-wall units, resulted in the negative pressure at the hotel's lower floors.
3. While the mold and mildew was pervasive throughout the building, the owner's consultant's preliminary report showed that water leaking in the building was similarly pervasive.
4. While there was less mold and mildew at the upper floors, it was precisely these areas that were not saturated during construction before the building was closed in, because these floors were not yet constructed.
5. Finally, while the HVAC through-the-wall unit as designed did theoretically take in less air than the bathroom fan exhausted, in reality, the two systems actually operated in equilibrium.

Thus, in each case the architect was able to counter the owner's factors with a logical contrary explanation that was consistent with the architect's theory of the case.

Meanwhile, the architect was able to develop its own empirical evidence which tended to undermine the owner's theory of negative pressure as the cause for mold and mildew as follows:

1. The areas of the rooms nearest the core of the building and where there was likely to be the greatest amount of moist air (i.e., the bathrooms) evidenced almost no signs of mildew contamination.
2. The primary mold and mildew problem was not in the rooms but in the partition walls; it was the mold and mildew behind the wallpaper that created the repair problem. In fact, the HVAC system had almost nothing to do with the air within the partition wall. Water leaking into those walls from outside was the only logical explanation.
3. Areas where the leaks were thoroughly repaired did not have any significant reoccurrence of mold and mildew.

What all of the foregoing indicates is that in construction failure cases, the pattern of failure can be critical in successfully litigating these cases. Each side must find an explanation for every observed phenomenon which is consistent with his theory of the failure. The party who can best match the pattern of failure with his theory of failure will almost always prevail.

Contract Review

In the initial stages of a construction failure dispute, a thorough contract review should be undertaken.

A contractor is responsible for the performance of construction under a performance specification. A performance specification usually describes the construction and also requires the finished construction to perform in a certain way. Although the contractor builds to the specified work description, he is nevertheless liable if the work does not perform according to the specified performance criteria.

A construction failure attributable to the work's failure to perform as required in the specification will result in contractor liability. Under such circumstances, the contractor's defensive options are limited. First, he should consider whether the failure is actually the result of not meeting performance characteristics. Thus, for example, the contractor who warrants that a roof will not leak does not necessarily warrant its structural integrity.

Second, the contractor should examine whether the specification was performable as written. This defense may be viable if the physical description of the work in the specifications renders the performance criteria impossible to attain. For example, if a beam is specified as resistive to a 10-ton load with a 1.25-in. (3.17-cm) deflection over 10 ft (3.05 m), but the descriptive specification limits the materials to untempered steel of a thickness of no greater than 0.5 in. (1.27 cm), the performance requirements may be rendered unattainable by the specification description. This defense of impossibility of performance is often raised and, almost as often, fails because the impossibility must be objective (that is, impossible for anyone to perform, not just this particular contractor), not merely economically burdensome.

The contractor's third option is to attempt to share liability with the designer who drafted the specifications, and who may have written an inadequate specification, so that the costs of repair are shared between contractor and designer. The unusual situation of designer liability for the contractor's deviation from the specifications is likely to occur, if at all, in the context of the designer's inspection of defective work that goes unnoticed or ignored. Most contracts provide that such inspections do not waive claims against the contractor for defective work. Nevertheless, those provisions do not necessarily relieve the designer who is negligent in his inspection of deficient construction.

The Case Study

In the case study the owner argued that the architect was responsible not only for the poor design of the HVAC systems, but the contractor's poor performance as well. According to the owner, the architect had a duty to inspect the work and sign detailed certificates of completion which were the basis for payment to the contractor. Under either theory, argued the owner, the architect should bear liability for defective construction, which in that case was a leaky building.

Because the architect-owner agreement was a modified version of a standard American Institute of Architects (AIA) form of architect-owner agreement, the architect was able to raise several legitimate defenses to the owner's legal theory.

First, the architect correctly asserted that under its contract with the owner, it was to provide construction administration only as and to the extent requested by the owner. In that case the owner had only requested sporadic and walk-through type inspections.

Second, the architect was required, based on his periodic visits, to:

> Keep the [owner] informed of the progress and quality of the work, and shall endeavor to guard the [owner] against defects and deficiencies in the work of the contractor.

The owner relied heavily for his argument on this language.

Nevertheless, the same contract provision also stated that the architect was not required to make "exhaustive" or "continuous" on-site inspections and was to become only "generally familiar" with the work. Moreover the architect-owner agreement contained the following typical AIA provision:

> The architect shall not have control or charge of and shall not be responsible for construction means, methods, techniques, sequences, or procedures, or for safety precautions and programs in connection with the work, or for the failure of any of them to carry out the work in accordance with the Contract Documents.

This provision combined with the owner's expert witness agreeing that this was a standard contract provision that should be read literally, severely undermined the owner's contention that the architect should be responsible for the contractor's poor performance.

The Construction Failure Trail

Introduction

Even after a thorough case preparation and the marshalling of provable facts and events to support one's position, understanding the unique considerations common in most construction failure trials often means the difference between winning and losing. The purpose of this section is to identify those critical issues at trial and suggest how they can best be addressed.

Proving Failure to Comply with Plans and Specifications

A contractor is liable when he fails to follow the contract documents if that breach of contract causes the failure. Stated conversely, a contractor who complies with plans and specifications is generally not liable for a construction failure. But who has the burden of proof to demonstrate compliance with plans and specifications or lack thereof? Is it the plaintiff-owner who must prove breach of contract or the defendant-contractor who must establish the defense of compliance with plans and specifications?

Similarly, where an architect is sued for faulty design, is it sufficient for the owner to simply demonstrate the construction failure or must the owner also prove that the contractor built in accordance with the contract documents drafted by the architect?

The resolution of this issue often can determine the outcome of a construction failure case. Typically, the failure is obvious: the bridge collapses, the glass cracks, the roof leaks. But the reconstruction of the construction process, which could have predated the failure by years, is often quite arduous and can result in a trial record that is ambiguous at best as to the contractor's compliance with the contract documents.

At the end of a trial against a contractor, if the owner has the burden of proof, the inconclusive record will result in a finding of no contractor liability. But if the burden of proof is on the contractor to support his defense of contract compliance, the inconclusive record will result in his liability. Similarly, in the owner-architect trial, if the owner need only prove the failure, without proving the contractor's compliance with applicable plans and specifications, this greatly increases the chances that the owner will prevail.

It is the author's view that the owner as plaintiff should have the burden of proving the contractor's specific failures to comply with the applicable contract documents. Theoretically, every construction failure can result from either faulty construction, inadequate design, improper maintenance, or an act of God. It would be unduly burdensome to the contractor to impose liability on him long after a job is finished, regardless of the owner's proof, simply because he was unable to reconstruct the construction process sufficiently to demonstrate contract compliance. Most of the cases which have decided this issue support that view.[44]

The Case Study

The thrust of the owner's case against the architect was the contention that the operation of through-the-wall individually controlled HVAC room units, in combination with an excess exhaust capacity created by continuously operating ceiling exhaust units, caused a negative pressure in each guest room. This, the owner argued, caused an influx of humid air, bringing moisture into the building which ultimately caused the mold and mildew problems.

The owner sought to prove its case by presenting a local Turtle Beach mechanical engineer who testified that the HVAC design was faulty and should have provided for a building with "slightly positive pressure." The owner also presented representatives of A.B.C. & Associates to opine that the influx of "moist" air caused directly the mold and mildew in dispute. These opinions were bolstered by various charts purporting to show patterns of mold and mildew in the exterior walls where the through-the-wall HVAC units were located.

The architect's response was several fold. First, regarding the alleged poor design, even the owner's witnesses conceded that individually controlled, through-the-wall HVAC units are the accepted method in the design and construction industry for a hotel facility of this sort. So, too, were the type of continuously operating internal bathroom exhaust systems.

Second, while the owner had presented a significant amount of anecdotal information about instances of negative pressure, the objective evidence suggested otherwise. The exhaust fans, in practice, tended to operate in equilibrium with the wall units, creating no "negative pressure." Any influx of air when unit balcony doors were opened was more likely caused by a gentle breeze off the Atlantic Ocean than negative pressure. And a severe negative pressure at the hotel's lower floors was demonstrated to have resulted from the owner's failure to operate the make up air system to compensate for the kitchen exhaust. In short, there was significant doubt that the negative pressure situation, on which the owner's claim was based, even existed.

Third, upon close examination, a thorough survey of the pattern of mold and mildew suggested strongly that the condition resulted from water leaks (a construction problem not resulting from poor design). While it was true that there was a pattern of mold and mildew around the HVAC units, the units were located in the exterior walls where there was also extensive rainwater leaking. Also, the worst mold and mildew growth was within the partition areas, where rainwater leaking was considerable and which cavities had virtually no connection to the HVAC units. Moreover, in almost every case, the further away an area was from areas of leaks, the less mold and mildew developed.

All of this suggested strongly that the mold and mildew at this hotel was caused by rainwater leaking that occurred during and after construction.

The Reconstructed Project: The Proverbial "Exhibit No. 1"

The axiom that a picture is worth a thousand words is particularly true when a failed construction has been rebuilt. If the project has been reconstructed totally in accordance with the original design, subjected to the same conditions as the construction that failed, and holds up, that very strongly suggests that something other than poor design, probably poor construction, caused the original failure. Conversely, if the new construction involves a substantial upgrading in the design criteria, then one can often infer that the original design was inadequate and needed upgrading. Of course, if the new construction fails in the same way after monitored compliance with the contract documents, the owner probably need not bother suing the original contractor for failing to comply with plans and specifications.

Accordingly, if a project has been reconstructed after a failure, it is critical that the parties in the dispute thoroughly understand the criteria for the new construction and thoroughly investigate the performance of the reconstruction.

The Case Study

At the time of trial the owner of the Hotel had not gone ahead with a major repair effort. Nevertheless, several factors relating to the interim repairs and hotel operation combined strongly to undermine the allegations that design defects resulted in mold and mildew contamination.

First, the arbitration of the case against the architect was heard at the hotel that was the subject of dispute. The arbitrators who heard the case stayed at the hotel. From their exposure to the project, still using the allegedly defective through-the-wall HVAC units, the arbitrators could see first-hand that the units had good capacity to dehumidify, cool, and regulate room conditions without causing significant "negative pressure" zones. It is true that the owner contended that interim modifications in the HVAC exhaust systems allowed the systems to operate satisfactorily. However, it was simply not credible that the modifications implemented could have had any significant effect on the alleged negative pressure problems.

Second, the owner did provide a mock-up of what the owner said was a system of two rooms as designed. According to the owner, the mock-up duplicated the mold and mildew problem that was the subject of the dispute. It was true that in those rooms using the specified through-the-wall units, mold and mildew did form. However, several anomalies in the testing methods and defects in the mock-up combined to totally undermine its persuasiveness.

The owner sealed off the room from outside circulation, which was not in accordance with the original design intent. The HVAC units used were found to have mechanical problems causing them not to dehumidify. And finally, the moni-

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[44] *See, e.g., Baldwin-Lima Hamilton Corp. v. United States*, 434 F.2d 1371 (Ct. Cl. 1970); *Roberts v. United States Great Am. Co.*, 357 F.2d 938, 949 (Ct. Cl. 1966).

tored data, taken from continuous readings by monitoring equipment, were so anomalous that either the data was totally unreliable or the owner's experts tampered with the data to fabricate the intended result. In short, the owner's botched mock-up did not support the owner's position and undermined the owner's credibility.

Finally, at the third floor where mold and mildew contamination had been most severe, the owner had made a general repair effort which was completed a year before arbitration. That area was then subject to the same conditions which the owner contended caused negative pressure and contaminated the hotel. Yet, the same area showed no signs of renewed mold and mildew contamination. This fact strongly supported the architect's contention that the original mold and mildew problem was caused by rainwater leaks, and once the leaks stopped, so too the mold and mildew stopped.

Special Considerations for the Designer

A designer of original construction should carefully consider a recommendation for reconstruction of a failed job. If he suggests following the same design and the reconstruction fails, he has helped to prove his own liability for both failures. If he advocates a new design, he impliedly admits that there were deficiencies in the original design.

The Appropriate Use of Inspection Reports

Most construction projects involve some type of periodic inspection to verify the percentage of completion and to monitor whether the work is being constructed in accordance with the contract documents. If written records of such inspection are kept, they provide a valuable reference in the event of a subsequent failure.

Such records rarely note deficiencies in construction that have gone uncorrected. Usually, it is the inspector's job not only to note construction problems but to see to their correction. Accordingly, inspectors rarely note problems without also seeing that they are rectified. Also, even in the heat of litigation, inspectors, anxious to minimize their own culpability, will usually claim that they did a good job of inspection and noted no deficiencies that remained uncorrected. The question becomes, therefore, how best to utilize such evidence.

Many contractor-litigants forward the waiver defense, contending that by inspecting and accepting the work, the owner's representative (the inspector) observed and accepted the defective work, thereby waiving the claims which are the subject of the litigation. Generally, however, this is a very risky and rarely successful tactic.

First, most construction contracts provide that the inspectors have no authority to accept defective work or that inspection and approval is not acceptance of defective work. Thus, under such contractual schemes, the waiver defense fails as a matter of law.

Second, the waiver defense actually assumes that the work installed was defective. Indeed, how can an inspector waive defective work unless it was in fact defective? Thus, in asserting the defense, the contractor may effectively prove that his installation was defective—precisely the opposite of what he intends.

For the contractor, a far more effective approach to favorable inspection reports is to introduce them, not to show waiver, but to demonstrate that the work as originally constructed complied in every possible way with the applicable contract documents.

The Case Study

Most architects will say that they are not liable for "inspections" of defective work because, under standard AIA documents, they merely "observe" the work. Nevertheless, an architect who observes defective work and does nothing about it exposes himself to liability. Such architect liability, however, does not relieve the contractor of his liability if he fails to comply with plans and specifications.

In the case of the hotel mold and mildew contamination and the architect's contention that rainwater leaks were the cause, the owner also argued that the architect, who had inspection duties, also should have done more to protect the owner from construction defects resulting in water leaks.

The problem with this argument for the owner was the contract documents on which he relied. This was not a job in which the architect was obligated to make detailed inspections. Rather, as the owner's expert witnesses all admitted, the applicable contract documents called only for "observation" as and when requested by the owner and provided that the architect was not responsible for the contractor's failure to build according to the applicable plans and specifications.

The Contractor's Duty to Warn

Particularly when it appears that the contractor has complied with the applicable contract documents, an owner seeking to establish the contractor's liability may attempt one of several alternative theories. The most common is the contention by an owner that even if faulty design caused the construction failure, the contractor breached his "duty to warn" the owner of the defect in design. Although this contention seems to place responsibility for defective design exactly where it ought not to be, some authority supports the view that a contractor does have a duty to warn an owner of defects of which he knows or has reason to know.[45]

Properly applied, however, this rule of law should never result in the liability of a contractor who has exercised even minimal diligence. In practice, the rule requires only that the contractor may not proceed with construction and remain silent even when he knows or has good reason to know that the design is deficient. This is a particularly vital public safeguard because it is the using public who often are victims of failed construction. The contractor has no affirmative duty to professionally investigate the design or redesign of the proposed construction. His only duty is to warn of what is obvious or should be obvious.

Owners who wish to establish contractor liability for failing to warn are usually unsuccessful. Moreover, it is a defense which should never be set forth by the design professional. When the owner raises the contractor's duty to warn of a

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[45] *See Beacon Constr. Co. v. United States*, 314 F.2d 501 (Ct. Cl. 1963) (a contractor must correct at his cost all patent errors in the contract documents which he did not bring to the attention of the owner before bid); *Berg v. United States*, 455 F.2d 1037 (Ct. Cl. 1971) (same); *Ridley Inv. Co. v. Croll*, 56 Del. 208, 192 A.2d 925 (1963) (if the contractor warns the owner of a defect and the owner directs the contractor to proceed, the contractor cannot be liable to the owner); *Glass v. Wiesner*, 172 Kan. 133, 238 P.2d 712 (1951) (same).

known defect, he effectively concedes the issue of faulty design—a concession which will help the contractor's own contention that the problem is one of design and not faulty construction. Similarly, it would be ridiculous for the design professional to raise this defense, because in doing so he concedes his own poor design and, at best, will share responsibility for the construction failure. Even if a contractor is liable for failing to warn of a poor design, the designer remains liable for that deficient design.

Poor Workmanship Versus Contract Compliance

In addition to his duty to comply with the contract documents, the contractor also has a duty implied in every construction contract to prosecute his work in a good and workmanlike manner. Thus, the nails must be driven straight; the shingles must be aligned; the welds must be clean and complete; the trim must be plum and fitted; the paint must be applied uniformly. These and other elements of construction are not likely to be specifically described in contract specifications.

A problem arises, however, when applicable specifications describe work procedures which are not in accordance with industry standards of good workmanship. For example, if a contract specifies 24-h concrete curing and the standard industry practice is 72-h curing, what is the contractor's obligation? Or when industry practice for stain-resistant floor sealant is application of three coats, has a contractor complied with his obligation of good workmanship when he follows specifications that require only one coating?

The case authority on this issue is very limited. It is the author's view that the contractor's duty of good workmanship must be reconciled consistently with the explicit requirements of the contract documents. The duty should not transcend the explicit obligations of the contract documents. Thus, in the curing example, if the specifications require 24-h curing, the contractor is required only to do just that. Similarly, referring to the second example, if the contractor provides one coat of sealant, he has fulfilled his obligations for that project. Any other standard would impose upon the contractor the unreasonable burden of second-guessing every detailed specification he sees.

However, if the contractor has reason to know that a specified construction practice will fail, then he probably has a duty to warn the appropriate parties of the potential for failure, but not to upgrade the specification on his own.

The Case Study

In any construction failure controversy where water leaks in finished construction are in dispute, the issue of poor workmanship is likely to be a major issue. Was roof shingle installed according to industry standards? Was the flashing installed according to accepted procedures? Was caulking done properly? At the same time, where the contractor is a party, he will likely scrutinize contract requirements for roofing and exterior cladding to suggest that he was responsible for nothing not specifically required in applicable specifications.

In the mold and mildew litigation where the contractor was not a party, it was the owner who contended that the project specifications provided inadequate detail for the exterior cladding for the building, which utilized an EIFS system. The architect responded as follows.

First, the original design called for stucco-clad structure. It was the contractor who suggested the EIFS system to effect a substantial cost reduction. The owner agreed to that substitution without consulting or otherwise involving the architect.

Second, while the architect wrote no specification for installation of the EIFS system, the architect did require that the EIFS system be installed according to the standard specification of the EIFS system manufacturer. This was found adequate by the arbitrators.

Proving Deficient Design

The party seeking to prove poor design and the designer seeking to demonstrate the adequacy of the design usually agree that the construction failed. The issue then is: Why did the construction fail? If the construction as specified can be duplicated and subjected to the conditions at the time of failure, the performance of the construction can establish almost conclusively the adequacy or inadequacy of the original design. Indeed, from that model, the alleged deviation from the specifications by the contractor can also be duplicated, and if the construction failure is repeated, that subsequent failure can be compelling evidence of the contractor's failure to comply with the applicable contract documents originally. A reconstructed project often provides just such a model if the original plans and specifications were followed for the reconstruction.

Because the model can be such compelling evidence, the risks of setting up a model may be substantial. For example, if the contractor sets up a model to demonstrate poor design, but the model performs perfectly, the contractor thereby proves that the cause of the failure was something other than poor design, usually the contractor's deviation from the contract documents. Similarly, the designer who insists on reconstruction according to the original specifications does much to undermine the owner's case against the original contractor and inculpate himself if the subsequent construction fails.

Standards Applicable to the Design Professional

Architects and engineers often wonder whether the designer in the one- or two-person offices in rural America must exercise the same degree of care and skill as the most prominent design teams in the nation's large metropolitan areas. A designer is liable for negligence only if he fails to exercise reasonable care under the circumstances, a standard which may vary according to local practice.

In context, however, concerns regarding the applicable design criteria or standards of care usually become quite beside the point. No matter where the designer practices and no matter what the local standards, one rule is universal: The purchaser of a construction and the public have a right to expect that the design will work—the bridge is structurally sound; the skyscraper will stand; the garage door will open and close. If the design fails, the particular standard of care usually is irrelevant. The designer usually will be held liable for a design that does not work.

The Case Study

The architect demonstrated that HVAC designs similar to the subject design are used successfully in hundreds of similar projects throughout the country, including projects with climatic conditions similar to Turtle Beach.

The owner did contend initially that design standards in Turtle Beach might be different than elsewhere around the country. This was intended to enhance the credibility of the owner's local mechanical engineering expert. Unfortunately, however, no expert introduced by the owner could articulate how HVAC design standards for Turtle Beach were different from HVAC design standards applicable generally.

Most significant, however, was the architect's proof that in fact the design under attack worked adequately. Regardless of the design standard, there was no design defect.

Experts

Opinion evidence regarding the cause of a construction failure is almost always indispensable. The contractor wants to present opinion evidence of poor design, while the designer hopes to present evidence that the failure resulted from the contractor's failure to comply with the applicable contract documents.

In litigation generally, each side looks for the most qualified and impressive experts in the field who can testify favorably. The weaker one's position, the more difficult it may be to find favorable expert testimony. Regardless of the strength of one's case, however, in construction failure litigation particularly, the selection, preparation, and presentation of expert testimony is critical and very often outcome determinative.

It is true that the most credible expert witness generally will prevail. It is not, however, the length of an expert's resume that makes him most credible. Rather, the expert who gives the explanation that makes the most sense to the judge or jury hearing the case will be believed. The experts who make the most sense are those whose theories of causation are based on the objective physical evidence, the records of the job, and the application of the laws of science and common sense to the objective data.

The Case Study

The experts called by the owner had impeccable credentials. A.B.C. & Associates was one of the country's leading experts on moisture in structures and both witnesses from that firm were educated at among the nation's top institutions of higher learning. They testified based upon two years of study that the infiltration of humid air caused by a poorly designed HVAC system caused the mold and mildew conditions at the Hotel. Both witnesses cited several examples of "negative pressure" to support their conclusions.

Unfortunately for the owner, however, its experts failed to analyze the problem at the hotel objectively, nor did they attempt to determine the cause of the mold and mildew contamination consistent with all available data. Rather, these experts hit upon a theory of designer liability and attempted to bend or exaggerate or characterize the available data to support that theory. While this approach had superficial appeal, it left these experts terribly vulnerable to cross-examination and scrutiny by other equally qualified experts.

Thus, the owner's experts attributed the inflow of air at the lower and middle floors to negative pressure caused by unit HVAC units. Only later was it discovered that this inflow of air was caused by the owners shutting down the make-up air systems for the hotel kitchen.

The owner's experts saw air blow in as exterior doors opened into guest rooms and attributed that phenomenon to "negative pressure." More likely, an explanation was that a breeze was blowing in off the Atlantic Ocean.

The owner's experts saw a pattern of mold and mildew nearest the HVAC room units as an indication that air introduced by the HVAC unit caused the mold and mildew. However, these exterior walls were also the location of greatest rainwater leaking, the more likely cause of the problem.

Far worse, the owner's experts simply ignored data or patterns that were inconsistent with their theories of causation.

In fact, the pattern of mold and mildew conformed to the areas of greatest leaking, not areas of purported "negative pressure." In fact, the room location with the most moisture in the air (the bathroom) was the area of least mold and mildew because these were not areas where leaking occurred. In fact, where on the third floor the exterior walls were made watertight, mold and mildew did not appear.

Thus, the objective data as a whole strongly supported the view that leaks caused by poor construction, and not the flow of air within the Hotel, caused the mold and mildew problems. It was this objective data that established the credibility of the architect's expert witnesses and severely undermined the theory of the owner's case.

Causation

Generally, a contractor is liable for a construction failure only when he fails to construct in accordance with the contract documents. Conversely, the designer is liable only for design deficiencies in the plans and specifications. Sometimes these general rules prompt a generalized investigation into the performances of the contractor and designer, with the intention of discovering deviations from the specifications by the contractor or application of inappropriate design standards by the architect or engineer. However, breaches of contract by the contractor and the application of the wrong design criteria by the designer are immaterial unless those events caused the construction failure that is the subject of dispute. Similarly, just because a design is deficient does not mean that the deficiency caused the failure.

Thus, in the case of the failure of a concrete slab on grade, it may be established that the slab thickness was undersized by half an inch, that certain soil compaction procedures were omitted, and that the form work was sloppy and somewhat out of line. All of that may seem quite pertinent unless the designer located a 6-in. (152 mm) slab with no real structural characteristics directly atop a settling trash pit and the slab cracked only because it settled into the sinking fill. In that case, the contractor breached his contract, but the breach had nothing to do with the failure.

Or, for example, in the case of a roof failure, it may be that the shingles specified tended to rip off in high winds, that the roof insulation was vulnerable to high humidity, and that the supporting framing was slightly under strength to meet accepted margins of safety. However, if the roof leaks because the contractor omitted a waterproof membrane and did a shoddy job of installing the roof shingles, the arguably faulty design is not pertinent unless it caused or helped to cause the failure.

It is possible, although rare, that poor construction and poor design combine to cause a failure that would not have occurred except for both the faulty construction and the poor design. A good example is the roof that collapses because the architect undersized supporting beams and the contractor placed the beams every 3 ft (0.91 m) rather than every 2 ft (0.60 m) as specified. In such cases, the designer and contractor should be held jointly and severally liable.[46]

The Case Study

The architect's contention regarding causation was that the mold and mildew did not result from an influx of air (negative pressure), but that the overwhelming weight of evidence suggested that the likely cause of mold and mildew was water leaks.

All of the objective evidence was consistent with the contention that leaks had caused the mold and mildew. The pattern of leaks corresponded to the pattern of mold and mildew. And the known observations of actual conditions simply did not support the negative pressure causes or conditions espoused by the owner and its experts.

CONCLUSION

Construction failure disputes are almost always resolved according to the weight of objective evidence presented by the most credible experts. Based on the mistakes that were made in the prior case studies and the results that followed, certain guidelines emerge.

First, in attempting to establish the liability of a contractor or architect, do not attempt to make that party bear a responsibility which exceeds those set forth in the applicable contract documents. If the contractor did not design, do not, except in the clearest of cases, sue the contractor for not warning of design deficiencies. And if the architect performed under standard AIA documents, do not charge the architect with the responsibility for the contractor's poor work. In either case, such theories waste time and expense while undermining a proponent's credibility.

Second, pursue a theory of the case that is consistent with all of the objective evidence, even if that requires the concession of minor points. A theory of causation which attempts to contradict any substantial objective evidence is not credible and will not prevail.

Third, hire experts because they are capable, honest, and credible. Any expert that is willing to be engaged to support a predetermined theory of the case will likely maximize the cost of litigation while minimizing the likelihood of success.

The Case Study

The mold and mildew dispute was the subject of two trials because the owner-architect agreement protected the architect from arbitrating in the same proceeding with the contractor. The owner pressed his arbitration with the architect, the party against whom the owner contended it had the more substantial claim. In order to maximize the potential recovery against the architect, the owner apportioned its damages very much against the architect, claiming that design deficiencies caused 85 to 90% of the mold and mildew damages.

For all of the foregoing reasons, the arbitrators disagreed totally with the owner's contentions, dismissing the owner's claims against the architect and awarding the architect fees due for services rendered. Even more unfortunate for the owner, only weeks after concluding its arbitration with the architect, it commenced its arbitration against the contractor. At the subsequent arbitration, the contractor was able to discover and present the owner's prior presentation claiming the mold and mildew resulted primarily from poor design. As a result, the owner's recovery against the contractor was minimal. Thus, the owner proceeded against both designer and contractor, and because of its poor judgment in case preparation and litigation tactics, recovered substantially from neither.

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[46] *See Northern Petrochemical Co. v. Thorsen & Thorshov, Inc.*, 297 Minn. 118, 211 N.W.2d 159 (1983); *Liberty Mut. Ins. Co. v. Vanderbush Sheet Metal Co.*, 512 F. Supp. 1159 (E.D. Mich. 1981).

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A Conceptual System of Moisture Performance Analysis

by Mark T. Bomberg[1] *and Cliff J. Shirtliffe*[1]

In a manual such as this one, individual aspects of moisture control are discussed in separate, discipline-oriented chapters, even though such a treatment of the subject matter does not allow the integration of these various aspects into a comprehensive strategy of moisture control. Yet, there is a need for consolidating the multitude of findings of the research and field studies in the rapidly developing science of environmental control in buildings. This chapter attempts to fill this need by introducing a conceptual system of moisture performance analysis.

Performance of whole buildings as it depends on building components, e.g., external envelope, mechanical and electrical systems, and operational conditions (defined by climate and occupancy of the building), must also be related to the selection of materials forming the components of the building system. In this process, the materials are selected on the basis of structural and environmental control considerations [*1*]. Yet, while the structural design is well defined, this is not the case with the environmental control process. In the worst case, the environmental design is based on experience gained by the designer in the trial and error process.

Heat, air, and moisture transport across a building envelope are inseparable phenomena. Each influences the other and is influenced by all the materials contained within the building envelope. Often we simplify the process of design by relating control of each phenomenon to a particular material or component. The thermal insulation, for example, is perceived to control heat transfer and the air barrier to control air leakage (Table 1). Likewise, the rain screen and vapor barrier eliminate ingress of moisture into the system.

While selected for one reason, these materials and components perform many different and interrelated functions and frequently contribute to several of the processes that control overall system performance. For instance, while controlling air leakage, an air barrier system [*2*] may also provide effective control of moisture flow. Similarly, by increasing temperature in the wall cavity, a thermal insulating sheathing may also reduce the degree of condensation in the cavity [*3*]. In the process of environmental control, the interactions between heat, air, and moisture transports must also be reviewed. And to ensure that all aspects of the building envelope perform effectively, we must deal with heat, air, and moisture transport collectively.

The primary function of the building envelope is to provide shelter from the outdoor environment and to enclose a comfortable indoor space. To do this, the envelope needs structural integrity and durability, particularly if it is to resist moisture damage. Of all environmental conditions, excessive moisture poses the biggest threat to integrity and durability, accounting for most of the damage in building envelopes. Many construction materials contain moisture, most notably, masonry or concrete. These materials demonstrate excellent performance characteristics as long as the moisture does not compromise the structural or physical integrity. However, excessive moisture jeopardizes both the material and its functionality.

When does a given moisture content become "excessive?" How do climate, operating conditions, and adjacent materials affect the wetting and drying of the materials? In designing for environmental control, professionals integrate two very different conceptual processes. One involves specific testing and analysis; the other encompasses broad qualitative assessments based on experience, judgment, and knowledge of what makes a building envelope function under a given set of conditions. On the analytical side is a complex array of tools, models, and data which describe the material, structural, and environmental factors relating to the building envelope. On the qualitative side is a sense of how a particular building envelope would function in that environment.

For example, a vapor barrier is typically classified at 1 perm (57 ng/m^2 Pa), a unit that for wood frame housing in given environmental conditions represents a sufficiently small flow of vapor flow. However, in calculations made for different regions of Canada using a complex model of heat, air, and moisture transport, barriers with permeance ranging from 0.1 to 10 perms could be found applicable [*4*].

So, despite the move to define vapor barriers by a precise measurements, the selection of the most appropriate environmental barrier involves both conceptual logic and mathematical analysis. Designers must still conduct an overall qualitative assessment to determine whether the barrier, chosen for its quantitative properties, would actually function in the specific application.

In this respect, there is a growing disparity [*5*] between the selection of traditional materials for typical buildings and rapidly changing characteristics of new materials. In the absence of data on their field performance, the moisture-related data on new materials and components must be developed through laboratory testing. But what information is needed? And what tests should be used to produce this information? There being, at the present time, no established design process relating to moisture control, this chapter postulates a concept of such a process, an integrated approach to

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TABLE 1—Environmental barriers and driving forces.[a]

Driving Force	Environmental Barrier	Design Feature
Vapor pressure	Vapor barrier	Vapor diffusion control
Wind pressure + rain	Pressure equalized rain (PER) screen	Eliminates wind pressure difference across rain screen
Rain	Air gap with weather barrier and flashings	Provides capillary break and leads water away
Groundwater	Dampproofing, gravel or crushed stone layer	Provides capillary break
Air pressures (wind loads, stack, etc.)	Air barrier (continuous airtight material and load support)	Carries wind loads to the desired location
Air pressure + high indoor humidity	Air barrier	Controls moisture flow via air leakage
Wind pressure difference	Weather barrier with load support	Eliminates effects of windwashing
Temperature difference	Thermal insulation	Reduces the rate of heat flow
High temperature, e.g., fire	Thermal barrier, e.g., drywall	Prevents rapid temperature rise on susceptible materials

[a] Note that in Table 1, in accordance with the *Oxford American Dictionary*, we use term barriers for all elements that control advance (retard) flows of heat, air, or moisture.

the development of moisture control strategies in buildings, modeled after a well-developed process of structural design.

APPROACH

The selection of materials for use in the building envelope is done by architects and designers. This selection is based on previous experience and the current information gathered during a number of successive design refinements, during which some aspects of the performance and the interaction of materials and systems are reviewed and revised accordingly. The knowledge gained on each application may be used in the later applications of the same system. This review of the design is informal, and its efficiency depends greatly on the experience with the particular construction system that the designer's team has. Often, when lacking experience with the particular construction system, the designer will produce a design that has not been optimized in terms of cost nor in the use of materials, especially newer materials.

A more rigorous approach is needed, where both material and system performance could be related to the specific climatic and service conditions that the envelope may experience. This analysis should involve computer-based analysis of moisture flow, air leakage, and temperature distribution in building elements and systems. The concept of such an approach to the design of moisture control in a building envelope and a building environment is presented in this chapter.

In developing a comprehensive moisture performance analysis, we shall use an analogy with the process of structural design, a concept introduced in the Scandinavian Moisture Research Program [*6*] and employed at Lund University [*7–9*]. The structural design process, Table 2, involves the following stages: selecting materials for the structural element, identifying the loads and mechanisms of load transfer, predicting the actual stresses and strains in the analyzed element, comparing these with the permissible levels of stress and deformation, verifying the material selection, and, when necessary, modifying the elements' dimensions. Structural design is a closed-loop process; it starts with a material and analyzes how well this material could perform a specified function in the system. In the structural design, all the system interactions are introduced into the load factors, and the dimensioning of the structure was achieved during one stage of calculations. Neither type nor dimensions of the material are likely to be modified at the later stage of the design.

TABLE 2—Pattern of structural design.

Stage of Analysis	Comments
1. Material pre-selection	Previous experience
2. Loads	Superposition, interaction
3. Mechanics of load transfer	Elastic regions
4. Predicted stress-strain	Worst case
5. Critical stress-strain	Safety factor, interactions
6. Material modification (dimensions)	Price versus property

This is not the case when designing moisture controls in the building system. As shown in Fig. 1, the interactions between heat, air, and moisture transfer phenomena lead to the situation where none of these design aspects may be analyzed in isolation from each other. A change in one aspect of design must be analyzed in terms of other aspects of climatic control. For instance, an increased thermal insulation that results in a change of heat flow rate may change the likelihood of inter-

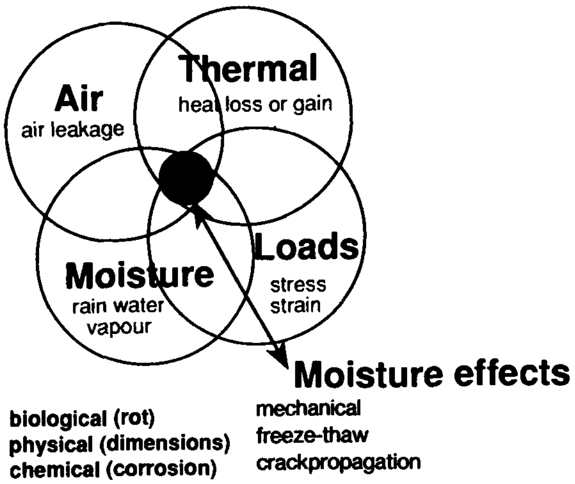

FIG. 1—Interaction between heat, air, and moisture transfer phenomena.

TABLE 3—Moisture performance analysis system.

Stage of Analysis	Comments
1. Material pre-selection	Preliminary selection
2. Moisture sources	Climate and use dependent Time dependent
3. Moisture transfer	Single-phase flows Multi-phase flow
4. Predicted moisture content	Time and space dependent Worst case scenario
5. Critical moisture content (cumulative exposure time)	Accessible porosity Total time of wetness
6. Material modification	Design modification

stitial vapor condensation, reduce drying potential of materials within the structure, etc. Thus, the design of moisture control may require performing multi-stage calculations (iterative loops). Nevertheless, within each of these iterative loops the structural analogy may be applied. Table 3 shows that iterative loops were comprised of the following stages:

1. Selecting materials for initial analysis.
2. Identifying the sources of moisture.
3. Identifying the types of moisture flows and interactions between heat, air, and moisture.
4. Predicting the distribution of moisture in the analyzed element at a given time.
5. Identifying the permissible level of the selected control parameters.
6. Modifying material selection.

The structural analogy concepts and the system of performance analysis [*10–15*] can be combined to produce a system of moisture performance analysis.

MOISTURE PERFORMANCE ANALYSIS

The system of moisture performance analysis requires the use of computational models to account for the effect of variable environmental conditions on moisture transfer through and moisture accumulation within the materials. From the distribution of moisture content in the material, as it varies with seasons of the year and length of service, one may determine if moisture content at any location exceeds the "critical" level of moisture associated with possible damage. The criteria for damage, called here "the limiting performance characteristics," are determined in independent laboratory experiments. The moisture performance analysis, as shown in Table 3, comprises six stages.

In the first stage of the analysis, one makes a preliminary material selection. This selection of material will be confirmed or modified in the process of further analysis.

In the second stage of the analysis, one identifies different sources of moisture. Some of these moisture sources depend on climatic conditions, e.g., rain or driving rain. Others depend on the service conditions and the design of the building element [*16*]. Some of the moisture sources occur only during the construction stage, e.g., construction moisture. Yet other sources may occur in a periodic fashion, such as drying from the surface of a material previously exposed to higher humidity [*17*].

In the third stage of the analysis, one identifies the main mechanisms of moisture transfer and selects a model for calculations [*18*]. A model based on single-phase moisture flows uses well-defined material characteristics such as vapor permeability or liquid conductivity, which, however, are difficult to measure [*19*]. A model based on multi-phase moisture flow is less elegant but uses material characteristics, such as moisture conductivity, that are easier to measure [*20–22*] (see Chapter 2).

Any model of moisture transfer must address three flows: heat, air, and moisture and their interactions. The need for simultaneous analysis of all three flows may be illustrated by a case of drying. The drying rate from the material surface is affected by many factors: temperature and moisture content at the surface, gradients of temperature and moisture content at the surface, infrared radiation to and from the surface, and air movement and mass transfer coefficient at the surface.

In the fourth stage of this analysis, one of two performance characteristics will be applied. These characteristics are moisture content (MC) and cumulative exposure time with respect to the specified effect (CET), i.e., the sum of the periods when moisture content exceeds the critical moisture content with respect to a specific effect of moisture.

The first characteristic, the moisture content, relates to those phenomena in which exceeding a specific level of moisture content under given temperature conditions is likely to result in immediate damage; for example, freezing a material initially saturated above a critical level will result in spalling or cracking of the material.

The second characteristic, cumulative exposure time, relates to all phenomena where a long-term exposure is involved in the deterioration process. In these cases, moisture may have insignificant impact on the short time basis (e.g., one or a few days); however, after many weeks, months, or years of exposure, these processes may result in a significant damage. Yet, as the long-term continuous exposure may have a different degree of severity than a series of intermittent exposures of the same total duration, both time and exposure severity factors must be considered.

The following concept of cumulative exposure time (CET) is proposed. CET is a sum of the interval of time when the actual moisture content is equal to or higher than the critical moisture content times the degree of severity of this exposure, namely

$$\text{CET} = \text{Sum}(I \cdot F_{ex}) \tag{1}$$

where I is the interval during which the actual moisture content is equal to or higher than the critical moisture content, and F_{ex} is the exposure severity factor.

The cumulative exposure time is needed for a number of moisture effects such as corrosion, mold growth, wood decay, or effect of moisture on thermal performance in all of which the degree of severity may vary with climatic conditions. For instance, corrosion of metals exposed to air occurs at different rates depending on temperature and humidity at the surface. The difference between the concept of "time of wetness" previously used in the durability research [*23*] and the "cumulative exposure time" introduced here is the presence of the factor F_{ex}.

The factor F_{ex} may vary between 0 and 1 depending on environmental conditions (temperature, moisture content, or relative humidity). For instance, a corrosion process may start, say at room temperature at 90% RH, but will proceed much faster at the same temperature and 98% RH (at this humidity even a small temperature variation can cause surface condensation that accelerates the corrosion process). Therefore, one could introduce a dependence of the factor F_{ex} on relative humidity, for instance, by postulating that $F_{ex} = 0$ at 90% and $F_{ex} = 1$ at 99.0%. The actual distribution of the F_{ex} factor, i.e., how it changes between values of 0 and 1 (linear, exponential, or stepwise) depends on the detailed knowledge of the deleterious effect of moisture. Not much is known at the present time how severity factors depend on temperature or humidity conditions. Making approximations, such as use of a linear dependence of F_{ex} on humidity, appears sufficient, since as shown by Becker [*15*] or Kashiwagi [*24*], there is a degree of latitude in use of weighing factors to evaluate performance of complex systems.

In the fifth stage of the analysis, the limiting levels of two performance characteristics discussed in the previous stage are identified. These limiting characteristics are termed "critical," namely

1. The critical moisture content (CMC).
2. The critical cumulative exposure time (CCET).

The first concept, CMC, implies that there is a point with a paramount significance for the analyzed effect of moisture. If the actual moisture content at any location of the material equals or exceeds the critical moisture content, CMC, there may be damage, i.e., the component may fail to maintain the required performance level or structural integrity.

The second concept, namely the critical cumulative exposure time, CCET, is defined as the total exposure time (i.e., the sum of intervals "*I*") determined under extreme conditions. It is equivalent to the period of reliable performance of the material (product) when the severity factor, defined in Eq 1, is one. Again, if, at any point in space and time, the actual value of CET exceeds the critical value, CCET, damage is expected.

Calculating cumulative exposure time provides a mechanism to evaluate effects of periodic or seasonal wetting and drying on materials and systems. In the above considerations, the severity factor describes a probability of the moisture damage. When the process is characterized by an "immediate damage," e.g., frost damage, a narrow range of moisture content brings probability of damage from a very low to a very high level (ascribed value of 1 for practical purposes). In case of cumulative processes such as mold, fungus growth, dimensional change, etc., probability of damage changes much slower with change in exposure conditions. When moisture content exceeds a critical value, the damage becomes probable (i.e., the severity factor becomes greater than zero). Yet, the process may take a long time before the product of time and severity factor reaches the critical value of CET.

In the sixth stage of the analysis, each of the two previously discussed performance characteristics, MC and CET, are compared with their limiting values, called the critical moisture content, with respect to the specified effect, or the critical cumulative exposure time, respectively. Comparing the predicted values of MC and CET with the critical levels (CMC and CCET) permits the use of performance analysis in moisture design.

On the level of material evaluation, these concepts assist in material selection. On the level of subsystem evaluation, these concepts help to modify the design since in each case the comparison between MC and CMC, or CET and CCET, becomes the basis for a decision in the design process.

AN EXAMPLE OF LIMITING MATERIAL PERFORMANCE CHARACTERISTICS

As previously discussed, a comparison between an actual performance characteristic such as moisture content or cumulative exposure period with the limiting value is the key element of the moisture performance analysis. As the calculation of the actual performance characteristics is discussed in many publications, notably in this manual, we deal with some of the limiting performance characteristics only.

Frost Durability

Frost durability of a material may be defined as its ability to withstand, without significant deterioration, the periods of freezing that actually occur throughout the whole period of service. This definition implies that frost durability is an environment-dependent property and that the same material may be durable under some field conditions but may be damaged under other conditions. Since the material must perform (be durable) under specific service conditions, one needs suitable means to examine the suitability of the material for the considered environment and to make a correct choice of material. Such means can be provided by moisture performance analysis where the moisture content of the material under actual service conditions is compared with its performance limits, i.e., CMC.

The concept of CMC with respect to freezing can be illustrated by reviewing the results of tests performed by Fagerlund [7] on two different types of clay bricks. Two cases shown above differ. While the critical degree of saturation was not reached during 240 h of water absorption for clay bricks shown in Fig. 2, the CMC is reached during 144 h of water absorption for material shown in Fig. 3.

Frost durability is represented here by the residual dynamic modulus, which is the dynamic Young's modulus divided by the modulus determined on the undisturbed specimen. Degree of saturation, *S*, is used on the other axis. The degree of saturation is the moisture content divided by the maximum that would be obtained if water has filled all the pores that are open and accessible for water ingress. The critical moisture content becomes in these notations the critical degree of saturation. The critical degree of saturation is the highest degree of saturation which may be found in a specimen without it being damaged under freezing.

Figures 2 and 3 show the stage when freeze-thaw cycling causes frost damage. The damage is characterized by a dramatic reduction in the residual dynamic modulus. Identical results are obtained with different numbers of freeze-thaw cycles or one-step freezing (noncycling simulation). Thus, the critical degree of saturation (representing critical moisture

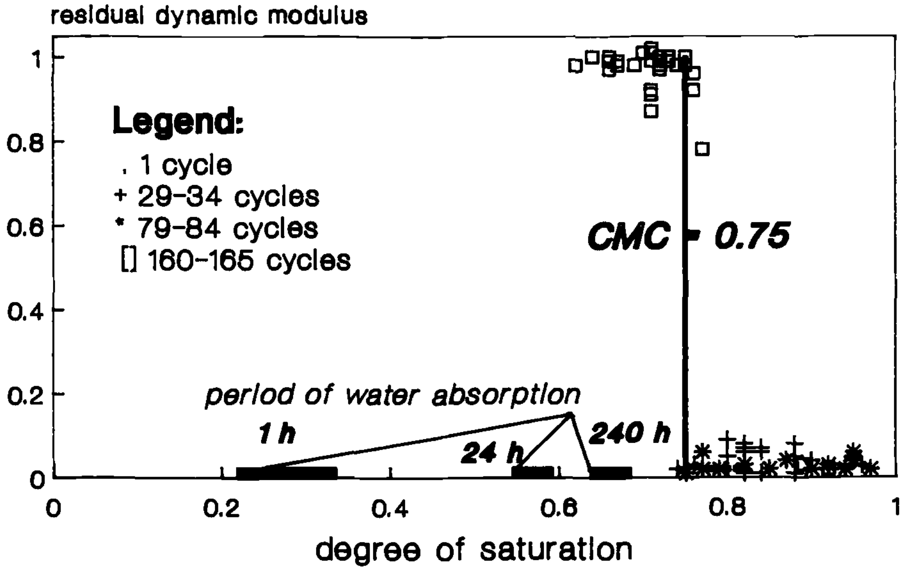

FIG. 2—Residual dynamic Young's modulus in freeze-thaw testing of a well-burnt clay brick with density 1860 kg/m^3 versus degree of moisture saturation.

content) is independent of the test method. This fact implies that the concept of CMC may be used as a performance criterion for this type of material.

When evaluating frost durability of the material, one must consider temperature of the material. Only when temperature falls below the point at which pore water freezes (slightly below 0°C) and the actual degree of saturation S_{act} exceeds the critical degree of saturation, S_{crit}, can frost damage in the material be expected (Fig. 4).

In practice, one may ascribe a given threshold probability to a sub-zero temperature for a given period of the year. Any occurrence of S_{act} higher than S_{crit} during this period would become a criterion for possible frost damage.

The above example illustrates two stages in the process of evaluating the probability of frost damage in the material. First, one determines the critical degree of saturation (critical moisture content) for freezing. Then one compares it with the actual degree of saturation predicted from the model for the specified climate. If, during the period of sub-zero temperatures, the actual degree of saturation exceeds the critical one, one may expect frost damage in this material.

Let us now compare the proposed evaluation of frost durability with the traditional one. Traditionally, after being subjected to moisture ingress (absorption) under specific environmental conditions, the specimen is subjected to a freeze-thaw test. But the thawing part of the freeze-thaw cycle may

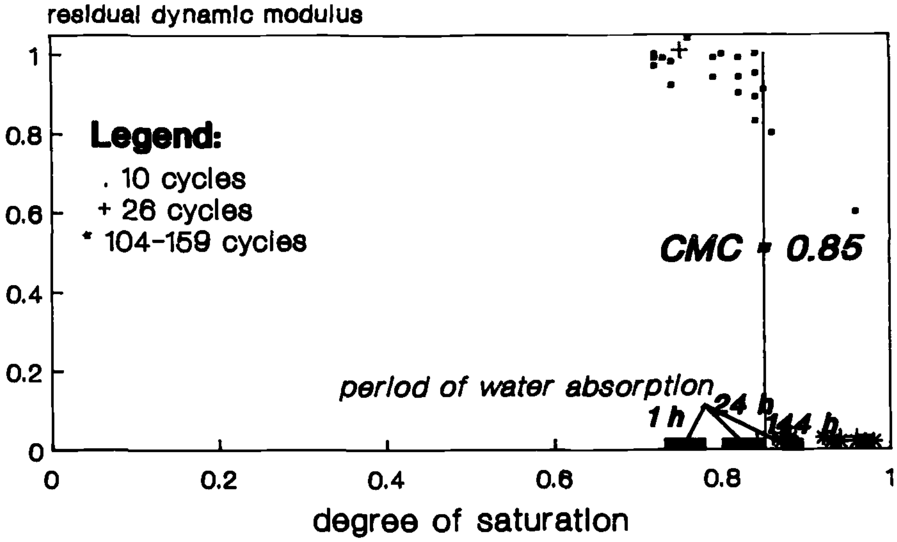

FIG. 3—Residual dynamic Young's modulus in freeze-thaw testing of an underburnt clay brick with density 1690 kg/m^3 versus degree of moisture saturation.

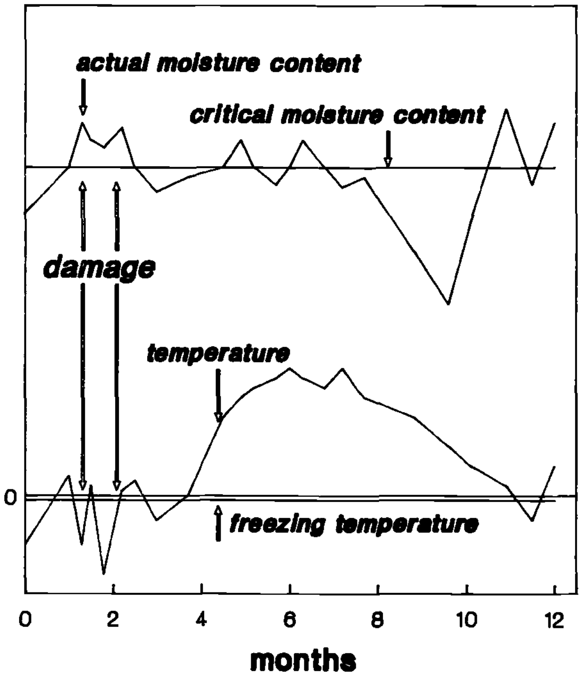

FIG. 4—Hypothetical curves of temperature and degree of actual saturation shown to highlight coincidence of conditions when frost damage is likely to occur.

also be used to stimulate moisture ingress into material. Such a test comprises cycling between two exposures, thawing in water (moisture ingress) and freezing in the air, for instance, ASTM Standard Test Method for Resistance of Concrete to Rapid Freezing and Thawing (C 666-90). In some cases, notably concrete, the degree of material saturation with moisture may increase with the duration of freeze-thaw cycling causing damage after a sufficiently large number of cycles. In other cases, the same conditions of freezing and thawing may not increase the degree of saturation at all. If the degree of saturation does not increase during the freeze-thaw cycling, one does not know whether this depends on a poor selection of the freeze-thaw conditions (conditions used for testing concrete may not be suitable for testing other materials) or on the nature of the tested material.

In addition to the critical degree of saturation defined by the means of residual dynamic modulus, Figs. 2 and 3 show results of isothermal water intake as a function of time (these clay bricks were immersed in water for different periods, e.g., 1, 24, 144, or 240 h). The short, thick line sections shown at the horizontal axis represent the degree of saturation attained during the water immersion test performed on several specimens. The degree of saturation for both types of clay bricks, S_{act}, increases with time of immersion.

What would be the outcome of a freezing test applied to these two clay bricks after they were immersed in water for a selected period, for instance 24 and 144 h. In the first case, both types of the clay bricks would be declared "frost durable"; in the second case (144 h of water absorption prior to the freeze-thaw test), the clay bricks shown in Fig. 2 would be thought "durable," but those in Fig. 3 would not. Would this mean that the clay bricks shown in Fig. 2 are durable under field conditions?

Actual moisture content depends on a balance between wetting and drying of the material in the building envelope and cannot be approximated by an arbitrary procedure such as a day or even a week-long immersion in water. While the worst-case scenario could be approximated by such a procedure, it requires, however, a check if the moisture accumulation under different conditions of wetting (e.g., condensation of thermally driven vapor) would exceed that obtained under water immersion, see Bomberg [*25*].

MOISTURE PERFORMANCE EVALUATION AND THE DESIGN PROCESS

Heat losses or gains, air leakage, and moisture transfer are influenced by the characteristics of all materials contained within the building element. Material selection must therefore be among the considerations given to the whole system. It implies that the moisture performance analysis must be performed as several iterations on different levels of construction hierarchy. (The concept of hierarchy was introduced in the performance analysis [*10*] to link different levels of consideration starting from the micro-structures and going through materials, products, and elements up to the construction systems.)

Is this iterative process of moisture performance evaluation compatible with a typical architectural design procedure? The answer is yes—both processes are very similar. The moment an architect, intentionally or not, starts to modify a "proven" design, the success of the final design is largely dependent on the type of questions that members of the design team raise and the answers they receive. In discussing design procedure, Strelka [*26*] stated that: "It also requires a willingness to change not only minor details, but the basic design itself, if the feedback information indicates that this is desirable. To do this necessitates that the design be kept as flexible as possible until the consequences of any design proposal are fully reviewed."

To compare the architectural design process with that of moisture performance analysis, we review the design of an air barrier in the exterior wall. In this example, as discussed by Strelka [*26*], the information flow starts with a search for suitable materials. Typical questions that are asked about air barrier materials are about their ability to be extended, about pliability, adhesion, means of attachment, connection, support, aging (change of material characteristics with time), weathering, and repairs. After developing an initial design, the designer addresses all intersections and joints between building elements (foundation-wall, wall-floor, wall-roof, wall-wall, wall-windows, and doors). To expect satisfactory performance in these details, the designer must continue to ask questions on the performance of the whole system: What rate of air leakage is permitted? Does the leakage occur in one place? How imperative is energy control? How critical is risk of drafts? Several iterations in design may be required until the answers to all these questions indicate that the designed element will have a satisfactory performance.

This example illustrates that after the preliminary material

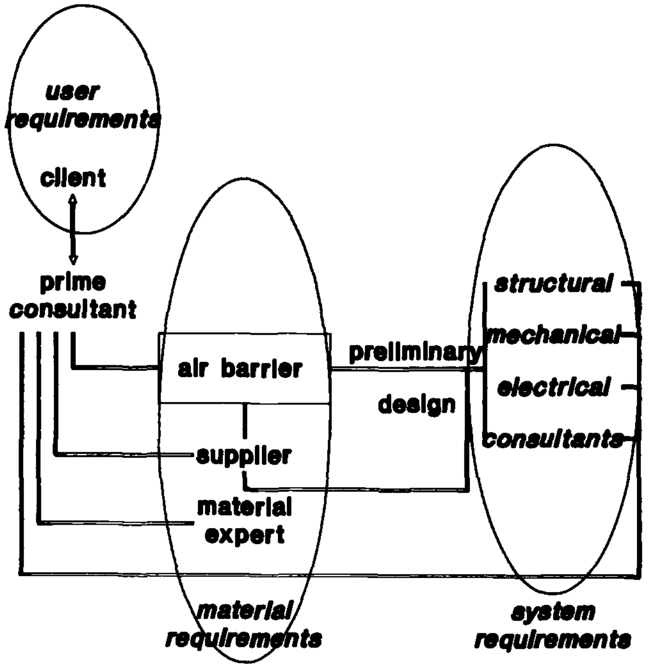

FIG. 5—Flow of information during design of air barrier (see text).

selection is completed the designer performs an analysis of its performance. Such analysis continues, and the next information loop includes the review of preliminary design with the structural, electrical, and mechanical consultants (Fig. 5).

The primary consultant must then review buildability aspects such as material installation under different weather conditions, degree of needed labor skills, and construction tolerances. This review must also address the long-term performance under service conditions: aging of the materials, stress and deformations during service, projected cost of repairs, and maintenance. At any stage, the design may have to be modified, a new material selected, and the process repeated.

As shown in the above example, the designer or the prime consultant is always performing a sort of performance evaluation. So, how is this analysis affecting the design process?

Application of moisture performance analysis introduces two new aspects:

1. It becomes a formal and recognized part of the design considerations.
2. It introduces a framework of organized procedures enforcing a review of specific performance aspects and replacing ad hoc questions or assumptions.

Figure 6 illustrates the interactive character of the design process performed stepwise in a number of iterative loops.

As the professional judgment involves experience gained when evaluating the field performance of similar construction systems, the evaluation process comprises the review of field performance of similar systems (combined with review of architectural details in the proposed system and assessment of their buildability), the review of laboratory tests on materials, or mock-up tests on components as well as predic-

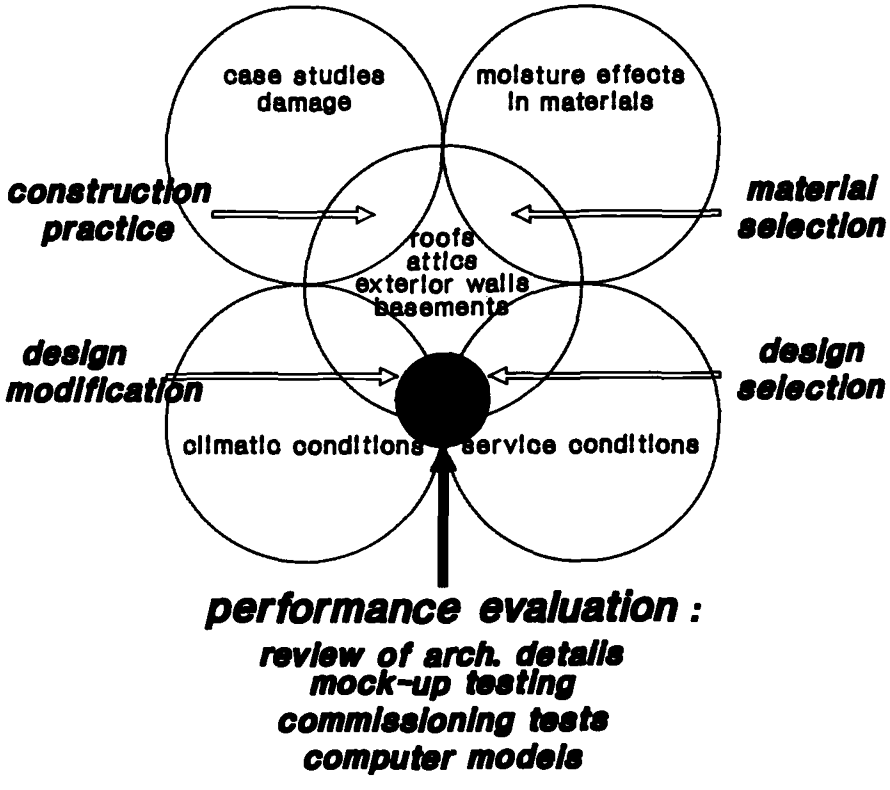

FIG. 6—Evaluation of performance on the level of building element and system.

tion of the system reliability and cost of maintenance. In some cases, even commissioning tests may be requested.

CONCLUDING REMARKS

The general strategy of moisture performance analysis, which was presented in this chapter, is based on the structural analogy. While the designer has always been performing some assessment of performance, application of the suggested moisture performance analysis would make it a recognized part of the design process and replace the current, unstructured manner of review of moisture performance aspects.

The importance of such an organized framework of procedures cannot be overstated. The use of moisture performance analysis to formalize certain aspects of an architectural design process and to assist in predicting field performance and durability of materials should facilitate the use of new materials. Because of the iterative nature of the design process and the complexity of the issues, the introduction of moisture performance analysis will help to identify the need for enhancement of performance-oriented heat and mass transfer models.

In this chapter we have expanded the performance concepts to develop an approach for evaluating moisture performance of materials and systems. This approach assumes that all appropriate calculational models and necessary material characteristics would have already been developed (observe the extrapolation of current knowledge stated in the introduction). With the capability to calculate moisture content in different locations of the building envelope and to observe how moisture content changes during the whole year, the actual moisture contents may be compared to those levels that are critical with respect to different performance aspects. The latter is a material characteristic.

A comparison between the actual and critical levels of moisture becomes a very important step in the process of evaluation. As discussed in the example limiting material characteristics, the testing effect of freeze-thaw on material with an arbitrary degree of saturation (in most currently used test methods the degree of saturation is unknown) does not tell much about frost durability under field conditions. On the contrary, the actual degree of moisture saturation is calculated from the model that simulates field conditions as closely as it is possible to achieve.

The authors have not attempted to develop a complete set of procedures for evaluating moisture performance, as at the present time the gaps in our knowledge and the lack of appropriate material characteristics prevent such a development. The authors have only attempted to show that such a development is possible and in some instances within the reach of our current capabilities.

This chapter shows the direction where much more research effort is necessary; nevertheless, the authors hope that this chapter will greatly increase the likelihood of an ultimate solution by creating synergy. As synergy implies that the whole will be greater than the sum of the parts, we hope that moisture performance analysis combined with enhanced model development will lead to significant improvements in design of moisture control in building envelopes.

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THE FOLLOWING IS A BRIEF BIBLIOGRAPHY of general use and interest on the selected subject of moisture control in buildings. Some of the texts are available from local libraries; others are available through university libraries or book stores. All should be available through the publishers. The brief annotations aid the readers in selecting those publications most appropriate for their particular needs. References in the individual chapters of this manual provide more information on specific subjects relating to moisture control in buildings. The brief annotations aid the readers in selecting those publications most appropriate for their particular needs.

HANDBOOKS

Handbook of Fundamentals, American Society of Heating, Refrigerating and Air Conditioning Engineers, 1791 Tullie Circle, NE, Atlanta, 1989.

The handbook includes several chapters related to moisture in buildings, but little with regard to mold and mildew per se. Reissued every five years, the next issue will be published in 1994. The book provides much additional information on mechanical equipment and data needed for proper selection.

Construction Principles, Materials, and Methods, by Harold B. Olin et al., The Institute of Financial Institutions, Chicago, IL, 1980.

An excellent fundamental text directed primarily at single family housing. The issue of moisture control is recognized as a major concern and discussed in the very first chapters. Highly recommended.

Architectural Graphics Standards, by Ramsey/Sleeper, Robert T. Packard, AIA, Editor, John Wiley and Sons, New York.

An excellent standard reference handbook on building design. It contains much information on the design of moisture-resistant buildings, but the information is spread throughout the book and thus not readily accessed.

Department of Energy Moisure Control Handbook, by Joseph Lstiburek and John Carmody, NTIS, Springfield, 1992.

A comprehensive guide for moisture-resistant new housing construction prepared for the U.S. Department of Energy.

Moisture Control Handbook—Principles and Practices for Residential and Small Commerical Buildings, by Joseph Lstiburek and John Carbody, Van Nostrand Reinhold, New York, 1993.

An expanded and revised version of the *Department of Energy Moisture Control Handbook*. Chapter 17 of this manual is adapted from both the original *DOE Handbook* and from the *Moisture Control Handbook—Principles and Practices for Residential and Small Commerical Buildings.*

Dampness in Buildings, by Alan C. Oliver, Nichols Publishing, New York, 1988.

Originally published in England, the book is directed towards British building practices and climate, but contains much information of general interest, particularly for moderate and humid climates. The book also contains perhaps the best exposition on the issue of rising damp.

Manual of Tropical Housing and Building, by Koenigsberger et al., Longman Group, London, 1980.

Also written by an Englishman, this is a well-developed text that specifically addresses tropical climates, those that are (1) warm and humid, and (2) warm and dry. This book discusses the different requirements for these two types of tropical climates, specifically the advantage of a low thermal mass to reduce excessive condensation in warm and humid climates.

Envelope Design Guidelines for Federal Office Buildings: Thermal Integrity and Airtightness, by Andrew K. Persily, NISTIR 4821, National Institute of Standards and Technology, Gaithersburg, MD, 1993.

Primarily concerned with airtightness and energy efficiency, the guidelines provide many useful suggestions for the design and construction of building envelopes to prevent rain penetration and condensation. Developed by the National Institute of Standards and Technology (NIST) under contract to the General Services Administration (GSA), the report underwent an exhaustive review through the National Institute for Building Sciences (NIBS) and thus can be considered a consensus document.

Mold and Mildew in Hotel and Motel Guest Rooms in Hot, Humid Climates, American Hotel and Motel Association, Washington, 1991.

The publication reports on a study conducted under the auspices of AH&MA. It discusses moisture problems experienced in the hospitality industry in warm and humid climates and proposes solutions.

PROCEEDINGS OF WORKSHOPS/SYMPOSIA/CONFERENCES (IN CHRONOLOGICAL ORDER)

Moisture Migration in Buildings, ASTM STP 779, M. Lief and H. R. Trechsel, Editors, American Society for Testing and Materials, Philadelphia, PA, 1982.

Somewhat dated, but these symposium proceedings still provide useful information. The papers are divided into individual parts: Roofing, Walls, Standards and Tests, and General Topics.

Moisture Control in Buildings, Erv Bales and Heinz Trechsel, Editors, Building Thermal Envelope Coordinating Council/National Institute of Building Science (BTECC/NIBS), Washington, DC, 1984.

Proceedings of a workshop to identify research needs. The publication includes three background papers, six technical papers, and a discussion summary including a proposed research agenda. The publication will be useful to those interested in gaining deeper insights into research issues related to moisture control.

Symposium on Air Infiltration, Ventilation, and Moisture Transfer, David Eakin, Editor, Building Thermal Envelope Coordinating Council/National Institute of Building Sciences (BTECC/NIBS), Washington, DC, 1986.

The first major symposium that linked ventilation, infiltration, and moisture control in buildings. One purpose of the symposium was to develop a concensus on research needs on the interactions of the three building performance issues and to prepare an outline for proposed design guidelines on moisture control, ventilation, and infiltration for commercial buildings.

Water Vapor Transmission through Building Materials and Systems, Heinz R. Trechsel and Mark Bomberg, Editors, American Society for Testing and Materials, Philadelphia, PA, 1989.

Proceedings of a symposium more narrowly focused on the characterization and measurement of vapor transport.

Bugs, Mold and Rot, Erv Bales and William Rose, Editors, Building Thermal Envelope Coordinating Council/National Institute of Building Science (BTECC/NIBS), Washington DC, 1991.

Proceedings of the first workshop on moisture in buildings to place major emphasis on biological agents, insect pests, and the health of building occupants. Highly recommended.

Thermal Performance of the Exterior Envelopes of Buildings V, Jeff Christian, Editor, ASHRAE, Atlanta, 1992.

Proceedings of the latest in a series of Conferences held jointly by ASHRAE, DOE, and BTECC over the last 15 years. These conferences were directed primarily toward energy conservation, but they all also had sessions on moisture. In the latest conference, held in December 1992, moisture was a major part of the conference, and a large number of interesting technical presentations on the subject of moisture in buildings were included.

Subject Index

ALPHABETICAL LIST OF UNITS

Factors with an asterisk (*) are exact

(Symbols of SI units given in parentheses)

To convert from	to	Multiply by
abampere	ampere (A)	1.000 000*E+01
abcoulomb	coulomb (C)	1.000 000*E+01
abfarad	farad (F)	1.000 000*E+09
abhenry	henry (H)	1.000 000*E−09
abmho	siemens (S)	1.000 000*E+09
abohm	ohm (Ω)	1.000 000*E−09
abvolt	volt (V)	1.000 000*E−08
acre foot[13]	cubic metre (m^3)	1.233 489 E+03
acre[13]	square metre (m^2)	4.046 873 E+03
ampere hour	coulomb (C)	3.600 000*E+03
angstrom	metre (m)	1.000 000*E−10
are	square metre (m^2)	1.000 000*E+02
astronomical unit	metre (m)	1.495 979 E+11
atmosphere, standard	pascal (Pa)	1.013 250*E+05
atmosphere, technical (= 1 kgf/cm^2)	pascal (Pa)	9.806 650*E+04
bar	pascal (Pa)	1.000 000*E+05
barn	square metre (m^2)	1.000 000*E−28
barrel (for petroleum, 42 gal)	cubic metre (m^3)	1.589 873 E−01
board foot	cubic metre (m^3)	2.359 737 E−03
British thermal unit (International Table)[14]	joule (J)	1.055 056 E+03
British thermal unit (mean)	joule (J)	1.055 87 E+03
British thermal unit (thermochemical)	joule (J)	1.054 350 E+03
British thermal unit (39°F)	joule (J)	1.059 67 E+03
British thermal unit (59°F)	joule (J)	1.054 80 E+03
British thermal unit (60°F)	joule (J)	1.054 68 E+03
Btu (International Table)·ft/(h·ft^2·°F) (thermal conductivity)	watt per metre kelvin [W/(m·K)]	1.730 735 E+00
Btu (thermochemical)·ft/(h·ft^2·°F) (thermal conductivity)	watt per metre kelvin [W/(m·K)]	1.729 577 E+00
Btu (International Table)·in/(h·ft^2·°F) (thermal conductivity)	watt per metre kelvin [W/(m·K)]	1.442 279 E−01
Btu (thermochemical)·in/(h·ft^2·°F) (thermal conductivity)	watt per metre kelvin [W/(m·K)]	1.441 314 E−01
Btu (International Table)·in/(s·ft^2·°F) (thermal conductivity)	watt per metre kelvin [W/(m·K)]	5.192 204 E+02
Btu (thermochemical)·in/(s·ft^2·°F) (thermal conductivity)	watt per metre kelvin [W/(m·K)]	5.188 732 E+02
Btu (International Table)/h	watt (W)	2.930 711 E−01
Btu (International Table)/s	watt (W)	1.055 056 E+03
Btu (thermochemical)/h	watt (W)	2.928 751 E−01
Btu (thermochemical)/min	watt (W)	1.757 250 E+01
Btu (thermochemical)/s	watt (W)	1.054 350 E+03
Btu (International Table)/ft^2	joule per square metre (J/m^2)	1.135 653 E+04
Btu (thermochemical)/ft^2	joule per square metre (J/m^2)	1.134 893 E+04

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[1] The U.S. Metric Law of 1866 gave the relationship, 1 metre equals 39.37 inches. Since 1893 the U.S. yard has been derived from the metre. In 1959 a refinement was made in the definition of the yard to bring the U.S. yard and the yard used in other countries into agreement. The U.S. yard was changed from 3600/3937 m to 0.9144 m exactly. The new length is shorter by exactly two parts in a million.

At the same time it was decided that any data in feet derived from and published as a result of geodetic surveys within the U.S. would remain with the old standard (1 ft = 1200/3937 m) until further decision. This foot is named the U.S. survey foot.

All conversion factors for units of land measure in these tables referenced to this footnote are based on the U.S. survey foot and the following relationships: 1 fathom = 6 feet; 1 rod (pole or perch) = 16½ feet; 1 chain = 66 feet; 1 mile (U.S. statute) = 5280 feet.

[1] The Fifth International Conference on the Properties of Steam in 1956 defined the calorie (International Table) as 4.1868 J. Therefore, the exact conversion for Btu (International Table) is 1.055 055 852 62 E+03 J.

To convert from	to	Multiply by
Btu (International Table)/(ft$^2\cdot$s)	watt per square metre (W/m^2)	1.135 653 E+04
Btu (International Table)/(ft$^2\cdot$h)	watt per square metre (W/m^2)	3.154 591 E+00
Btu (thermochemical)/(ft$^2\cdot$h)	watt per square metre (W/m^2)	3.152 481 E+00
Btu (thermochemical)/(ft$^2\cdot$min)	watt per square metre (W/m^2)	1.891 489 E+02
Btu (thermochemical)/(ft$^2\cdot$s)	watt per square metre (W/m^2)	1.134 893 E+04
Btu (thermochemical)/(in$^2\cdot$s)	watt per square metre (W/m^2)	1.634 246 E+06
Btu (International Table)/(h$\cdot$ft$^2\cdot$°F) (thermal conductance)[15]	watt per square metre kelvin [W/(m$^2\cdot$K)]	5.678 263 E+00
Btu (thermochemical)/(h$\cdot$ft$^2\cdot$°F) (thermal conductance)[15]	watt per square metre kelvin [W/(m$^2\cdot$K)]	5.674 466 E+00
Btu (International Table)/(s$\cdot$ft$^2\cdot$°F)	watt per square metre kelvin [W/(m$^2\cdot$K)]	2.044 175 E+04
Btu (thermochemical)/(s$\cdot$ft$^2\cdot$°F)	watt per square metre kelvin [W/(m$^2\cdot$K)]	2.042 808 E+04
Btu (International Table)/lb	joule per kilogram (J/kg)	2.326 000*E+03
Btu (thermochemical)/lb	joule per kilogram (J/kg)	2.324 444 E+03
Btu (International Table)/(lb$\cdot$°F) (heat capacity)	joule per kilogram kelvin [J/(kg$\cdot$K)]	4.186 800*E+03
Btu (thermochemical)/(lb$\cdot$°F) (heat capacity)	joule per kilogram kelvin [J/(kg$\cdot$K)]	4.184 000*E+03
Btu (International Table)/ft^3	joule per cubic metre (J/m^3)	3.725 895 E+04
Btu (thermochemical)/ft^3	joule per cubic metre (J/m^3)	3.723 402 E+04
bushel (U.S.)	cubic metre (m^3)	3.523 907 E−02
calorie (International Table)[14]	joule (J)	4.186 800*E+00
calorie (mean)	joule (J)	4.190 02 E+00
calorie (thermochemical)	joule (J)	4.184 000*E+00
calorie (15°C)	joule (J)	4.185 80 E+00
calorie (20°C)	joule (J)	4.181 90 E+00
calorie (kilogram, International Table)	joule (J)	4.186 800*E+03
calorie (kilogram, mean)	joule (J)	4.190 02 E+03
calorie (kilogram, thermochemical)	joule (J)	4.184 000*E+03
cal (thermochemical)/cm^2	joule per square metre (J/m^2)	4.184 000*E+04
cal (International Table)/g	joule per kilogram (J/kg)	4.186 800*E+03
cal (thermochemical)/g	joule per kilogram (J/kg)	4.184 000*E+03
cal (International Table)/(g$\cdot$°C)	joule per kilogram kelvin [J/(kg$\cdot$K)]	4.186 800*E+03
cal (thermochemical)/(g$\cdot$°C)	joule per kilogram kelvin [J/(kg$\cdot$K)]	4.184 000*E+03
cal (thermochemical)/min	watt (W)	6.973 333 E−02
cal (thermochemical)/s	watt (W)	4.184 000*E+00
cal (thermochemical)/(cm$^2\cdot$s)	watt per square metre (W/m^2)	4.184 000*E+04
cal (thermochemical)/(cm$^2\cdot$min)	watt per square metre (W/m^2)	6.973 333 E+02
cal (thermochemical)/(cm$^2\cdot$s)	watt per square metre (W/m^2)	4.184 000*E+04
cal (thermochemical)/(cm$\cdot$s$\cdot$°C)	watt per metre kelvin [W/(m$\cdot$K)]	4.184 000*E+02
cd/in^2	candela per square metre (cd/m^2)	1.550 003 E+03
carat (metric)	kilogram (kg)	2.000 000*E−04
centimetre of mercury (0°C)	pascal (Pa)	1.333 22 E+03
centimetre of water (4°C)	pascal (Pa)	9.806 38 E+01
centipoise (dynamic viscosity)	pascal second (Pa$\cdot$s)	1.000 000*E−03
centistokes (kinematic viscosity)	square metre per second (m^2/s)	1.000 000*E−06
chain[13]	metre (m)	2.011 684 E+01
circular mil	square metre (m^2)	5.067 075 E−10
clo	kelvin square metre per watt (K$\cdot$m^2/W)	1.55 E−01
cup	cubic metre (m^3)	2.365 882 E−04
curie	becquerel (Bq)	3.700 000*E+10
darcy[16]	square metre (m^2)	9.869 233 E−13
day	second (s)	8.640 000*E+04
day (sidereal)	second (s)	8.616 409 E+04
degree (angle)	radian (rad)	1.745 329 E−02
degree Celsius	kelvin (K)	$T_K = t_C + 273.15$
degree centigrade	[see 4.4.2]	
degree Fahrenheit	degree Celsius (°C)	$t_C = (t_F - 32)/1.8$

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[15] In ISO 31 this quantity is called *coefficient of heat transfer.*

[16] The darcy is a unit for measuring permeability of porous solids.

To convert from	to	Multiply by
degree Fahrenheit	kelvin (K)	$T_{\mathrm{K}} = (t_{°\mathrm{F}} + 459.67)/1.8$
degree Rankine	kelvin (K)	$T_{\mathrm{K}} = T_{°\mathrm{R}}/1.8$
°F·h·ft^2/Btu (International Table) (thermal resistance)[17]	kelvin square metre per watt (K·m^2/W)	1.761 102 E-01
°F·h·ft^2/Btu (thermochemical) (thermal resistance)[17]	kelvin square metre per watt (K·m^2/W)	1.762 280 E-01
°F·h·ft^2/[Btu (International Table)·in] (thermal resistivity)	kelvin metre per watt (K·m/W)	6.933 471 E+00
°F·h·ft^2/[Btu (thermochemical)·in] (thermal resistivity)	kelvin metre per watt (K·m/W)	6.938 113 E+00
denier	kilogram per metre (kg/m)	1.111 111 E-07
dyne	newton (N)	1.000 000*E-05
dyne·cm	newton metre (N·m)	1.000 000*E-07
dyne/cm^2	pascal (Pa)	1.000 000*E-01
electronvolt	joule (J)	1.602 19 E-19
EMU of capacitance	farad (F)	1.000 000*E+09
EMU of current	ampere (A)	1.000 000*E+01
EMU of electric potential	volt (V)	1.000 000*E-08
EMU of inductance	henry (H)	1.000 000*E-09
EMU of resistance	ohm (Ω)	1.000 000*E-09
ESU of capacitance	farad (F)	1.112 650 E-12
ESU of current	ampere (A)	3.335 6 E-10
ESU of electric potential	volt (V)	2.997 9 E+02
ESU of inductance	henry (H)	8.987 554 E+11
ESU of resistance	ohm (Ω)	8.987 554 E+11
erg	joule (J)	1.000 000*E-07
erg/(cm^2·s)	watt per square metre (W/m^2)	1.000 000*E-03
erg/s	watt (W)	1.000 000*E-07
faraday (based on carbon-12)	coulomb (C)	9.648 70 E+04
faraday (chemical)	coulomb (C)	9.649 57 E+04
faraday (physical)	coulomb (C)	9.652 19 E+04
fathom[13]	metre (m)	1.828 804 E+00
fermi (femtometre)	metre (m)	1.000 000*E-15
fluid ounce (U.S.)	cubic metre (m^3)	2.957 353 E-05
foot	metre (m)	3.048 000*E-01
foot (U.S. survey)[13]	metre (m)	3.048 006 E-01
foot of water (39.2°F)	pascal (Pa)	2.988 98 E+03
ft^2	square metre (m^2)	9.290 304*E-02
ft^2/h (thermal diffusivity)	square metre per second (m^2/s)	2.580 640*E-05
ft^2/s	square metre per second (m^2/s)	9.290 304*E-02
ft^3 (volume; section modulus)	cubic metre (m^3)	2.831 685 E-02
ft^3/min	cubic metre per second (m^3/s)	4.719 474 E-04
ft^3/s	cubic metre per second (m^3/s)	2.831 685 E-02
ft^4 (second moment of area)[18]	metre to the fourth power (m^4)	8.630 975 E-03
ft/h	metre per second (m/s)	8.466 667 E-05
ft/min	metre per second (m/s)	5.080 000*E-03
ft/s	metre per second (m/s)	3.048 000*E-01
ft/s^2	metre per second squared (m/s^2)	3.048 000*E-01
footcandle	lux (lx)	1.076 391 E+01
footlambert	candela per square metre (cd/m^2)	3.426 259 E+00
ft·lbf	joule (J)	1.355 818 E+00
ft·lbf/h	watt (W)	3.766 161 E-04
ft·lbf/min	watt (W)	2.259 697 E-02
ft·lbf/s	watt (W)	1.355 818 E+00
ft-poundal	joule (J)	4.214 011 E-02
g, standard free fall	metre per second squared (m/s^2)	9.806 650*E+00

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[17] In ISO 31 this quantity is called *thermal insulance* and the quantity *thermal resistance* has the unit K/W.

[18] This is sometimes called the moment of section or area moment of inertia of a plane section about a specified axis.

To convert from	to	Multiply by
gal	metre per second squared (m/s^2)	1.000 000*E-02
gallon (Canadian liquid)	cubic metre (m^3)	4.546 090 E-03
gallon (U.K. liquid)	cubic metre (m^3)	4.546 092 E-03
gallon (U.S. dry)	cubic metre (m^3)	4.404 884 E-03
gallon (U.S. liquid)	cubic metre (m^3)	3.785 412 E-03
gallon (U.S. liquid) per day	cubic metre per second (m^3/s)	4.381 264 E-08
gallon (U.S. liquid) per minute	cubic metre per second (m^3/s)	6.309 020 E-05
gallon (U.S. liquid) per hp·h (SFC, specific fuel consumption)	cubic metre per joule (m^3/J)	1.410 089 E-09
gamma	tesla (T)	1.000 000*E-09
gauss	tesla (T)	1.000 000*E-04
gilbert	ampere (A)	7.957 747 E-01
gill (U.K.)	cubic metre (m^3)	1.420 653 E-04
gill (U.S.)	cubic metre (m^3)	1.182 941 E-04
grade	degree (angular)	9.000 000*E-01
grade	radian (rad)	1.570 796 E-02
grain	kilogram (kg)	6.479 891*E-05
grain/gal (U.S. liquid)	kilogram per cubic metre (kg/m^3)	1.711 806 E-02
gram	kilogram (kg)	1.000 000*E-03
g/cm^3	kilogram per cubic metre (kg/m^3)	1.000 000*E+03
gf/cm^2	pascal (Pa)	9.806 650*E+01
hectare	square metre (m^2)	1.000 000*E+04
horsepower (550 ft·lbf/s)	watt (W)	7.456 999 E+02
horsepower (boiler)	watt (W)	9.809 50 E+03
horsepower (electric)	watt (W)	7.460 000*E+02
horsepower (metric)	watt (W)	7.354 99 E+02
horsepower (water)	watt (W)	7.460 43 E+02
horsepower (U.K.)	watt (W)	7.457 0 E+02
hour	second(s)	3.600 000*E+03
hour (sidereal)	second (s)	3.590 170 E+03
hundredweight (long)	kilogram (kg)	5.080 235 E+01
hundredweight (short)	kilogram (kg)	4.535 924 E+01
inch	metre (m)	2.540 000*E-02
inch of mercury (32°F)	pascal (Pa)	3.386 38 E+03
inch of mercury (60°F)	pascal (Pa)	3.376 85 E+03
inch of water (39.2°F)	pascal (Pa)	2.490 82 E+02
inch of water (60°F)	pascal (Pa)	2.488 4 E+02
in^2	square metre (m^2)	6.451 600*E-04
in^3 (volume)[19]	cubic metre (m^3)	1.638 706 E-05
in^3 (section modulus)[19]	metre cubed (m^3)	1.638 706 E-05
in^3/min	cubic metre per second (m^3/s)	2.731 177 E-07
in^4 (second moment of area)[18]	metre to the fourth power (m^4)	4.162 314 E-07
in/s	metre per second (m/s)	2.540 000*E-02
in/s^2	metre per second squared (m/s^2)	2.540 000*E-02
kayser	1 per metre (1/m)	1.000 000*E+02
kelvin	degree Celsius (°C)	$t_{\mathrm{C}} = T_{\mathrm{K}} - 273.15$
kilocalorie (International Table)	joule (J)	4.186 800*E+03
kilocalorie (mean)	joule (J)	4.190 02 E+03
kilocalorie (thermochemical)	joule (J)	4.184 000*E+03
kilocalorie (thermochemical)/min	watt (W)	6.973 333 E+01
kilocalorie (thermochemical)/s	watt (W)	4.184 000*E+03
kilogram-force (kgf)	newton (N)	9.806 650*E+00
kgf·m	newton metre (N·m)	9.806 650*E+00
$kgf·s^2/m$ (mass)	kilogram (kg)	9.806 650*E+00
kgf/cm^2	pascal (Pa)	9.806 650*E+04
kgf/m^2	pascal (Pa)	9.806 650*E+00
kgf/mm^2	pascal (Pa)	9.806 650*E+06
km/h	metre per second (m/s)	2.777 778 E-01

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[19] The exact conversion factor is 1.638 706 4*E-05.

To convert from	to	Multiply by
kilopond (1 kp = 1 kgf)	newton (N)	9.806 650*E+00
kW·h	joule (J)	3.600 000*E+06
kip (1000 lbf)	newton (N)	4.448 222 E+03
kip/in^2 (ksi)	pascal (Pa)	6.894 757 E+06
knot (international)	metre per second (m/s)	5.144 444 E−01
lambert	candela per square metre (cd/m^2)	1/π *E+04
lambert	candela per square metre (cd/m^2)	3.183 099 E+03
langley	joule per square metre (J/m^2)	4.184 000*E+04
light year	metre (m)	9.460 55 E+15
litre[20]	cubic metre (m^3)	1.000 000*E−03
lm/ft^2	lumen per square metre (lm/m^2)	1.076 391 E+01
maxwell	weber (Wb)	1.000 000*E−08
mho	siemens (S)	1.000 000*E+00
microinch	metre (m)	2.540 000*E−08
micron (deprecated term, use micrometre)	metre (m)	1.000 000*E−06
mil	metre (m)	2.540 000*E−05
mile (international)	metre (m)	1.609 344*E+03
mile (U.S. statute)[13]	metre (m)	1.609 347 E+03
mile (international nautical)	metre (m)	1.852 000*E+03
mile (U.S. nautical)	metre (m)	1.852 000*E+03
mi^2 (international)	square metre (m^2)	2.589 988 E+06
mi^2 (U. S. statute)[13]	square metre (m^2)	2.589 998 E+06
mi/h (international)	metre per second (m/s)	4.470 400*E−01
mi/h (international)	kilometre per hour (km/h)	1.609 344*E+00
mi/min (international)	metre per second (m/s)	2.682 240*E+01
mi/s (international)	metre per second (m/s)	1.609 344*E+03
millibar	pascal (Pa)	1.000 000*E+02
millimetre of mercury (0°C)	pascal (Pa)	1.333 22 E+02
minute (angle)	radian (rad)	2.908 882 E−04
minute	second (s)	6.000 000*E+01
minute (sidereal)	second (s)	5.983 617 E+01
oersted	ampere per metre (A/m)	7.957 747 E+01
ohm centimetre	ohm meter (Ω·m)	1.000 000*E−02
ohm circular-mil per foot	ohm metre (Ω·m)	1.662 426 E−09
ounce (avoirdupois)	kilogram (kg)	2.834 952 E−02
ounce (troy or apothecary)	kilogram (kg)	3.110 348 E−02
ounce (U.K. fluid)	cubic metre (m^3)	2.841 306 E−05
ounce (U.S. fluid)	cubic metre (m^3)	2.957 353 E−05
ounce-force	newton (N)	2.780 139 E−01
ozf·in	newton metre (N·m)	7.061 552 E−03
oz (avoirdupois)/gal (U.K. liquid)	kilogram per cubic metre (kg/m^3)	6.236 023 E+00
oz (avoirdupois)/gal (U.S. liquid)	kilogram per cubic metre (kg/m^3)	7.489 152 E+00
oz (avoirdupois)/in^3	kilogram per cubic metre (kg/m^3)	1.729 994 E+03
oz (avoirdupois)/ft^2	kilogram per square metre (kg/m^2)	3.051 517 E−01
oz (avoirdupois)/yd^2	kilogram per square metre (kg/m^2)	3.390 575 E−02
parsec	metre (m)	3.085 678 E+16
peck (U.S.)	cubic metre (m^3)	8.809 768 E−03
pennyweight	kilogram (kg)	1.555 174 E−03
perm (0°C)	kilogram per pascal second square metre [kg/(Pa·s·m^2)]	5.721 35 E−11
perm (23°C)	kilogram per pascal second square metre [kg/(Pa·s·m^2)]	5.745 25 E−11
perm·in (0°C)	kilogram per pascal second metre [kg/(Pa·s·m)]	1.453 22 E−12
perm·in (23°C)	kilogram per pascal second metre [kg/(Pa·s·m)]	1.459 29 E−12
phot	lumen per square metre (lm/m^2)	1.000 000*E+04

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[20] In 1964 the General Conference on Weights and Measures reestablished the name litre as a special name for the cubic decimetre. Between 1901 and 1964 the litre was slightly larger (1.000 0.28 dm^3); in the use of high-accuracy volume data of that time interval, this fact must be kept in mind.

To convert from	to	Multiply by
pica (printer's)	metre (m)	4.217 518 E−03
pint (U.S. dry)	cubic metre (m^3)	5.506 105 E−04
pint (U.S. liquid)	cubic metre (m^3)	4.731 765 E−04
point (printer's)	metre (m)	3.514 598*E−04
poise (absolute viscosity)	pascal second (Pa·s)	1.000 000*E−01
pound (lb avoirdupois)[21]	kilogram (kg)	4.535 924 E−01
pound (troy or apothecary)	kilogram (kg)	3.732 417 E−01
lb·ft^2 (moment of inertia)	kilogram square metre (kg·m^2)	4.214 011 E−02
lb·in^2 (moment of inertia)	kilogram square metre (kg·m^2)	2.926 397 E−04
lb/(ft·h)	pascal second (Pa·s)	4.133 789 E−04
lb/ft·s	pascal second (Pa·s)	1.488 164 E+00
lb/ft^2	kilogram per square metre (kg/m^2)	4.882 428 E+00
lb/ft^3	kilogram per cubic metre (kg/m^3)	1.601 846 E+01
lb/gal (U.K. liquid)	kilogram per cubic metre (kg/m^3)	9.977 637 E+01
lb/gal (U.S. liquid)	kilogram per cubic metre (kg/m^3)	1.198 264 E+02
lb/h	kilogram per second (kg/s)	1.259 979 E−04
lb/hp·h (SFC, specific fuel consumption)	kilogram per joule (kg/J)	1.689 659 E−07
lb/in^3	kilogram per cubic metre (kg/m^3)	2.767 990 E+04
lb/min	kilogram per second (kg/s)	7.559 873 E−03
lb/s	kilogram per second (kg/s)	4.535 924 E−01
lb/yd^3	kilogram per cubic metre (kg/m^3)	5.932 764 E−01
poundal	newton (N)	1.382 550 E−01
poundal/ft^2	pascal (Pa)	1.488 164 E+00
poundal·s/ft^2	pascal second (Pa·s)	1.488 164 E+00
pound-force (lbf)[22]	newton (N)	4.448 222 E+00
lbf·ft	newton metre (N·m)	1.355 818 E+00
lbf·ft/in	newton metre per metre (N·m/m)	5.337 866 E+01
lbf·in	newton metre (N·m)	1.129 848 E−01
lbf·in/in	newton metre per metre (N·m/m)	4.448 222 E+00
lbf·s/ft^2	pascal second (Pa·s)	4.788 026 E+01
lbf·s/in^2	pascal second (Pa·s)	6.894 757 E+03
lbf/ft	newton per metre (N/m)	1.459 390 E+01
lbf/ft^2	pascal (Pa)	4.788 026 E+01
lbf/in	newton per metre (N/m)	1.751 268 E+02
lbf/in^2 (psi)	pascal (Pa)	6.894 757 E+03
lbf/lb (thrust [mass] ratio)	newton per kilogram (N/kg)	9.806 650 E+00
quart (U.S. dry)	cubic metre (m^3)	1.101 221 E−03
quart (U.S. liquid)	cubic metre (m^3)	9.463 529 E−04
rad (absorbed dose)	gray (Gy)	1.000 000*E−02
rem (dose equivalent)	sievert (Sv)	1.000 000*E−02
rhe	1 per pascal second [1/(Pa·s)]	1.000 000*E+01
rod[13]	metre (m)	5.029 210 E+00
roentgen	coulomb per kilogram (C/kg)	2.58 000*E−04
rpm (r/min)	radian per second (rad/s)	1.047 198 E−01
second (angle)	radian (rad)	4.848 137 E−06
second (sidereal)	second (s)	9.972 696 E−01
shake	second (s)	1.000 000*E−08
slug	kilogram (kg)	1.459 390 E+01
slug/ft·s	pascal second (Pa·s)	4.788 026 E+01
slug/ft^3	kilogram per cubic metre (kg/m^3)	5.153 788 E+02
statampere	ampere (A)	3.335 640 E−10
statcoulomb	coulomb (C)	3.335 640 E−10
statfarad	farad (F)	1.112 650 E−12
stathenry	henry (H)	8.987 554 E+11
statmho	siemens (S)	1.112 650 E−12
statohm	ohm (Ω)	8.987 554 E+11
statvolt	volt (V)	2.997 925 E+02

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[21] The exact conversion factor is 4.535 923 7*E−01.

[22] The exact conversion factor is 4.448 221 615 260 5*E+00.

To convert from	to	Multiply by
stere	cubic metre (m^3)	1.000 000*E+00
stilb	candela per square metre (cd/m^2)	1.000 000*E+04
stokes (kinematic viscosity)	square metre per second (m^2/s)	1.000 000*E−04
tablespoon	cubic metre (m^3)	1.478 676 E−05
teaspoon	cubic metre (m^3)	4.928 922 E−06
tex	kilogram per metre (kg/m)	1.000 000*E−06
therm (European Community)[23]	joule (J)	1.055 06 E+08
therm (U.S.)[23]	joule (J)	1.054 804*E+08
ton (assay)	kilogram (kg)	2.916 667 E−02
ton (long, 2240 lb)	kilogram (kg)	1.016 047 E+03
ton (metric)	kilogram (kg)	1.000 000*E+03
ton (nuclear equivalent of TNT)	joule (J)	4.184 E+09[24]
ton of refrigeration (= 12 000 Btu/h)	watt (W)	3.517 E+03
ton (register)	cubic metre (m^3)	2.831 685 E+00
ton (short, 2000 lb)	kilogram (kg)	9.071 847 E+02
ton (long)/yd^3	kilogram per cubic metre (kg/m^3)	1.328 939 E+03
ton (short)/yd^3	kilogram per cubic metre (kg/m^3)	1.186 553 E+03
ton (short)/h	kilogram per second (kg/s)	2.519 958 E−01
ton-force (2000 lbf)	newton (N)	8.896 443 E+03
tonne	kilogram (kg)	1.000 000*E+03
torr (mmHg, 0°C)	pascal (Pa)	1.333 22 E+02
unit pole	weber (Wb)	1.256 637 E−07
W·h	joule (J)	3.600 000*E+03
W·s	joule (J)	1.000 000*E+00
W/cm^2	watt per square metre (W/m^2)	1.000 000*E+04
W/in^2	watt per square metre (W/m^2)	1.550 003 E+03
yard	metre (m)	9.144 000*E−01
yd^2	square metre (m^2)	8.361 274 E−01
yd^3	cubic metre (m^3)	7.645 549 E−01
yd^3/min	cubic metre per second (m^3/s)	1.274 258 E−02
year (365 days)	second (s)	3.153 600*E+07
year (sidereal)	second (s)	3.155 815 E+07
year (tropical)	second (s)	3.155 693 E+07

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[23] The therm (European Community) is legally defined in the Council of the European Communities Directive 80/181/EC of December 20, 1979. The therm (U.S.) is legally defined in the *Federal Register*, Vol 33, No. 146, p. 10756, of July 27, 1968. Although the European therm, which is based on the International Table Btu, is frequently used by engineers in the U.S., the therm (U.S.) is the legal unit used by the U.S. natural gas industry.

[24] Defined (not measured) value.

CLASSIFIED LIST OF UNITS

To convert from	to	Multiply by

ACCELERATION

ft/s^2	metre per second squared (m/s^2)	3.048 000*E-01
free fall, standard (*g*)	metre per second squared (m/s^2)	9.806 650*E+00
gal	metre per second squared (m/s^2)	1.000 000*E-02
in/s^2	metre per second squared (m/s^2)	2.540 000*E-02

ANGLE

degree	radian (rad)	1.745 329 E-02
minute	radian (rad)	2.908 882 E-04
second	radian (rad)	4.848 137 E-06
grade	degree (angular)	9.000 000*E-01
grade	radian (rad)	1.570 796 E-02

AREA

acre[13]	square metre (m^2)	4.046 873 E+03
are	square metre (m^2)	1.000 000*E+02
barn	square metre (m^2)	1.000 000*E-28
circular mil	square metre (m^2)	5.067 075 E-10
ft^2	square metre (m^2)	9.290 304*E-02
hectare	square metre (m^2)	1.000 000*E+04
in^2	square metre (m^2)	6.451 600*E-04
mi^2 (international)	square metre (m^2)	2.589 988 E+06
mi^2 (U.S. statute)[13]	square metre (m^2)	2.589 998 E+06
yd^2	square metre (m^2)	8.361 274 E-01

BENDING MOMENT OR TORQUE (See 3.4.4)

dyne·cm	newton metre (N·m)	1.000 000*E-07
kgf·m	newton metre (N·m)	9.806 650*E+00
ozf·in	newton metre (N·m)	7.061 552 E-03
lbf·in	newton metre (N·m)	1.129 848 E-01
lbf·ft	newton metre (N·m)	1.355 818 E+00

BENDING MOMENT OR TORQUE PER UNIT LENGTH

lbf·ft/in	newton metre per metre (N·m/m)	5.337 866 E+01
lbf·in/in	newton metre per metre (N·m/m)	4.448 222 E+00

CAPACITY (See VOLUME)

DENSITY (See MASS PER UNIT VOLUME)

ELECTRICITY AND MAGNETISM[25]

abampere	ampere (A)	1.000 000*E+01
abcoulomb	coulomb (C)	1.000 000*E+01
abfarad	farad (F)	1.000 000*E+09
abhenry	henry (H)	1.000 000*E-09
abmho	siemens (S)	1.000 000*E+09

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[25] ESU means electrostatic cgs unit. EMU means electromagnetic cgs unit.

To convert from	to	Multiply by
abohm	ohm (Ω)	1.000 000*E−09
abvolt	volt (V)	1.000 000*E−08
ampere hour	coulomb (C)	3.600 000*E+03
EMU of capacitance	farad (F)	1.000 000*E+09
EMU of current	ampere (A)	1.000 000*E+01
EMU of electric potential	volt (V)	1.000 000*E−08
EMU of inductance	henry (H)	1.000 000*E−09
EMU of resistance	ohm (Ω)	1.000 000*E−09
ESU of capacitance	farad (F)	1.112 650 E−12
ESU of current	ampere (A)	3.335 6 E−10
ESU of electric potential	volt (V)	2.997 9 E+02
ESU of inductance	henry (H)	8.987 554 E+11
ESU of resistance	ohm (Ω)	8.987 554 E+11
faraday (based on carbon-12)	coulomb (C)	9.648 70 E+04
faraday (chemical)	coulomb (C)	9.649 57 E+04
faraday (physical)	coulomb (C)	9.652 19 E+04
gamma	tesla (T)	1.000 000*E−09
gauss	tesla (T)	1.000 000*E−04
gilbert	ampere (A)	7.957 747 E−01
maxwell	weber (Wb)	1.000 000*E−08
mho	siemens (S)	1.000 000*E+00
oersted	ampere per metre (A/m)	7.957 747 E+01
ohm centimetre	ohm metre (Ω·m)	1.000 000*E−02
ohm circular-mil per foot	ohm metre (Ω·m)	1.662 426 E−09
statampere	ampere (A)	3.335 640 E−10
statcoulomb	coulomb (C)	3.335 640 E−10
statfarad	farad (F)	1.112 650 E−12
stathenry	henry (H)	8.987 554 E+11
statmho	siemens (S)	1.112 650 E−12
statohm	ohm (Ω)	8.987 554 E+11
statvolt	volt (V)	2.997 925 E+02
unit pole	weber (Wb)	1.256 637 E−07

ENERGY (Includes WORK)

British thermal unit (International Table)[14]	joule (J)	1.055 056 E+03
British thermal unit (mean)	joule (J)	1.055 87 E+03
British thermal unit (thermochemical)	joule (J)	1.054 350 E+03
British thermal unit (39°F)	joule (J)	1.059 67 E+03
British thermal unit (59°F)	joule (J)	1.054 80 E+03
British thermal unit (60°F)	joule (J)	1.054 68 E+03
calorie (International Table)	joule (J)	4.186 800*E+00
calorie (mean)	joule (J)	4.190 02 E+00
calorie (thermochemical)	joule (J)	4.184 000*E+00
calorie (15°C)	joule (J)	4.185 80 E+00
calorie (20°C)	joule (J)	4.181 90 E+00
calorie (kilogram, International Table)	joule (J)	4.186 800*E+03
calorie (kilogram, mean)	joule (J)	4.190 02 E+03
calorie (kilogram, thermochemical)	joule (J)	4.184 000*E+03
electronvolt	joule (J)	1.602 19 E−19
erg	joule (J)	1.000 000*E−07
ft·lbf	joule (J)	1.355 818 E+00
ft-poundal	joule (J)	4.214 011 E−02
kilocalorie (International Table)	joule (J)	4.186 800*E+03
kilocalorie (mean)	joule (J)	4.190 02 E+03
kilocalorie (thermochemical)	joule (J)	4.184 000*E+03
kW·h	joule (J)	3.600 000*E+06
therm (European Community)[23]	joule (J)	1.055 06 E+08

To convert from	to	Multiply by
therm (U.S.)[23]	joule (J)	1.054 804*E+08
ton (energy equivalent of TNT)	joule (J)	4.184 E+09[24]
W·h	joule (J)	3.600 000*E+03
W·s	joule (J)	1.000 000*E+00

ENERGY PER UNIT AREA TIME

To convert from	to	Multiply by
Btu (International Table)/(ft^2·s)	watt per square metre (W/m^2)	1.135 653 E+04
Btu (International Table)/(ft^2·h)	watt per square metre (W/m^2)	3.154 591 E+00
Btu (thermochemical)/(ft^2·s)	watt per square metre (W/m^2)	1.134 893 E+04
Btu (thermochemical)/(ft^2·min)	watt per square metre (W/m^2)	1.891 489 E+02
Btu (thermochemical)/(ft^2·h)	watt per square metre (W/m^2)	3.152 481 E+00
Btu (thermochemical)/(in^2·s)	watt per square metre (W/m^2)	1.634 246 E+06
cal (thermochemical)/(cm^2·min)	watt per square metre (W/m^2)	6.973 333 E+02
cal (thermochemical)/(cm^2·s)	watt per square metre (W/m^2)	4.184 000*E+04
erg/(cm^2·s)	watt per square metre (W/m^2)	1.000 000*E−03
W/cm^2	watt per square metre (W/m^2)	1.000 000*E+04
W/in^2	watt per square metre (W/m^2)	1.550 003 E+03

FLOW (See MASS PER UNIT TIME or VOLUME PER UNIT TIME)

FORCE

To convert from	to	Multiply by
dyne	newton (N)	1.000 000*E−05
kilogram-force	newton (N)	9.806 650*E+00
kilopond (kp)	newton (N)	9.806 650*E+00
kip (1000 lbf)	newton (N)	4.448 222 E+03
ounce-force	newton (N)	2.780 139 E−01
pound-force (lbf)[22]	newton (N)	4.448 222 E+00
lbf/lb (thrust/weight [mass] ratio)	newton per kilogram (N/kg)	9.806 650 E+00
poundal	newton (N)	1.382 550 E−01
ton-force (2000 lbf)	newton (N)	8.896 443 E+03

FORCE PER UNIT AREA (See PRESSURE)

FORCE PER UNIT LENGTH

To convert from	to	Multiply by
lbf/ft	newton per metre (N/m)	1.459 390 E+01
lbf/in	newton per metre (N/m)	1.751 268 E+02

HEAT

To convert from	to	Multiply by
Btu (International Table)·ft/(h·ft^2·°F) (thermal conductivity)	watt per metre kelvin [W/(m·K)]	1.730 735 E+00
Btu (thermochemical)·ft/(h·ft^2·°F) (thermal conductivity)	watt per metre kelvin [W/(m·K)]	1.729 577 E+00
Btu (International Table)·in/(h·ft^2·°F) (thermal conductivity)	watt per metre kelvin [W/(m·K)]	1.442 279 E−01
Btu (thermochemical)·in(h·ft^2·°F) (thermal conductivity)	watt per metre kelvin [W/(m·K)]	1.441 314 E−01
Btu (International Table)·in/(s·ft^2·°F) (thermal conductivity)	watt per metre kelvin [W/(m·K)]	5.192 204 E+02
Btu (thermochemical)·in/(s·ft^2·°F) (thermal conductivity)	watt per metre kelvin [W/(m·K)]	5.188 732 E+02
Btu (International Table)/ft^2	joule per square metre (J/m^2)	1.135 653 E+04
Btu (thermochemical)/ft^2	joule per square metre (J/m^2)	1.134 893 E+04
Btu (International Table)/(h·ft^2·°F) (thermal conductance)[15]	watt per square metre kelvin [W/(m^2·K)]	5.678 263 E+00
Btu (thermochemical)/(h·ft^2·°F) (thermal conductance)[15]	watt per square metre kelvin [W/(m^2·K)]	5.674 466 E+00

To convert from	to	Multiply by
Btu (International Table)/(s·ft^2·°F)	watt per square metre kelvin [W/(m^2·K)]	2.044 175 E+04
Btu (thermochemical)/(s·ft^2·°F)	watt per square metre kelvin [W/(m^2·K)]	2.042 808 E+04
Btu (International Table)/lb	joule per kilogram (J/kg)	2.326 000*E+03
Btu (thermochemical)/lb	joule per kilogram (J/kg)	2.324 444 E+03
Btu (International Table)/(lb·°F) (heat capacity)	joule per kilogram kelvin [J/(kg·K)]	4.186 800*E+03
Btu (thermochemical)/(lb·°F) (heat capacity)	joule per kilogram kelvin [J/(kg·K)]	4.184 000*E+03
Btu (International Table)/ft^3	joule per cubic metre (J/m^3)	3.725 895 E+04
Btu (thermochemical)/ft^3	joule per cubic metre (J/m^3)	3.723 402 E+04
cal (thermochemical)/(cm·s·°C)	watt per metre kelvin [W/(m·K)]	4.184 000*E+02
cal (thermochemical)/cm^2	joule per square metre (J/m^2)	4.184 000*E+04
cal (thermochemical)/(cm^2·min)	watt per square metre (W/m^2)	6.973 333 E+02
cal (thermochemical)/(cm^2·s)	watt per square metre (W/m^2)	4.184 000*E+04
cal (International Table)/g	joule per kilogram (J/kg)	4.186 800*E+03
cal (thermochemical)/g	joule per kilogram (J/kg)	4.184 000*E+03
cal (International Table)/(g·°C)	joule per kilogram kelvin [J/(kg·K)]	4.186 800*E+03
cal (thermochemical)/(g·°C)	joule per kilogram kelvin [J/(kg·K)]	4.184 000*E+03
cal (thermochemical)/min	watt (W)	6.973 333 E−02
cal (thermochemical)/s	watt (W)	4.184 000*E+00
clo	kelvin square metre per watt (K·m^2/W)	1.55 E−01
°F·h·ft^2/Btu (International Table) (thermal resistance)[17]	kelvin square metre per watt (K·m^2/W)	1.761 102 E−01
°F·h·ft^2/Btu (thermochemical) (thermal resistance)[17]	kelvin square metre per watt (K·m^2/W)	1.762 280 E−01
°F·h·ft^2/[Btu (International Table)·in] (thermal resistivity)	kelvin metre per watt (K·m/W)	6.933 471 E+00
°F·h·ft^2/[Btu (thermochemical)·in] (thermal resistivity)	kelvin metre per watt (K·m/W)	6.938 113 E+00
ft^2/h (thermal diffusivity)	square metre per second (m^2/s)	2.580 640*E−05

LENGTH

To convert from	to	Multiply by
angstrom	metre (m)	1.000 000*E−10
astronomical unit	metre (m)	1.495 979 E+11
chain[13]	metre (m)	2.011 684 E+01
fathom[13]	metre (m)	1.828 804 E+00
fermi (femtometre)	metre (m)	1.000 000*E−15
foot	metre (m)	3.048 000*E−01
foot (U.S. survey)[13]	metre (m)	3.048 006 E−01
inch	metre (m)	2.540 000*E−02
light year	metre (m)	9.460 55 E+15
microinch	metre (m)	2.540 000*E−08
micron (deprecated term, use micrometre)	metre (m)	1.000 000*E−06
mil	metre (m)	2.540 000*E−05
mile (international nautical)	metre (m)	1.852 000*E+03
mile (U.S. nautical)	metre (m)	1.852 000*E+03
mile (international)	metre (m)	1.609 344*E+03
mile (U.S. statute)[13]	metre (m)	1.609 347 E+03
parsec	metre (m)	3.085 678 E+16
pica (printer's)	metre (m)	4.217 518 E−03
point (printer's)	metre (m)	3.514 598*E−04
rod[13]	metre (m)	5.029 210 E+00
yard	metre (m)	9.144 000*E−01

LIGHT

To convert from	to	Multiply by
cd/in^2	candela per square metre (cd/m^2)	1.550 003 E+03
footcandle	lux (lx)	1.076 391 E+01
footlambert	candela per square metre (cd/m^2)	3.426 259 E+00

To convert from	to	Multiply by
lambert	candela per square metre (cd/m^2)	3.183 099 E+03
lm/ft^2	lumen per square metre (lm/m^2)	1.076 391 E+01

MASS

carat (metric)	kilogram (kg)	2.000 000*E−04
grain	kilogram (kg)	6.479 891*E−05
gram	kilogram (kg)	1.000 000*E−03
hundredweight (long)	kilogram (kg)	5.080 235 E+01
hundredweight (short)	kilogram (kg)	4.535 924 E+01
kgf·s^2/m (mass)	kilogram (kg)	9.806 650*E+00
ounce (avoirdupois)	kilogram (kg)	2.834 952 E−02
ounce (troy or apothecary)	kilogram (kg)	3.110 348 E−02
pennyweight	kilogram (kg)	1.555 174 E−03
pound (lb avoirdupois)[21]	kilogram (kg)	4.535 924 E−01
pound (troy or apothecary)	kilogram (kg)	3.732 417 E−01
slug	kilogram (kg)	1.459 390 E+01
ton (assay)	kilogram (kg)	2.916 667 E−02
ton (long, 2240 lb)	kilogram (kg)	1.016 047 E+03
ton (metric)	kilogram (kg)	1.000 000*E+03
ton (short, 2000 lb)	kilogram (kg)	9.071 847 E+02
tonne	kilogram (kg)	1.000 000*E+03

MASS PER UNIT AREA

oz/ft^2	kilogram per square metre (kg/m^2)	3.051 517 E−01
oz/yd^2	kilogram per square metre (kg/m^2)	3.390 575 E−02
lb/ft^2	kilogram per square metre (kg/m^2)	4.882 428 E+00

MASS PER UNIT CAPACITY (See MASS PER UNIT VOLUME)

MASS PER UNIT LENGTH

denier	kilogram per metre (kg/m)	1.111 111 E−07
lb/ft	kilogram per metre (kg/m)	1.488 164 E+00
lb/in	kilogram per metre (kg/m)	1.785 797 E+01
lb/yd	kilogram per metre (kg/m)	E.4960 546 E−01
tex	kilogram per metre (kg/m)	1.000 000*E−06

MASS PER UNIT TIME (Includes FLOW)

perm (0°C)	kilogram per pascal second square metre [kg/(Pa·s·m^2)]	5.721 35 E−11
perm (23°C)	kilogram per pascal second square metre [kg/(Pa·s·m^2)]	5.745 25 E−11
perm·in (0°C)	kilogram per pascal second metre [kg/(Pa·s·m)]	1.453 22 E−12
perm·in (23°C)	kilogram per pascal second metre [kg/(Pa·s·m)]	1.459 29 E−12
lb/h	kilogram per second (kg/s)	1.259 979 E−04
lb/min	kilogram per second (kg/s)	7.559 873 E−03
lb/s	kilogram per second (kg/s)	4.535 924 E−01
lb/(hp·h) (SFC, specific fuel consumption)	kilogram per joule (kg/J)	1.689 659 E−07
ton (short)/h	kilogram per second (kg/s)	2.519 958 E−01

MASS PER UNIT VOLUME (Includes DENSITY and MASS CAPACITY)

grain/gal (U.S. liquid)	kilogram per cubic metre (kg/m^3)	1.711 806 E−02
g/cm^3	kilogram per cubic metre (kg/m^3)	1.000 000*E+03
oz (avoirdupois)/gal (U.K. liquid)	kilogram per cubic metre (kg/m^3)	6.236 023 E+00

To convert from	to	Multiply by
oz (avoirdupois)/gal (U.S. liquid)	kilogram per cubic metre (kg/m³)	7.489 152 E+00
oz (avoirdupois)/in³	kilogram per cubic metre (kg/m³)	1.729 994 E+03
lb/ft³	kilogram per cubic metre (kg/m³)	1.601 846 E+01
lb/in³	kilogram per cubic metre (kg/m³)	2.767 990 E+04
lb/gal (U.K. liquid)	kilogram per cubic metre (kg/m³)	9.977 637 E+01
lb/gal (U.S. liquid)	kilogram per cubic metre (kg/m³)	1.198 264 E+02
lb/yd³	kilogram per cubic metre (kg/m³)	5.932 764 E−01
slug/ft³	kilogram per cubic metre (kg/m³)	5.153 788 E+02
ton (long)/yd³	kilogram per cubic metre (kg/m³)	1.328 939 E+03
ton (short)/yd³	kilogram per cubic metre (kg/m³)	1.186 553 E+03

POWER

Btu (International Table)/h	watt (W)	2.930 711 E−01
Btu (International Table)/s	watt (W)	1.055 056 E+03
Btu (thermochemical)/h	watt (W)	2.928 751 E−01
Btu (thermochemical)/min	watt (W)	1.757 250 E+01
Btu (thermochemical)/s	watt (W)	1.054 350 E+03
cal (thermochemical)/min	watt (W)	6.973 333 E−02
cal (thermochemical)/s	watt (W)	4.184 000*E+00
erg/s	watt (W)	1.000 000*E−07
ft·lbf/h	watt (W)	3.766 161 E−04
ft·lbf/min	watt (W)	2.259 697 E−02
ft·lbf/s	watt (W)	1.355 818 E+00
horsepower (550 ft·lbf/s)	watt (W)	7.456 999 E+02
horsepower (boiler)	watt (W)	9.809 50 E+03
horsepower (electric)	watt (W)	7.460 000*E+02
horsepower (metric)	watt (W)	7.354 99 E+02
horsepower (water)	watt (W)	7.460 43 E+02
horsepower (U.K.)	watt (W)	7.457 0 E+02
kilocalorie (thermochemical)/min	watt (W)	6.973 333 E+01
kilocalorie (thermochemical)/s	watt (W)	4.184 000*E+03
ton of refrigeration (= 12 000 Btu/h)	watt (W)	3.517 E+03

PRESSURE OR STRESS (FORCE PER UNIT AREA)

atmosphere, standard	pascal (Pa)	1.013 250*E+05
atmosphere, technical (= 1 kgf/cm²)	pascal (Pa)	9.806 650*E+04
bar (meteorological atmosphere)	pascal (Pa)	1.000 000*E+05
centimetre of mercury (0°C)	pascal (Pa)	1.333 22 E+03
centimetre of water (4°C)	pascal (Pa)	9.806 38 E+01
dyne/cm²	pascal (Pa)	1.000 000*E−01
foot of water (39.2°F)	pascal (Pa)	2.988 98 E+03
gf/cm²	pascal (Pa)	9.806 650*E+01
inch of mercury (32°F)	pascal (Pa)	3.386 38 E+03
inch of mercury (60°F)	pascal (Pa)	3.376 85 E+03
inch of water (39.2°F)	pascal (Pa)	2.490 82 E+02
inch of water (60°F)	pascal (Pa)	2.488 4 E+02
kgf/cm²	pascal (Pa)	9.806 650*E+04
kgf/m²	pascal (Pa)	9.806 650*E+00
kgf/mm²	pascal (Pa)	9.806 650*E+06
kip/in² (ksi)	pascal (Pa)	6.894 757 E+06
millibar	pascal (Pa)	1.000 000*E+02
millimetre of mercury (0°C)	pascal (Pa)	1.333 22 E+02
poundal/ft²	pascal (Pa)	1.488 164 E+00
lbf/ft²	pascal (Pa)	4.788 026 E+01
lbf/in² (psi)	pascal (Pa)	6.894 757 E+03
psi	pascal (Pa)	6.894 757 E+03

To convert from	to	Multiply by
torr (mmHg, 0°C)	pascal (Pa)	1.333 22 E+02

RADIATION UNITS

To convert from	to	Multiply by
curie	becquerel (Bq)	3.700 000*E+10
rad	gray (Gy)	1.000 000*E−02
rem	sievert (Sv)	1.000 000*E−02
roentgen	coulomb per kilogram (C/kg)	2.580 000*E−04

SPEED (See VELOCITY)

STRESS (See PRESSURE)

TEMPERATURE

To convert from	to	Multiply by
degree Celsius	kelvin (K)	$T_K = t_{°C} + 273.15$
degree Fahrenheit	degree Celsius (°C)	$t_{°C} = (t_{°F} - 32)/1.8$
degree Fahrenheit	kelvin (K)	$T_K = (t_{°F} + 459.67)/1.8$
degree Rankine	kelvin (K)	$T_K = T_{°R}/1.8$
kelvin	degree Celsius (°C)	$t_{°C} = T_K - 273.15$

TIME

To convert from	to	Multiply by
day	second (s)	8.640 000*E+04
day (sidereal)	second (s)	8.616 409 E+04
hour	second (s)	3.600 000*E+03
hour (sidereal)	second (s)	3.590 170 E+03
minute	second (s)	6.000 000*E+01
minute (sidereal)	second (s)	5.983 617 E+01
second (sidereal)	second (s)	9.972 696 E−01
year (365 days)	second (s)	3.153 600*E+07
year (sidereal)	second (s)	3.155 815 E+07
year (tropical)	second (s)	3.155 693 E+07

TORQUE (See BENDING MOMENT)

VELOCITY (Includes SPEED)

To convert from	to	Multiply by
ft/h	metre per second (m/s)	8.466 667 E−05
ft/min	metre per second (m/s)	5.080 000*E−03
ft/s	metre per second (m/s)	3.048 000*E−01
in/s	metre per second (m/s)	2.540 000*E−02
km/h	metre per second (m/s)	2.777 778 E−01
knot (international)	metre per second (m/s)	5.144 444 E−01
mi/h (international)	metre per second (m/s)	4.470 400*E−01
mi/min (international)	metre per second (m/s)	2.682 240*E+01
mi/s (international)	metre per second (m/s)	1.609 344*E+03
mi/h (international)	kilometre per hour (km/h)[26]	1.609 344*E+00
rpm (r/min)	radian per second (rad/s)	1.047 198 E−01

VISCOSITY

To convert from	to	Multiply by
centipoise (dynamic viscosity)	pascal second (Pa·s)	1.000 000*E−03
centistokes (kinematic viscosity)	square metre per second (m^2/s)	1.000 000*E−06
ft^2/s	square metre per second (m^2/s)	9.290 304*E−02
poise	pascal second (Pa·s)	1.000 000*E−01
poundal·s/ft^2	pascal second (Pa·s)	1.488 164 E+00
lb/(ft·h)	pascal second (Pa·s)	4.133 789 E−04
lb/(ft·s)	pascal second (Pa·s)	1.488 164 E+00
lbf·s/ft^2	pascal second (Pa·s)	4.788 026 E+01

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[26] Although speedometers may read km/h, the SI unit is m/s.

To convert from	to	Multiply by
lbf·s/in^2	pascal second (Pa·s)	6.894 757 E+03
rhe	1 per pascal second [1/(Pa·s)]	1.000 000*E+01
slug/(ft·s)	pascal second (Pa·s)	4.788 026 E+01
stokes	square metre per second (m^2/s)	1.000 000*E−04

VOLUME (Includes CAPACITY)

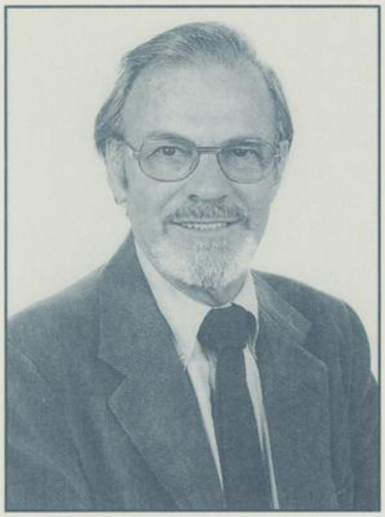
To convert from	to	Multiply by
acre-foot[13]	cubic metre (m^3)	1.233 489 E+03
barrel (oil, 42 gal)	cubic metre (m^3)	1.589 873 E−01
board foot	cubic metre (m^3)	2.359 737 E−03
bushel (U.S.)	cubic metre (m^3)	3.523 907 E−02
cup	cubic metre (m^3)	2.365 882 E−04
ounce (U.S. fluid)	cubic metre (m^3)	2.957 353 E−05
ft^3	cubic metre (m^3)	2.831 685 E−02
gallon (Canadian liquid)	cubic metre (m^3)	4.546 090 E−03
gallon (U.K. liquid)	cubic metre (m^3)	4.546 092 E−03
gallon (U.S. dry)	cubic metre (m^3)	4.404 884 E−03
gallon (U.S. liquid)	cubic metre (m^3)	3.785 412 E−03
gill (U.K.)	cubic metre (m^3)	1.420 653 E−04
gill (U.S.)	cubic metre (m^3)	1.182 941 E−04
in^3 [see footnote 19]	cubic metre (m^3)	1.638 706 E−05
litre [see footnote 20]	cubic metre (m^3)	1.000 000*E−03
ounce (U.K. fluid)	cubic metre (m^3)	2.841 306 E−05
ounce (U.S. fluid)	cubic metre (m^3)	2.957 353 E−05
peck (U.S.)	cubic metre (m^3)	8.809 768 E−03
pint (U.S. dry)	cubic metre (m^3)	5.506 105 E−04
pint (U.S. liquid)	cubic metre (m^3)	4.731 765 E−04
quart (U.S. dry)	cubic metre (m^3)	1.101 221 E−03
quart (U.S. liquid)	cubic metre (m^3)	9.463 529 E−04
stere	cubic metre (m^3)	1.000 000*E+00
tablespoon	cubic metre (m^3)	1.478 676 E−05
teaspoon	cubic metre (m^3)	4.928 922 E−06
ton (register)	cubic metre (m^3)	2.831 685 E+00
yd^3	cubic metre (m^3)	7.645 549 E−01

VOLUME PER UNIT TIME (Includes FLOW)

To convert from	to	Multiply by
ft^3/min	cubic metre per second (m^3/s)	4.719 474 E−04
ft^3/s	cubic metre per second (m^3/s)	2.831 685 E−02
gallon (U.S. liquid)/(hp·h)(SFC, specific fuel consumption)	cubic metre per joule (m^3/J)	1.410 089 E−09
in^3/min	cubic metre per second (m^3/s)	2.731 177 E−07
yd^3/min	cubic metre per second (m^3/s)	1.274 258 E−02
gallon (U.S. liquid) per day	cubic metre per second (m^3/s)	4.381 264 E−08
gallon (U.S. liquid) per minute	cubic metre per second (m^3/s)	6.309 020 E−05

WORK (See ENERGY)

ABOUT THE EDITOR



Heinz R. Trechsel

As principal of H. R. Trechsel Associates, Germantown, MD, Trechsel investigates moisture problems and their causes and develops appropriate remedial actions and acts as an expert witness in cases relating to moisture damage in buildings. He is also Criteria Manager for the Engineering Field Activity Chesapeake, Naval Facilities Engineering Command, Washington, DC.

Mr. Trechsel is a graduate architect of the Swiss Federal Institute of Technology in Zurich and a registered architect in the state of New York. Postgraduate work includes courses in building technology, economics, human factors, and in asbestos and lead paint abatement.

Previously, Trechsel was manager for building energy conservation and rehabilitation programs at the National Bureau of Standards (now National Institute for Standards and Technology). Before then, he was employed at the research laboratory of the United States Steel Corporation (now USX), developing innovative fireproofing methods and steel building products and systems such as walls, modular construction, and related test procedures. Immediately following graduation, he worked for several years as a designer in architectural offices in Europe and in New York.

A member of ASTM since 1961, Trechsel is active on Committees C16 on Thermal Insulation, D20 on Plastics, and E06 on Performance of Buildings. In 1986, he received the ASTM Award of Merit for his contributions to the development of methods and practices relating to air movements and moisture in buildings. He is currently Chairman of the Building Environment and Thermal Envelope Council (BETEC) under the auspices of the National Institute of Building Sciences and is a member of ASHRAE TC 4.4.

Trechsel has published extensively on moisture control in buildings, energy conservation, and building diagnostics and was coeditor of *Building Air Change Rate and Infiltration Measurements, STP 719; Moisture Migration in Buildings, STP 779; Measured Air Leakage of Buildings, STP 904;* and *Water Vapor Transmission Through Building Materials and Systems, STP 1039.*

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