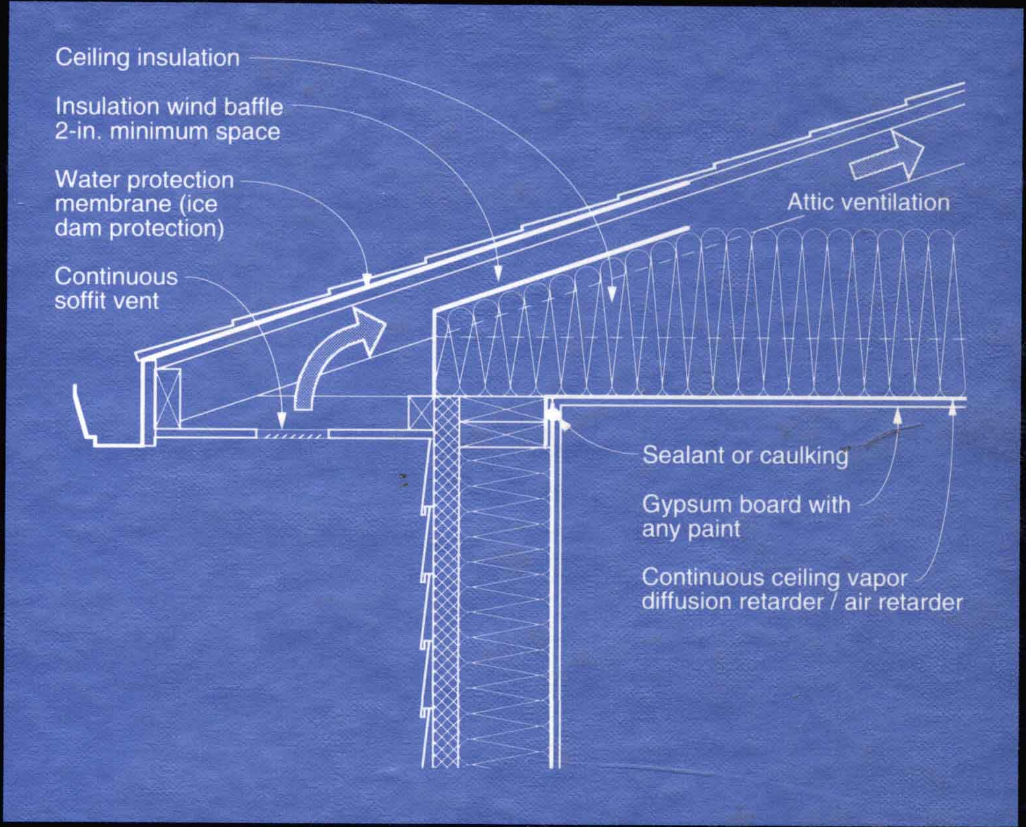
Moisture Control HANDBOOK



Principles and Practices for Residential and Small Commercial Buildings

Joseph Lstiburek / John Carmody

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Preface

The original version of this handbook was a product of the U.S. Department of Energy (DOE) Building Envelope Systems and Materials (BTESM) Research Program centered at Oak Ridge National Laboratory (ORNL). The major objective of the research effort in building moisture control is to provide information to builders, contractors, and building owners that will lead to the construction of energy-efficient walls, roofs, and foundations. The first edition of this handbook, published in 1991, represented one in a series of design tools produced to provide the most current design information.

For the first edition, ORNL formed a review panel of moisture experts to provide technical guidance for this effort. This group reviewed the outline as well as several drafts of the handbook, and through this process strengthened the technical content.

The construction details shown for heating, mixed, and cooling climates are based on moisture transport principles. A growing number of designers realize it is too costly and too risky to completely keep moisture from penetrating building envelopes. Building envelope materials occasionally have high initial moisture levels, and degradation of siding, sheathing, membranes, sealants, caulking, and flashings can contribute significantly to the moisture load. Thus, the approach is to keep moisture levels low within building assemblies by providing a path for moisture to periodically escape. A design strategy that assumes building envelopes may get wet and permits them to dry, presents a more forgiving and perhaps less costly alternative.

This handbook, revised by the authors, represents yet another step in helping designers and builders to understand and utilize moisture control strategies. It is very satisfying to see products seeded with a few public dollars lead to successful commercial products. The contents of this book include a systematic method of evaluating moisture problems and moisture control strategies. The handbook provides a valuable set of principles to have on hand as your designs evolve into future buildings.

Jeffrey Christian
Manager, Building Envelope Systems
and Materials Program
Oak Ridge National Laboratory
P.O. Box 2008
Building 3147, MS-6070
Oak Ridge, TN 37831-6070

Acknowledgments

This handbook represents a major revision, expansion, and refinement of the original *Moisture Control Handbook* prepared by the authors for the U.S. Department of Energy. Both this handbook and the earlier version on which it is based were made possible by the contributions and assistance of many people.

Sam Taylor of the U.S. Department of Energy was instrumental in the initiation of this project. He conceived of this handbook as a means of collecting and presenting existing information in a form useful to designers and builders. In addition, the handbook project was intended to identify areas where information was lacking, and thus, would serve as a needed element of the DOE Building Moisture Research effort. Sam's continuing contributions throughout the development of the project were appreciated.

The moisture handbook project was managed by Jeff Christian of Oak Ridge National Laboratory. The authors appreciate his contributions, criticism, and particularly his patience in coordinating this complex project over a long period of time.

Professor John Timusk, University of Toronto; and Gustav Handegord, formerly of the National Research Council of Canada, were the technical advisors to the project.

George Tsongas, Portland State University; Lester Shen, University of Minnesota; John Tooley and Neil Moyer, Florida Natural Retrofit; and Jim White, Canada Mortgage and Housing Corporation, provided guidance and advice. Finally, the manuscript was improved considerably by the editing of Pam Snopl.

Joseph Lstiburek
Building Science Corporation
Chestnut Hill, Massachusetts

John Carmody
Underground Space Center
University of Minnesota

Introduction

Moisture problems in buildings are prevalent throughout North America, almost independent of climate. They are viewed as the single largest factor limiting the useful service life of a structure. Elevated levels of moisture in buildings also can lead to serious health effects for occupants.

In residential buildings, homeowners (or their builders) may be faced with costly repairs in addition to suffering the health-related consequences of mold growth. In commercial structures, moisture problems can lead to lost revenues and litigation resulting from structural deterioration as well as worker health problems related to indoor air quality. In some cases, facilities must be closed while hundreds of thousands of dollars are spent on repairs, often incorrectly or ineffectively.

Until recently, very little consensus on moisture control existed in the building community. The information available was typically incomplete, contradictory, usually limited to specific regions, and in many cases misleading.

This handbook is intended to help homeowners, architects, mechanical engineers, and building contractors to understand mold and moisture problems in housing so that they can be prevented or corrected. While this book focuses on residential construction, many of the basic problems, principles, and solutions are similar for all building types.

In order to understand and prevent moisture problems, a building must be viewed as a complex system of interacting variables. Some of these interacting mechanisms include heat flow, air flow, moisture flow, and chemical and biological reactions within the building. People's behavior patterns, climate, building envelope design, construction practice, conditions during construction, and building operation are all factors influencing moisture problems and solutions.

The remainder of this introduction includes (1) a review of historical changes in housing construction that have led to increased moisture problems, (2) a set of goals for effective building design and construction, (3) a discussion of the variables involved in understanding a building as an overall system, and (4) a description of this handbook.

HISTORICAL CHANGES TO HOUSING CONSTRUCTION

In the last 50 years there have been some important changes to the way in which we build and operate buildings. These include: (1) the introduction of thermal insulation, (2) the development of tighter building enclosures, (3) the elimination of active chimneys, and (4) the introduction of forced air heating and cooling systems. These changes have influenced the occupants' health, safety, and comfort as well as the durability and affordability of the structure.

Thermal Insulation

When thermal insulation was widely introduced in the 1950's, its primary purpose was to reduce the heat flows into and out of buildings to make them more comfortable. Later, as energy conservation became important, insulation levels were increased to reduce operating costs. Clearly, thermal insulation is effective in achieving these goals.

A little understood by-product of the addition of thermal insulation, however, was the reduction of the drying potential of the building enclosure. Since heat and air flow through the building assemblies (roofs, walls, and foundations) are reduced, their ability to dry is diminished should they get wet from either interior or exterior sources. This impact of insulation is similar regardless of climate.

Tighter Building Enclosures

Building enclosures have become much tighter since the 1950's (Figure I-1). A typical building today is almost twice as tight as its counterpart built a few decades ago. The increase in tightness occurred as a result of the introduction of new materials and production techniques (sheet goods such as plywood, drywall, and precast panels), as well as a desire to increase comfort (eliminate drafts) and reduce energy usage (high heating and cooling costs). A tighter building results in a lower exchange of air between the interior conditioned space and the exterior. The lower the air change, the less the dilution of moisture and interior pollutants such as formaldehyde, other volatile organic compounds, radon, and carbon dioxide. This trend toward lower air change occurred simultaneously with the introduction of hundreds of thousands of new chemical compounds, materials, and products which were developed to satisfy the growing consumer demand for goods and furnishings.

This increase in interior pollutant sources combined with the decrease in the dilution of the air has resulted in higher indoor air pollutant concentrations. In commercial construction this has manifested itself in Sick Building Syndrome (SBS) complaints and cases of Building Related Illness (BRI). In residential construction the tighter enclosures also resulted in the reduction of a typical chimney's ability to exhaust combustion products which leads to spillage of these products, backdrafting of furnaces, water heaters, and fireplaces, and the associated health and safety problems. The most noticeable symptom of these changes is the increased levels of moisture in typical buildings. This manifests itself with mold and mildew on interior surfaces in cooling and heating climates as well as condensation on the interior of windows in heating climates.

Elimination of Active Chimneys

In residential and small facility construction, the trend towards using electric heating, heat pumps, and power vented, sealed combustion furnaces has resulted in the elimination of the traditional active chimney. Active

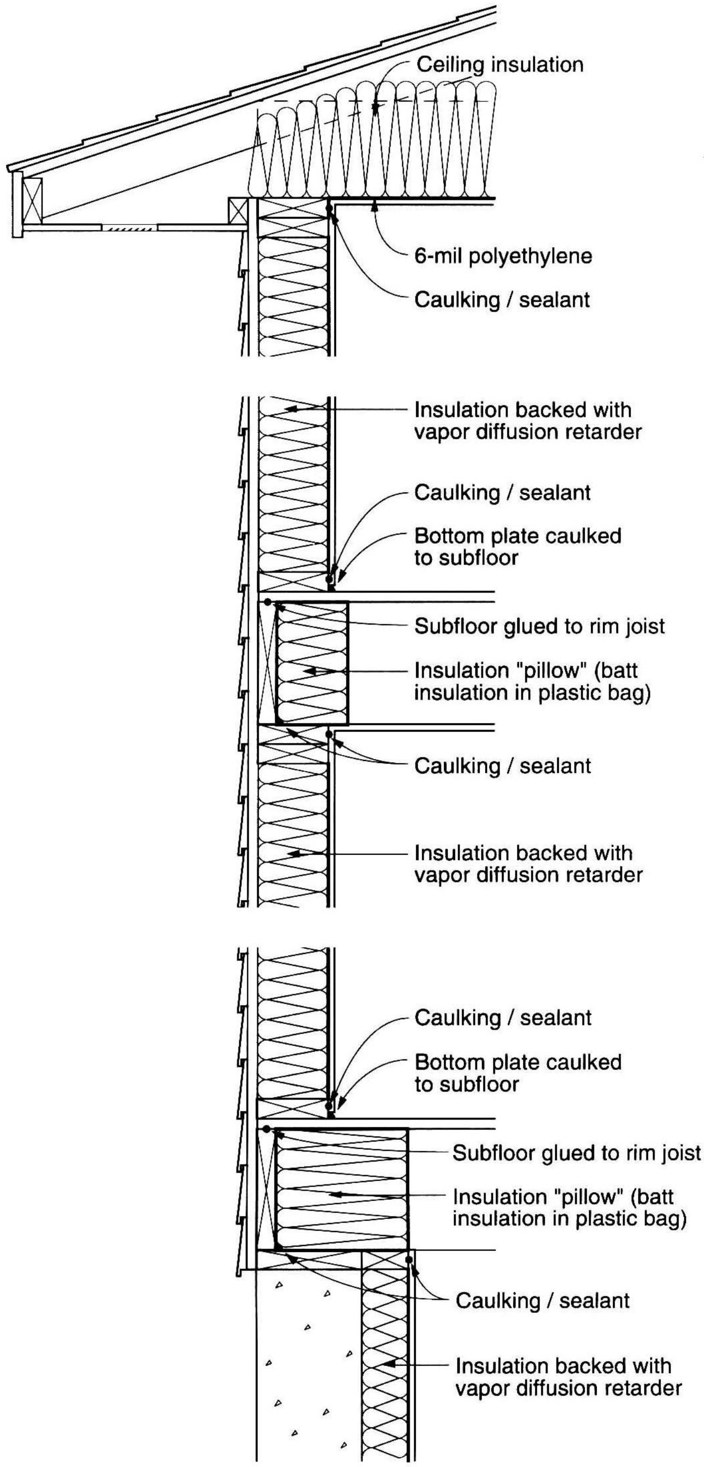

Figure I-1: This wall section illustrates tightly sealed, well-insulated construction. Increased insulation and tighter building enclosures improve energy use and thermal comfort, but can contribute to higher accumulations of moisture and various indoor air pollutants within the building envelope.

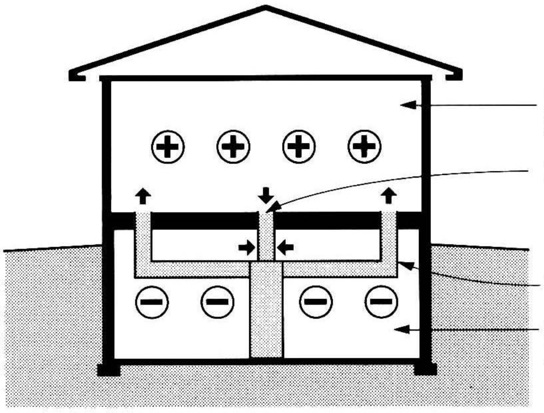

Figure I-2: In heating climates, a forced air system with leaky return ducts leads to pressurized living areas and depressurized basements. Warm, moisture-laden air is driven into the above-grade building assemblies, while radon and moisture from the soil is drawn into the basement.

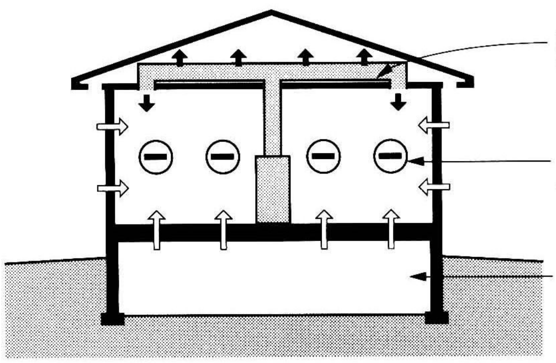

Figure I-3: In cooling climates, a forced air system with leaky supply ducts that are placed outside of the conditioned space leads to depressurized living areas. Warm, moisture-laden air from the exterior is drawn into the above-grade building assemblies.

chimneys were exhaust fans which extracted great quantities of air from the conditioned space and resulted in frequent air changes and the subsequent dilution of interior pollutants. Eliminating the "chimney fan" has led to an increase in levels of moisture and interior pollutants. Active chimneys also tended to depressurize conditioned spaces during heating periods, which reduced wetting of building assemblies from interior air transported moisture and led to a more forgiving building envelope.

Heating and Cooling Systems

In terms of building technology, forced air heating, ventilation, and air conditioning systems are rather recent innovations. Moving relatively large quantities of air around within building enclosures of increasing tightness has led to serious health, safety, durability, and operating cost issues.

In heating climates, supply duct systems are more extensive than return duct systems (Figure I-2). There are typically supply registers in each room, with common returns. Rooms are pressurized and common areas are depressurized by the combination of more extensive supply systems with leaky return ducts and interior door closure. The depressurization and pressurization of conditioned spaces is increased as the building envelope becomes tighter. This can lead to the infiltration of radon, moisture, pesticides, and soil gas in foundations. In addition, warm moisture-laden air can exfiltrate into wall and roof cavities, resulting in problems since higher levels of insulation have created lower drying potentials.

In cooling climates, supply ducts are often run exterior to the building envelope in attic, roof, and crawl spaces (Figure I-3). The supply ducts typically leak, leading to the depressurization of the building enclosure. Interior door closure with common return systems can also depressurize the main body of a building. The depressurization of the conditioned space results in the infiltration of hot, humid air from the exterior and subsequent problems with comfort, mold, mildew, and high cooling costs.

GOALS FOR EFFECTIVE DESIGN AND CONSTRUCTION

The major changes in housing construction over the past three decades have generally improved comfort and energy conservation, but they have also contributed to structural deterioration, major insurance and warranty problems, as well as health, safety, and comfort concerns.

It is not practical to return to constructing leaky building enclosures that lacked thermal insulation, and had less efficient heating and air conditioning systems. The marketplace demands sophisticated, high performance buildings operated and maintained intelligently. As improved building systems are evolving, it is important to state the basic goals of housing design and construction. These are health and safety, durability, comfort, and affordability. Achieving each of these goals depends in part on understanding and resolving moisture problems in buildings.

Health and Safety

Indoor air quality is the major factor that influences short-term and long-term health of occupants and is directly related to the concentration of pollutants within building enclosures. The source of pollutants in conditioned spaces, in order of impact, are:

- Combustion products
- Moisture and biological products
- Radon
- Formaldehyde and other volatile organic compounds (V.O.C.'s)
- Particulates
- Carbon dioxide

Each of these pollutants can be controlled by reducing the source. For example, properly installed gas or oil appliances and fireplaces can eliminate combustion by-products. Tight foundations coupled with air pressure control will prevent radon infiltration. Formaldehyde can be eliminated or reduced by using building products with zero or low formaldehyde emission ratings. The presence of other V.O.C.'s can be controlled by storing cleansers and cleaning agents outside of the conditioned space or by using safe, alternative products. Air filtration can control particulates and elimination of unvented space heaters controls excessive carbon dioxide and nitrogen by-products.

Mold and dust mite infestation produce the major health concerns related to excessive moisture in buildings. Strategies to prevent this problem are presented throughout this book. For example, control of excessive negative pressures and unconditioned make-up air in cooling climates will reduce the presence of moisture. Also, a correctly designed and constructed foundation will reduce the presence of moisture in heating and cooling climates.

Durability

It makes sense for the building industry to produce and operate facilities that will stand the test of time. A building should have a useful service life three to four times the mortgage period. If the mortgage period is 25 years, the useful service life should be between 75 and 100 years. While many facilities built at the turn of the century are still performing their function with grace and dignity, the same is not likely to be said a hundred years from now about many of today's buildings.

The development of a durable building starts with proper design and material selection. It also requires correct installation by the contractor as well as care and maintenance by the owner/occupant. It is unlikely that buildings will be maintained if they are not designed and built from the very start to be easily maintainable. Finally, the owner/occupant needs to be educated about the maintenance requirements of the building.

Historically, the single greatest factor affecting the durability of buildings has been excessive moisture. Moisture causes wood products to decay, metals to corrode, paint and coating systems to separate from substrate, and concrete and masonry to effloresce, spall, and flake. Changing moisture levels cause elements, assemblies, and entire buildings to move. Moisture problems often lead to maintenance nightmares. Control of moisture is proving to be a prerequisite for a durable building in all climate zones.

Comfort

Comfort involves satisfying the sensory perceptions of people. Comfort parameters include:

- Temperature/thermal comfort
- Moisture/relative humidity
- Odors/indoor air quality
- Vibration/noise
- Light/daylighting and illumination

There is an interrelationship between humidity and other comfort parameters such as temperature and odors. The ASHRAE psychrometric chart establishes the standard comfort zones for summer and winter (see Chapter 1). These comfort zones approximately cover the following ranges:

Winter Comfort Zone:
Temperature: 20-24°C (68-75°F)
Relative Humidity: 30-60%

Summer Comfort Zone:
Temperature: 23-26°C (72-78°F)
Relative Humidity: 25-60%

Affordability

The concept of affordability has different meanings for different people. Most will agree, however, that the market value of a house or commercial structure is one measure of its affordability. This figure is based on several components including the one-time cost of building construction, land, and financing. However, many are beginning to recognize that an affordable building must also minimize long-term operating costs for utilities and maintenance. Avoiding moisture problems plays a role in creating affordable housing by reducing costly repairs and maintenance.

FACTORS INFLUENCING DESIGN AND OPERATION OF BUILDINGS

Resolving moisture problems in buildings requires an approach that views the entire house, its external environment, and its occupants as an interrelated set of factors. Otherwise, if buildings are viewed as a set of isolated components or systems, solving one problem may simply create another one—or worse, the problem may never be diagnosed and solved correctly in the first place. By having an overall understanding of building systems, not only can moisture problems be addressed effectively, but other comfort, health, and energy use problems can be resolved simultaneously.

The factors influencing building design and operation can generally be divided into three groups: (1) climatic and environmental conditions, (2) building occupants, and (3) building systems and components. The manner in which buildings actually perform is governed by basic principles of building science including mechanisms of heat, air, and moisture flow, as well as chemical and biological reactions.

Climatic and Environmental Conditions

There are many ways to define climatic zones in North America. For the purpose of making recommendations regarding moisture control, a very simple division into three basic zones is acceptable (Figure I-4). These zones, defined more precisely in later chapters, are characterized by the type of environmental control they require for most of the year (heating, cooling, or mixed). Within these zones are areas of relative wetness or dryness as well as special microclimatic conditions. These variations in wetness within a particular climate zone generally do not dictate different strategies for moisture control. Instead, wetter conditions will simply indicate more potential for significant problems, and that building assemblies will be less forgiving than in dryer conditions.

Designing in response to the climate is an important concept, especially with respect to moisture problems. In heating climates one designs for heat and moisture that predictably move from the interior of the building to the exterior, while in cooling climates the reverse is true. In either case, it is relatively easy to design for a climate that is limited to all heating or all cooling conditions. When both heating and cooling are required over large portions of the year, design can be more complex since trade-offs must be made. This is particularly true when the climates are also wet, and therefore less forgiving.

In addition to being influenced by overall climatic and microclimatic conditions, a building's design and operation can be affected by the contaminants around and within the building. These include contaminants that may be built into or brought into the building.

An obvious example of the influence of the external environment can be found in a building placed on soil with high radon concentrations. External pollution sources also include outdoor air contaminants as well as excessive noise and vibration. Within the building, materials and furnishings contribute contaminants such as formaldehyde, while appliances may produce undesirable combustion products. The building occupants, as described below, also influence pollutant sources within a home.

Building Occupants

By controlling temperature and humidity, the occupants of a building significantly influence comfort, durability, health, and safety. Buildings in heating climates cannot be

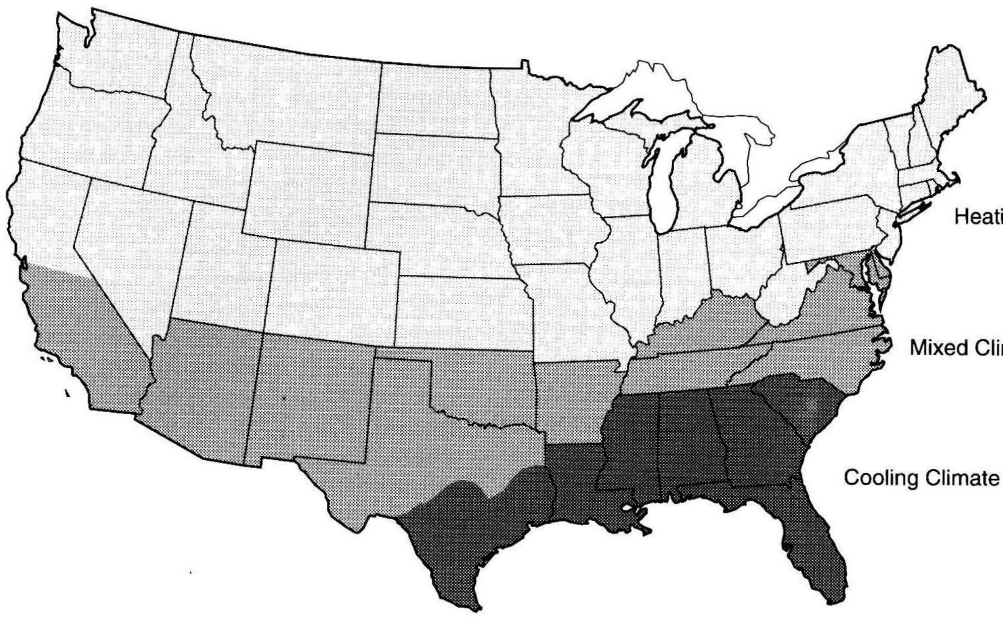

Figure I-4: United States climatic zones used for moisture recommendations.

operated safely and maximize durability if maintained at high levels of interior humidity during heating periods. Likewise, in wet, cooling climates buildings cannot be operated safely or maximize durability if interior temperatures are too low during the hot, humid cooling periods.

People also influence the indoor environment in other ways as well. They produce carbon dioxide, odors, heat, and moisture. In addition, they make choices that introduce various contaminants into the interior environment (i.e. hazardous chemicals, paint cleaners, cleansers, and tobacco smoke).

Building Systems and Components

A building consists of the building envelope and the subsystems contained within it. Building envelopes, which enclose the conditioned space, separate the interior and the occupants from the exterior environment. The building envelope is composed of assemblies including the exterior walls, foundation, ceiling, roof, windows, and doors. Subsystems include the equipment that heats, cools, and ventilates the conditioned space, as well as the structural, plumbing, and electrical systems.

The building itself must be viewed as a complex set of interrelated systems and components. A change in an element or subsystem can change the performance of an assembly, the building envelope, and ultimately change the characteristics of the entire building. In recent decades, there have been revolutionary developments in products, materials, and systems and the technology of construction has become quite complex. The building envelope and mechanical system interact with and influence interior environmental conditions as never before. For example, many buildings experience excessive depressurization of rooms, corridors, or interstitial spaces which can be a powerful mechanism in drawing moisture into building assemblies.

Mechanisms Underlying Building Performance

It has been stated that the building components, assemblies, and subsystems interact with each other. Moreover, the building interacts with the people who occupy it, as well as the environmental and climatic conditions in which it is placed. In order to diagnose, solve, and prevent moisture problems, as well as meet the broad goals for effective building design outlined earlier, these interactions must be understood. The underlying physical mechanisms that govern these interactions—heat flow, air flow, moisture flow, as well as chemical and biological reactions—are described in the first three chapters of the book.

ORGANIZATION OF THIS HANDBOOK

This handbook approaches moisture problems in buildings from several perspectives. The first three chapters present problems and fundamental principles related to moisture in buildings. Chapter 1—*Mold, Mildew, and Condensation*—examines surface moisture problems. The second chapter—*Moisture Movement*—examines how building assemblies get wet from both the exterior and interior; and Chapter 3—*Design Considerations for Building Assemblies*—introduces the concepts of acceptable performance, moisture balance, and the redistribution of moisture within building assemblies.

Chapters 4 through 6 apply the concepts outlined in the previous chapters and present specific moisture control practices for three basic U.S. climate zones (heating, mixed, and cooling). Each of these chapters begins with a set of strategies to be applied to the whole building, followed by a series of recommended wall, roof, and foundation assemblies. The commentary relating to each detail provides a brief summary of its key characteristics. More detailed explanations of the principles utilized in the development of the details can be found in the early chapters. Finally, Chapter 7 provides a series of brief case studies that illustrate typical moisture problems and solutions.

This handbook attempts to provide the basic principles for successfully designing and constructing building assembly details. Those readers desiring further information and depth are directed to the bibliography at the end of the book. References are provided where the specific issues raised may require further explanation, or where it was felt necessary to direct readers to particularly relevant research findings.

Whenever a specific construction practice in a particular climate presented in this handbook deviates from conventional practice or is unfamiliar, the reader is urged to consult with local code authorities to ensure its acceptability and compliance.

Moisture Control Handbook

Contents

CHAPTER 1

Mold, Mildew, and Condensation

The most common surface moisture-related problems, regardless of climate, are mold, mildew, and condensation. The single most important factor influencing these problems is relative humidity near surfaces. Understanding the factors that govern relative humidity will enable builders and designers to control surface-related moisture problems.

RELATIVE HUMIDITY AND VAPOR PRESSURE

The terms *absolute humidity, humidity ratio,* and *vapor pressure* refer to the same concept: air contains varying amounts of moisture in the gas or vapor form. The actual amount of moisture contained in air is referred to as *absolute humidity*. More precisely, the absolute humidity is the ratio of the mass of water vapor to the mass of dry air. This is also referred to as the *humidity ratio*.

Air is a mixture of several gases including oxygen, nitrogen, carbon dioxide, and water vapor. The total air pressure exerted by a volume of air in a given container on that container is the sum of the individual or partial pressures of the constituent gases which make up the air. The *vapor pressure* is the partial pressure of the water vapor gas on the container.

The amount of moisture air can hold is dependent on its temperature. The warmer air is, the more moisture it can hold; the cooler air is, the less moisture it can hold. Air is said to be saturated (or at 100 percent relative humidity) when it contains the maximum amount of moisture possible at a specific temperature. Air holding half the maximum amount of moisture at a given temperature has a relative humidity of 50 percent. *Relative humidity* is defined as the ratio of the amount of moisture contained in the air to the maximum amount of moisture the air can hold at a given temperature.

Impact of Moisture Amount on Relative Humidity

Figure 1-1 illustrates the concepts of relative and absolute humidity. Three sealed containers each hold the same amount of air (1000 pounds) and are kept at the same temperature (57° F). The containers are assumed to be airtight, watertight, and vaportight. At a temperature of 57° Fahrenheit, 1000 pounds of air is capable of holding approximately 10 pounds of water at a maximum.

The air in container A is completely dry—the relative and absolute humidities are both zero. Three pounds of moisture in the form of water vapor has been added to container B while the temperature remains the same. The absolute humidity (or humidity ratio) of container B is .003 (3 pounds of moisture/1000 pounds of air), while the relative humidity is 30 percent (3 pounds of moisture/10 pounds of maximum moisture capacity at 57° F). Container C holds 10 pounds of moisture in the form of water vapor. The absolute humidity (or humidity ratio) of container C is .010 (10 pounds of moisture/1000 pounds of air), while the relative humidity is 100 percent (10 pounds of moisture/10 pounds of maximum moisture

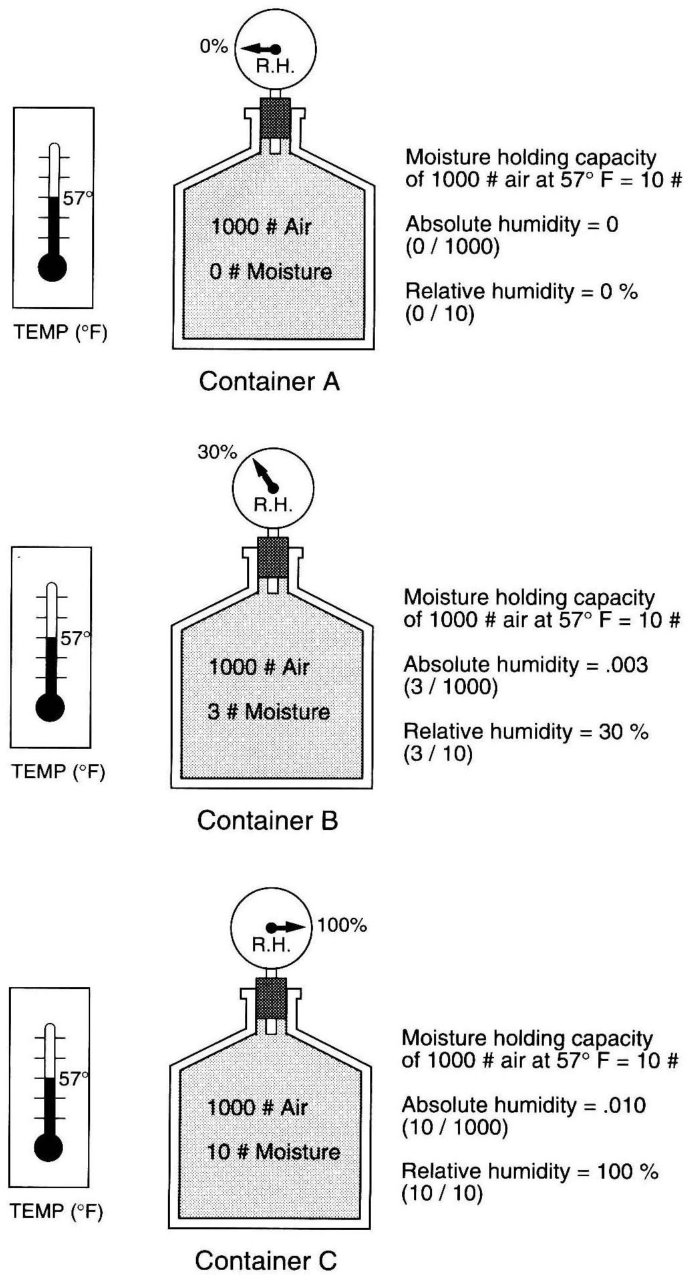

Figure 1-1: Impact of moisture content of air on relative humidity.

capacity at 57° F). The air in container C is at the saturation point—it cannot hold any more moisture in the form of water vapor. If additional moisture is introduced into container C, it will condense into liquid water.

Impact of Temperature on Relative Humidity

Figure 1-2 further illustrates the concepts of relative and absolute humidity and how they vary with temperature. As in Figure 1-1, three sealed containers each hold the same amount of air (1000 pounds). The containers are assumed to be airtight, watertight, and vaportight. Container D is at a temperature of 57° Fahrenheit and holds 5 pounds of moisture. At this temperature, 1000 pounds of air is capable of holding approximately 10 pounds of water at a maximum. Thus, the absolute humidity (or humidity ratio) of container D is .005 (5 pounds of moisture/1000 pounds of air), while the relative humidity is 50 percent (5 pounds of moisture/10 pounds of maximum moisture capacity at 57° F).

The amount of actual moisture in container E remains the same as in container D (5 pounds), however the temperature is increased to 77° Fahrenheit. At this warmer temperature, the air is capable of holding more moisture than it can at a colder temperature—1000 pounds of air can hold 20 pounds of moisture at maximum saturation. Because the actual amount of moisture remains the same in container E, the absolute humidity remains at .005 (5 pounds of moisture/1000 pounds of air). However, the relative humidity is reduced to 25 percent (5 pounds of moisture/20 pounds of maximum moisture capacity at 77° F).

In container F, the amount of actual moisture still remains at 5 pounds, but in this case the temperature is decreased to 37° Fahrenheit. The air is capable of holding less moisture at this colder temperature than it can at a warmer temperature—1000 pounds of air at 37° F can only hold 5 pounds of moisture when saturated. As with containers D and E, the absolute humidity remains at .005 (5 pounds of moisture/1000 pounds of air). Because of the diminished capacity of cold air to hold moisture, however, the relative humidity is increased to 100 percent (5 pounds of moisture/5 pounds of maximum moisture capacity at 37° F).

In Figure 1-1, the three containers are held at a constant temperature while the moisture content of the air increases. This raises both the absolute humidity and the relative humidity.

All three containers in Figure 1-2 hold precisely the same amount of moisture, yet the relative humidity increases as the temperature is reduced and decreases as the temperature rises. These simple illustrations demonstrate that relative humidity can be increased two ways—by increasing vapor pressure (moisture amount) and by decreasing temperature. The relationship between temperature, relative humidity, and absolute humidity is presented graphically on a simplified psychrometric chart in Figure 1-3.

The relationship between temperature, relative humidity, and vapor pressure can often be counterintuitive. For example, cold air is not capable of holding very much moisture, so cold air is dry in an absolute sense and has a low vapor pressure. However, the small amount of moisture present in the cold air is often very close to the maximum amount of moisture the air can hold at that temperature, so the air is at a very high relative humidity. Since the capacity of the air to hold moisture is reduced as temperature is decreased, only a very small addition of moisture is required to bring it to saturation.

In attempting to diagnose problems related to moisture in buildings, both relative humidity and temperature must be measured. In addition, since temperature and humidity can vary within spaces and buildings, taking measurements at several locations is desirable.

MOLD AND MILDEW IN BUILDINGS

Molds are simple plants of the group known as fungi that grow on the surfaces of objects. Mold discolors surfaces, leads to odor problems, and deteriorates building materials. In addition, mold growth can lead to allergic reactions in susceptible individuals as well as other potential health problems (hypersensitivity, other infectious diseases). Certain fungi found in indoor air produce mycotoxins which have been found to be carcinogenic (induces cancer), teratogenic (induces birth defects), immunosuppressive (reduces immune system performance), and oxigenic (poisons tissues) (Spengler et al. 1991).

Other agents of biological contamination can occur in many forms. Viruses, bacteria, protozoa, algae, and vapors derived from living organisms can become airborne (bioaerosols). Bacteria and fungi contribute to "organic dust" and have been linked to outbreaks of sick building syndrome (SBS). Furthermore, dust mites and cockroaches

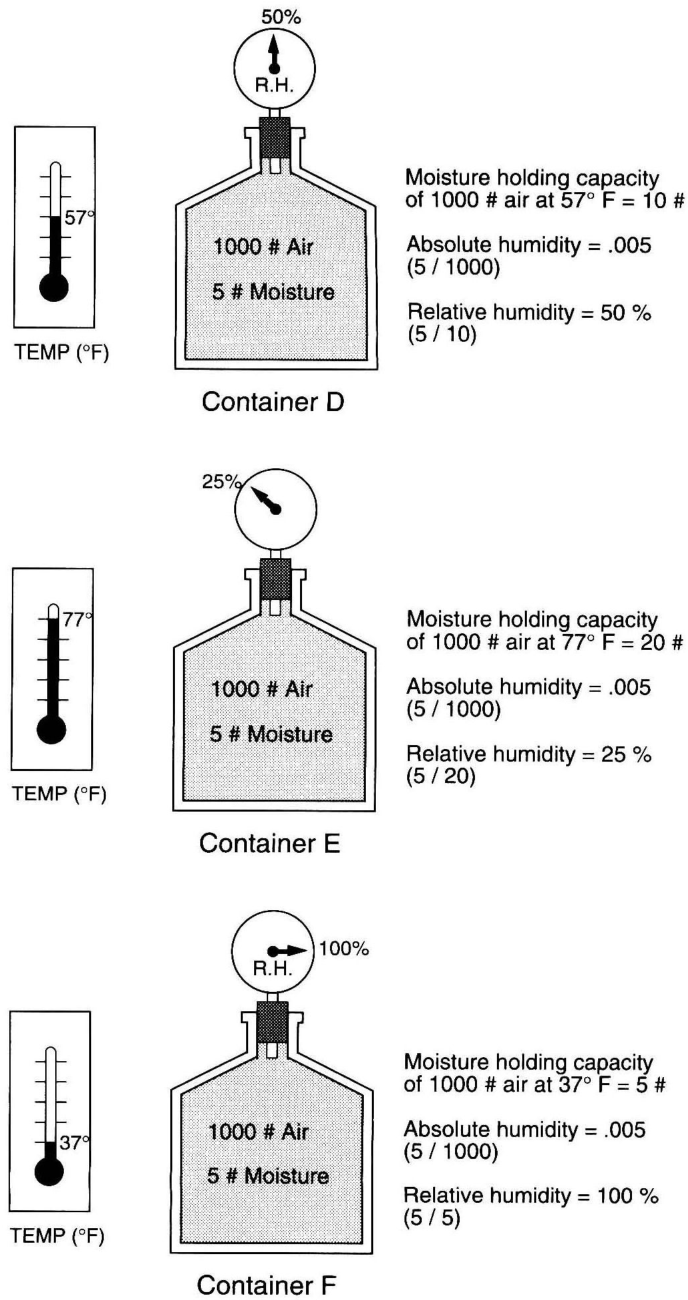

Figure 1-2: Impact of temperature change on relative humidity.

Note: Volumes of containers need to change slightly as temperature changes to follow the Ideal Gas Law.

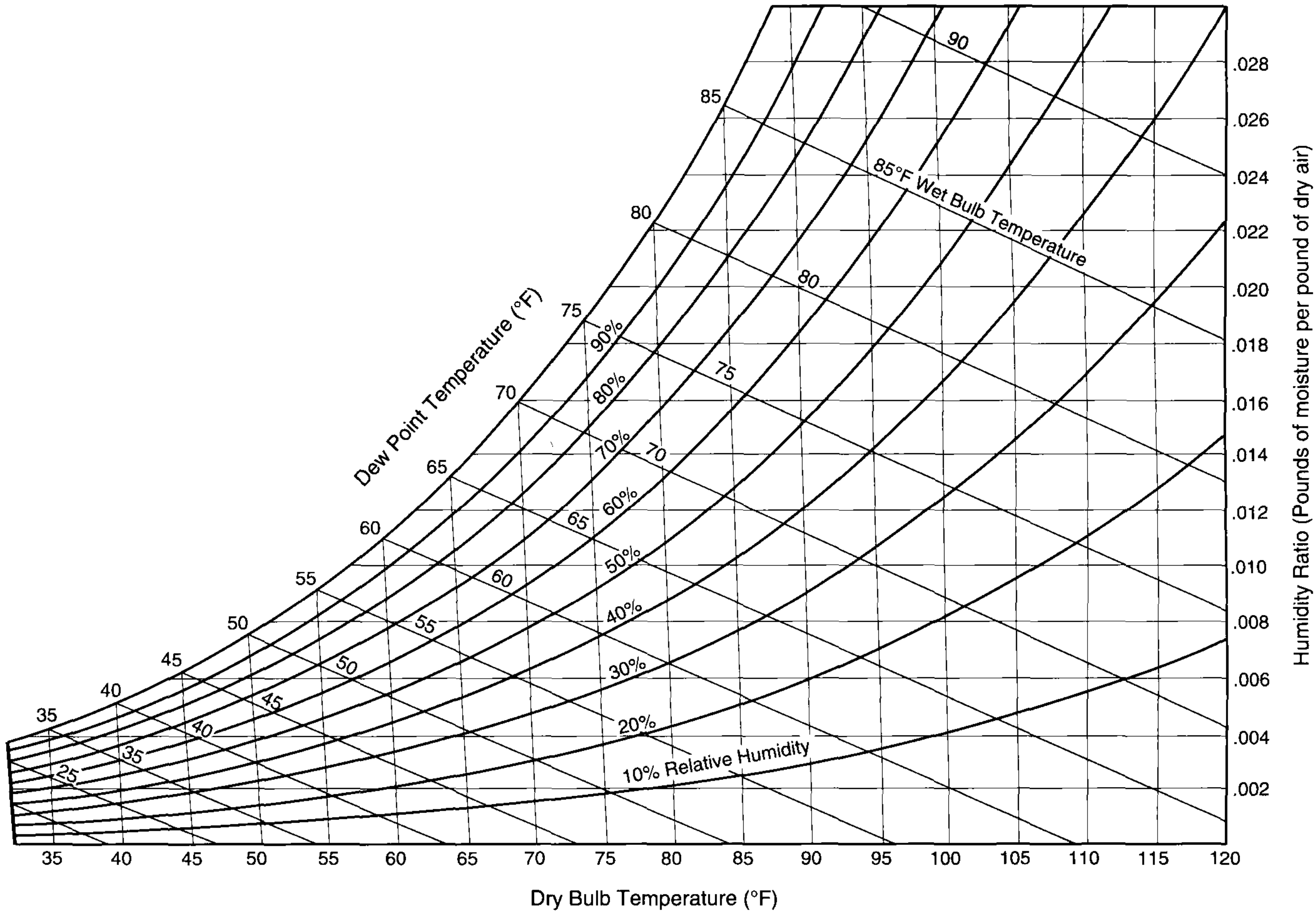

Figure 1-3: Simplified psychrometric chart.
Based on the chart in the 1989 *ASHRAE Handbook of Fundamentals.*

produce particulates which are allergenic or antigenic. Bioaerosols are also associated with tuberculosis, Legionnaire's disease, humidifier fever, hypersensitivity, pneumonitis, aspergillosis, allergic rhinitis, and viral respiratory infection. Fungal and bacterial growth can be curtailed if moisture levels are limited in organic materials. Dust mite growth can also be similarly inhibited. Relative humidities limited to 70 percent or lower at the surfaces of organic materials are typically necessary to limit these forms of biological growth (Samuelson and Samuelson 1990, AHMA 1991).

Most fungi have wind-borne spores, which are microscopic and buoyant. These suspended spores enter buildings as part of natural and controlled air change. Although exterior airborne concentrations vary seasonally, mold spores can be considered to be always present.

Molds cannot manufacture their own food, however they can utilize many commonly available compounds, such as starches, sugars, cellulose, lignins, fats, proteins, and complex hydrocarbons. Accordingly, many building materials provide nutrients for fungi. Examples are wood products, cotton fabrics, wool fabrics, hemp fabrics, organic dust and lint, soaps, oils, paints, adhesives, certain plastics, and vinyls.

Most fungi grow when the temperature is between 50 degrees and 100 degrees Fahrenheit, with optimum growth occurring between 75 degrees and 95 degrees. Some types of fungi can grow at temperatures as low as 35 degrees and as high as 120 degrees (AHMA 1991).

Molds also require moisture for growth. Moisture is necessary for the production of enzymes and other metabolic activities in order to digest carbohydrates, fats, and proteins. The optimum relative humidity for most fungal