Moisture Control in Buildings:

The Key Factor in Mold Prevention

2nd Edition

Heinz R. Trechsel
Mark T. Bomberg
Editors

ASTM INTERNATIONAL
Standards Worldwide

Moisture Control in Buildings: The Key Factor in Mold Prevention—2nd Edition

Heinz R. Trechsel and Mark T. Bomberg, Editors

ASTM Stock Number: MNL18-2nd

ASTM International
100 Barr Harbor Drive
PO Box C700
West Conshohocken, PA 19428–2959

Printed in the U.S.A.

Library of Congress Cataloging-in-Publication Data

Moisture control in buildings: the key factor in mold prevention/edited by Heinz R. Trechsel, Mark T. Bomberg—2nd ed.
p. cm.

"ASTM stock number: MNL18-2nd."
Includes bibliographical references.
ISBN 978-0-8031-7004-9
1. Dampness in buildings—Prevention. 2. Waterproofing. I. Trechsel, Heinz R. II. Bomberg, Mark.
TH9031.M26 2009
693.8′93—dc22 2009016036

Printed in Baltimore, MD
October 2009

Acknowledgments

First of all, the Editors wish to thank the chapter Authors for their contributions and hard work. This book could not have been written by any one single author. The field of moisture control is too large and varied and includes too many disciplines for one single person to master and to condense it all into a single volume. Among the authors, Wayne Tobiasson was particularly helpful with his frequent and sorely needed encouragement and advice. Wayne, much more than he probably realizes, is responsible for keeping the editorial and review process moving. Your dedicated services are greatly appreciated.

The second large group of experts who performed an extremely valuable, essential, and unselfish service are the reviewers. It really falls on them to carefully review the chapters for technical accuracy and relevance. We are deeply indebted to all of them.

Also, without the dedicated and continuing support of Kathleen Dernoga and Monica Siperko of the Staff of ASTM International, the second edition of MNL18 would never have been possible. Many thanks to both of you.

Finally, in the original conception of the first edition of MNL18, three personalities must be mentioned here for their invaluable assistance and encouragement. Foremost Wayne Ellis, former chairman of ASTM, to whom the first edition was dedicated, Paul Reece Achenbach, former Director of the Building Environment Division of the National Bureau of Standards (now NIST), who provided his great technical understanding of the entire concept of moisture control in buildings, and E.C. Shuman, of Penn State University and former Chairman of ASTM Committee E06, whose long term association with the subject provided many historical insights. Our heartfelt thanks to all three of them. Unfortunately, they are no longer with us, but will be remembered for years to come.

Heinz R. Trechsel and Mark T. Bomberg
Editors

REVIEWERS:

David E. Allen
Ervin L. Bales
Robert Bateman
Robert Bombino
Jon M. Boyd
Jan Carmeliet
David B. Eakin
Fred R. Eberle
John R. Edgar
Earl A. Ferguson
John E. Fernandez
William Freeborne
G. Robert Fuller
Stanley D. Gatland
Cynthia Gill
John Grunewald
Joseph R. Hagan
Andreas Holm
John K. Holton
Thomas M. Kenney
Kevin Knight
Peter Lagus
Jared B. Laurence
Mark Lawton
Sheldon J. Leavit
Kenneth Loefgren
Joseph R. Loferski
Mary E. McKnight
Hugh C. Miller
William R. Nash
Peter E. Nelson
Thomas F. O'Connor
Donald M. Onysko
J. Eric Peterson
Helene Hardy Pierce
Sylvio M. Plescia
Heinz F. Poppendiek
David Ritter
Carsten Rode
William B. Rose
Walter J. Rossiter
John A. Runkle
David W. Saum
Richard Scott
Max H. Sherman
Paul H. Shipp
Baird Smith
Steven Thorsell
Martha G. Van Geem
Michael F. Werner
David W. Yarbrough

Contents

Introduction

Well-designed buildings have many virtues, among them the ability to serve their intended purposes and to become a beautiful and essential shelter for human activities. Buildings also must resist various service loads, environmental stresses caused by temperature, humidity, wind and even those rare events of earthquakes or flooding. They must also provide a healthy indoor environment eliminating air pollutants; and they must maintain these functions over the full intended service life.

Most of these attributes can be affected by moisture. Uncontrolled moisture may reduce the structural soundness of buildings through dry rot in wood, corrosion in steel, freeze-thaw cycles in masonry, and other damage mechanisms. Moisture also can affect the health of occupants typically through the potential for breeding harmful organisms. With other words, uncontrolled moisture will negatively affect all the most vital attributes of buildings. On the other hand, moisture reduces the shrinking cracks of wood and furniture, and up to a point, is necessary to avoid respiratory discomfort. Thus, moisture is both a necessary constituency of our built environment and a potential liability. The issue, then, is not to eliminate moisture from our buildings, but to control it and its movements. Manual 18 addresses this general concept.

Over the 15 years since the publication of the first issue of MNL18, Moisture Control in Buildings, mold with its potential health effects have gained nationwide attention. When the first edition of this manual was exhausted, the sponsoring ASTM Committees C16 and E06 agreed with the consensus of the chapter authors that the need for the manual actually had increased and that an updated version was needed. All authors were given the option to do the update or rewrite their chapters. Those who were unable to do the revision were replaced by equally qualified authors.

As in the previous edition, the manual does not provide all details and requirements of the many technologies involved in controlling moisture in buildings, but it is focused on the major issues involved in the design, and selection of materials and the process of moisture resistive construction.

Since the manual is a collection of chapters prepared by individual authors, the reader may find instances of repetition or even conflicts between the chapters. To the extent that such conflicts reflect the current level of building science and of methods specific to moisture control in buildings, such conflicts were unavoidable. In such an instance we recommend that the reader review the references to the chapters to form his/her own opinion.

Although many chapters include specific recommendations, the editors caution the reader that each building is different, that conditions of building service and climate are different. Accordingly, no recommendations or details should be adopted without a careful analysis of the needs of the specific building. Where analytical means exist, these should be tried in lieu of cookbook solutions. Caution is advised as input data for material properties and weather data can be unreliable.

Many technical publications, research reports, and conference proceedings have been published on moisture control in buildings. However, to our knowledge, this manual is the only publication which provides under one cover the most important information relating to moisture problems in buildings and to serve as a desk-top reference manual for use by those who design, construct, sell, maintain, and own buildings and homes.

To increase the completeness of the Manual, three new chapters were added: Chapter 15 on *Details and Practice*, Chapter 25, on *Quality Management in Design and Construction of the Building Envelope*, and Chapter 28 *Towards Development of Methods for Assessment of Moisture-Originated Damage*. The details and practice should be helpful to design offices. Quality management responds to a concern that the details and material selections may be carefully developed during design, but are sometimes not exactly followed when the on-site construction management organization does not understand the importance of a particular selection or design. The last chapter and updated Chapter 27 look to the future.

We also dropped the chapter on modeling because ASTM MNL 40 on *Moisture Analysis and Condensation Control in Building Envelopes*, published in 2001, provides an in-depth state of the art of modeling. But we did include a brief discussion of mathematical models in Chapter 10, *Design Tools*. All other chapters were revised or updated, in some cases, such as Chapter 6, *Exterior Climate Data for Hygrothermal Analysis*, the revision led to what essentially is a new chapter.

The editors recognize that mechanical equipment has a significant impact on moisture control in buildings. However, a thorough discussion of the issue would require an entire book all by itself. Accordingly, we have included Chapter 9 on mechanical equipment to emphasize the importance of mechanical equipment and its design and to illustrate one engineer's thoughts on the issue.

The updated manual consists of four parts:

Part 1, "Fundamentals," discusses moisture transfer, condensation, and evaporation. Moisture related properties of building materials, organisms and health effects, climate and moisture sources.

Part 2, "Applications," discusses the technologies that affect the moisture balance in buildings and the techniques used to determine the suitability of materials, components, systems, and structures. There are chapters on air infiltration and ventilation, design tools, measurement techniques and instrumentation, troubleshooting, and a chapter on case studies.

Part 3, "Construction Principles and Recommendations" includes discussions of and recommendations to make both new and existing commercial and high buildings, new and existing residential buildings, as well as manufactured and historic buildings. One chapter is devoted to suggested construction details and one discusses roofing.

Part 4, "Implementation," discusses implementation mechanisms. This section is organized along a simple concept: First, the building should be designed, built, and repaired in accordance with the 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. Third, in the design office and on the construction site, the principles of recognized quality management must be observed to assure that what is constructed complies fully with the contract documents. And finally, when all else fails, there are arbitration and court proceedings to resolve conflicts. Each of these mechanisms is discussed to give the reader a good understanding of the process beyond just a good design and adequate specifications. The Manual closes with a look to the future and a discussion of a Conceptual System of Moisture Performance Analysis.

The editors would appreciate receiving any comments or criticisms, but they also hope that the second edition of MNL18 be as well received as the first edition was.

Heinz R. Trechsel and Mark T. Bomberg
Editors

MNL18-EB/Oct. 2009

1

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

Mavinkal K. Kumaran[1]

WATER, WHICH IS ABUNDANT ON OUR PLANET, naturally undergoes various physico-chemical processes and interacts with all living and nonliving entities. As much as water is essential for all life forms, it can also cause the degradation of many natural and manmade materials. This may be due to chemical, biological, or mechanical processes undergone by the material as a result of its interaction with water. Corrosion of metals is an example for chemical deterioration, decay of wood and wood-based material for biological, and cracking and spalling of masonry material for mechanical. Buildings that are constructed to last many decades include a number of materials that are susceptible to deterioration due to their interaction with moisture. Hence, building researchers, designers, and practitioners have always been interested in the role of moisture in the built environment.

The scientific and technical knowledge that is necessary to understand and interpret the consequences of the interaction between moisture and building materials was originally based on the work done by soil scientists [1–3]. In such an approach, building materials are regarded as porous bodies, like soil. The analogy is useful, but inadequate for building applications. Materials in the built environment simultaneously experience three inter-related transport processes:

- Heat transport
- Moisture transport
- Air transport

The last is often not an issue in soil science. During the past three decades or so, the approach from soil science was extended to understand the combined heat, air, and moisture (HAM) transport in building materials and components through major international collaborations [4–6] and through the efforts of researchers at major building research organizations. The knowledge that is available today can reasonably well answer questions such as:

1. How can the transport of heat, air, and 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 do air and moisture transports affect the energy efficiency of buildings?

More recently completed international collaborations [7] are expected to apply the knowledge to improve HAM analyses at the whole-building level.

Over the past three decades significant advances have been made in the experimental and analytical methods to determine the hygrothermal behavior of building materials and components as influenced by HAM interactions [8–14]. Later chapters in this handbook deal with various aspects of hygrothermal behavior of building materials, components, and systems individually. This chapter is intended to summarize our present knowledge of moisture storage and transport in building materials. This knowledge is fundamental to understand the complex interaction of heat, air, and moisture transport in the built environment.

The Thermodynamic States of Moisture

H_2O (or moisture), like any other pure substance, can exist in three states: solid (ice), liquid (water), and gas (water vapor). These three states of moisture can exist in buildings, depending upon the geographic location. 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 another 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 maximum vapor pressure is called the saturation vapor pressure at that temperature. There is only one temperature and saturation vapor pressure at which all three states can coexist. This coexistence is referred to as the triple point of water. The triple point temperature for water is 273.16 K and the corresponding saturation pressure is 611 Pa. At any other temperature, T, between 250 K and 330 K the following two equations yield the saturation vapor pressure, p_v, within a fraction of a percent.

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

[1] *Principal Research Officer, Institute for Research in Construction, National Research Council Canada, Ottawa K1A 0R6, Canada. E-mail: kumar.kumaran@nrc.gc.ca*

$$(p_v/\text{Pa}) = \exp\{22.565 - 2377.1/(T/\text{K}) - 33623/(T/\text{K})^{1.5}\} \quad \text{for } 273.16\ \text{K} < T < 330\ \text{K} \tag{2}$$

The unique relation between the saturation vapor pressure and temperature is the basis, as shown in the Appendix 1 to this chapter, for various psychrometric calculations in building applications.

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

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, partial pressure of water vapor, and the surface area of the solid. Furthermore, each material has its own characteristic affinity towards water; some less and others more. For example, glass fibers have very low affinity towards water molecules, whereas cellulose fibers have much higher affinity. At 23°C and 71.5 % RH a specimen of low-density glass fiber insulation adsorbs only 0.0034 kg kg^{-1} of water vapor, whereas a specimen of cellulose fiber insulation adsorbs 0.096 kg kg^{-1} [15]. The affinity of materials towards water is generally referred to as hygroscopicity. Those materials with high affinity are called hygroscopic materials. Many building materials, such as wood and wood-based materials, are hygroscopic.

Let us consider the state of an open-porous building material, after being exposed to the surrounding air for a long time (say 100 h). If the air is perfectly dry, the porous body will have no moisture content, or it also will be perfectly dry. As the surrounding air becomes humid, the whole surface of the porous body provides locations for water molecules to be adsorbed. This surface includes the gross geometrical surfaces as well as the surfaces offered by the pores. The former is often relatively small when compared with the latter. The geometrical surface area of one gram of silica gel is only several square centimetre's, whereas the surface area provided by the pore structure can be as high as 500 m^2 [16]. Therefore, the pore structure of porous building materials can provide large surface areas for the adsorption and storage of water molecules from ambient air.

At lower partial pressures (in comparison with the saturation vapor pressure), the adsorbed molecules form a monomolecular layer of water molecules on the surface of the porous body. As the partial pressure of the water vapor increases, multi-molecular layers of water begin to form in the pores. And as the partial pressure approaches the saturation pressure, droplets of liquid water or frost particles begin to appear within the porous body. From that point onwards water vapor rapidly condenses within the pores, and if the porous body is in contact with an environment of 100 % RH the pores eventually get saturated with water. The region of vapor pressure between the dry starting point to the point at which droplets begin to form is referred to as the hygroscopic range. In this range the storage of water molecules within the pores is mainly due to adsorption. From that point to the full saturation point at 100 % RH, water vapor condenses in the pore structure. The saturation vapor pressure within a pore structure is less than what is characteristic of free water surface. The difference depends on the pore dimension. Since the porous body is a collection of pores of varying pore dimensions, the condensation occurs continuously in a range of partial vapor pressures rather than at a specific vapor pressure.

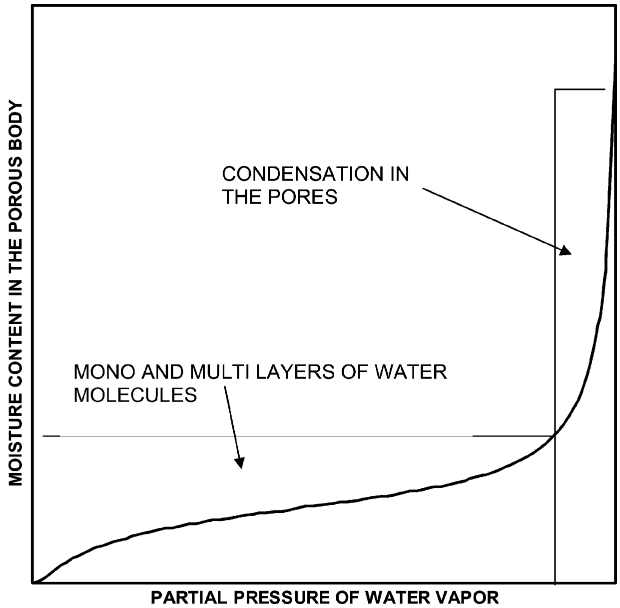


Fig. 1—Change in the storage of moisture in a porous building material as the partial pressure of water vapor in the ambient air increases from zero to full saturation value at a given temperature.

Figure 1 schematically shows the phenomenon that is described above. The curve indicates the maximum moisture content that can be attained by the porous body at a given partial vapor pressure at a given temperature. This maximum moisture content, at a given partial vapor pressure at a given temperature is also called the equilibrium moisture content. The total curve is called an *adsorption isotherm*. Naturally, such a curve for a given porous body is temperature dependent. For higher temperatures the curve will be shifted towards the vapor pressure axis and for lower temperatures it will be shifted away from the axis. However, for many building materials, the equilibrium moisture content when plotted against the relative humidity results in a single curve, independent of temperature [17]. For others, such as wood and wood-based materials, all the curves become much closely more grouped [18]. Hence, for practical applications in building science, the single curve that shows a relation between the equilibrium moisture content and rela-

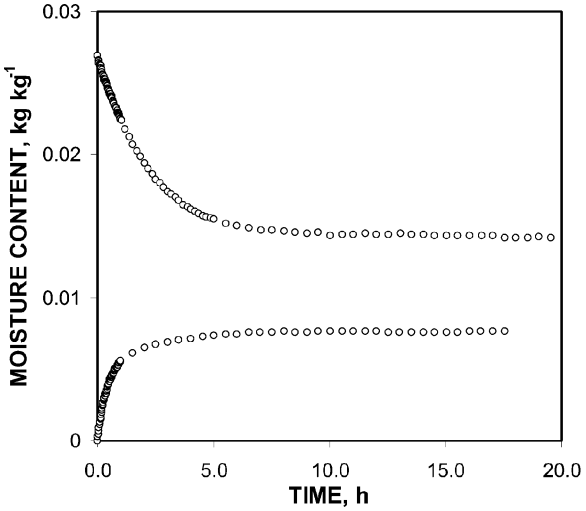


Fig. 2—Hysteresis shown by gypsum board at 22.5°C and 68.4 % RH. The upper curve shows desorption and the lower curve shows sorption.

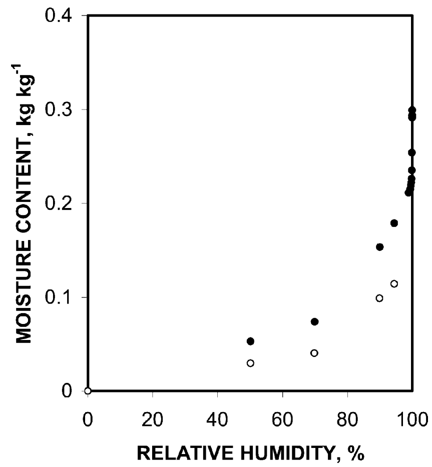


Fig. 3—Sorption/desorption data for a sample of fiber cement board that demonstrate the effect of hysteresis; the filled marks show desorption and the unfilled show sorption.

tive humidity is used for each building material. This curve is called the *sorption curve*.

Now let us consider the reverse of the process described above. A porous body is saturated with water and then placed in contact with air that is only partially saturated with water vapor for a long time. Then the porous body starts to dry out by releasing the moisture from its pores to the ambient air. This process is called desorption. Depending on the partial pressure of water vapor in the ambient air, the porous body reaches an equilibrium moisture content. Generally, the moisture content attained during the desorption process is higher than that attained during the sorption process, though the water vapor pressure in the ambient air may be the same. This phenomenon is called hysteresis. This is demonstrated in Fig. 2. A test specimen of gypsum board is dried and introduced in an environment at 22.5°C and 68.4 % RH [19]. The increase in the weight of the specimen due to sorption is continuously monitored. Similarly, another specimen of gypsum board that is initially conditioned at 95 % RH is also introduced to the same environment and the decrease in weight due to desorption is continuously monitored. As shown in Fig. 2, both specimens eventually come to equilibrium with the environment, but the equilibrium moisture content attained by desorption is higher than that attained by sorption.

Figure 2 implies that the adsorption isotherm shown may not be retraced if a desorption process is started from full saturation and drying is continued till the ambient air is perfectly dry. This indeed is the case with many building materials. Figure 3 shows a series of sorption and desorption test results on a sample of a fiber cement board [20]. The hysteresis shown by this material is clearly demonstrated in the figure.

ASTM Standard C1498 prescribes a procedure to determine the sorption/desorption curves for building materials in the hygroscopic range. This same method was used to determine the data given in Fig. 3, between 50 % RH and 95 % RH. Direct measurements of desorption at relative humidities close to 100 % are tedious if not impossible. An indirect method based on the use of pressure plates [21,22] is often used to determine the desorption curve close to saturation. The data close to saturation as shown in Fig. 3 were obtained using the pressure plate method. Information on the sorption and desorption curves of many building materials is available elsewhere [17,23–29].

Phase Changes

As stated earlier, moisture may be present in the built environment in the three natural states as well as in the adsorbed state. Subject to changes in temperature and vapor pressure, this moisture may undergo change of state, or phase transition, as shown in Fig. 4. 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.

Transport of Moisture

Moisture can move from one location to another in a porous body. This movement can happen to moisture in all four

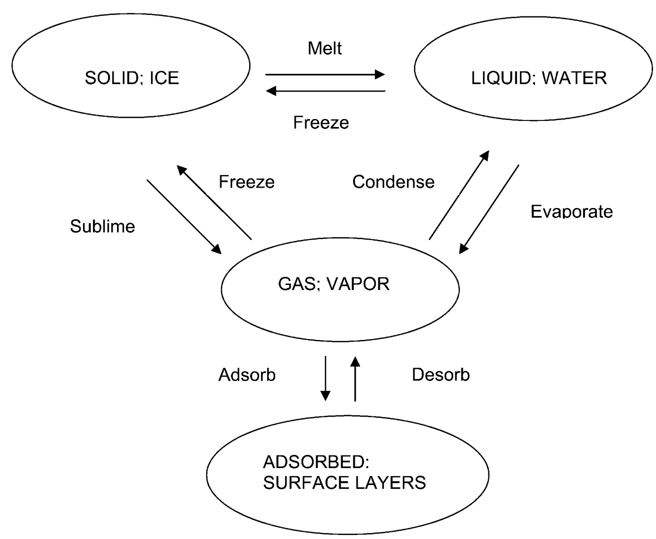


Fig. 4—Various processes undergone by moisture that involve phase changes.

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

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

states or phases; solid, liquid, vapor, or adsorbed. Molecules in liquid or vapor phases are very mobile when compared with molecules in solid or adsorbed phases. Hence the rate at which moisture is transported in the vapor or liquid phase is considerably higher than that in the solid or adsorbed phase. Therefore, building researchers have been mainly concerned about vapor and liquid transport, for the practical application of building physics.

A driving force or a difference in a driving potential between two locations within a medium brings about a transport process. The best known example is heat transport that is brought about by a difference in temperature. Then the driving potential for heat transfer is a temperature difference. Another example is the flow of electric current due to a difference in electro motive force. Flow of water due to a difference in height is yet another example. A difference in concentration of moisture is the primary reason for moisture transport between two locations. But this is not the only driving force. Temperature difference can induce moisture transfer. A difference in capillary force, though related to moisture concentration, is another driving force. Vapor pressure difference as well as relative humidity difference that are related to concentration difference can also be regarded as driving forces. For practical reasons a set of experimentally realizable driving potentials have been used by building physicists to quantify moisture transport in building materials. 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

$$J_B = -k \cdot grad\ \phi_B \quad (3)$$

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 transport coefficient, characteristic of the medium through which the transport occurs. Conventionally, J_B is expressed as the quantity of B transported across a plane of unit area that is normal to the direction of the transport, in unit time. Hence it is also called a flux or a flux density. For moisture transport J_B can be expressed in kg m^{-2} s^{-1}, for example.

Any flux can be three-dimensional and J_B in the Cartesian coordinate can have three components, J_{Bx}, J_{By}, and J_{Bz} in the directions x, y, and z, respectively. However, each component can be represented by an equation similar to Eq (3) as

$$J_{Bx} = -k_x \cdot \left(\frac{d}{dx}\right)\phi_{Bx} \quad (4)$$

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

$$k_x = k_y = k_z \quad (5)$$

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

Ideally the coefficient 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 for a given flux. The thermodynamics of transport processes [30,31] is one such theoretical method that may be used to select ϕs for heat and mass fluxes. The merit of this method was demonstrated [32,33] with reference to heat transport through dry glass fiber insulation. This has not yet been appropriately applied to various moisture transport processes. The traditional approach is to choose the driving potential based on experimental knowledge. For example, heat flux, J_q, through dry insulation can be expressed as

$$J_q = -\lambda \cdot grad\ T \quad (6)$$

where λ, the transport coefficient becomes the thermal conductivity of the dry insulation and the corresponding ϕ is temperature, T. It is well known that for the range of temperature in which buildings operate, λ is practically linearly dependent on temperature. For a wider range of temperature, this dependence may turn cubic due to the increasing dominance of the radiative component of heat transport at higher temperatures.

It is possible to write an equation similar to Eqs (3) or (4) for each of the moisture transport processes that have been listed in Table 1. But most of the transport coefficients so postulated are often rather complex functions of the corresponding ϕs. Experimental measurements and the associated data analyses for the determination of the functional dependence of the moisture transport coefficients on the corresponding ϕs are often very challenging. This is illustrated below with respect to water vapor transport and liquid water transport.

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

$$J_v = -\delta \cdot grad\ p \quad (7)$$

The transport coefficient δ in Eq (7) is called the water vapor permeability of the medium through which the vapor is transported. The vapor pressure at a given temperature can vary from zero to the saturation vapor pressure, and correspondingly the relative humidity can vary from 0 to 100 %. For some building materials, like glass fiber insulation [25] and perlite board [34] δ is independent of RH. For some other materials it marginally increases with RH; for calcium silicate insulation, it increases from 3.6×10^{-11} kg m^{-1} s^{-1} Pa^{-1} to only 6.7×10^{-11} kg m^{-1} s^{-1} Pa^{-1},

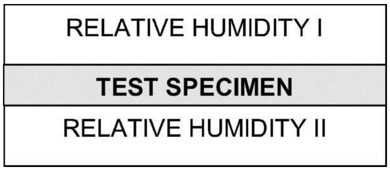


Fig. 5—Schematic drawing of an experiment for the determination of water vapor permeability.

as the RH changes from 10 % to 100 % [28]. For yet another class of materials the dependency of δ on RH is rather significant; for plywood at 10 % RH it could be as low as 5×10^{-13} kg m^{-1} s^{-1} Pa^{-1} whereas at 100 % RH it could be as high as 4×10^{-11} kg m^{-1} s^{-1} Pa^{-1} [34].

The standard means for the determination of δ is schematically shown in Fig. 5. A specimen of known area and thickness that separates two spaces differing in relative humidity is allowed to attain a steady state of vapor transfer across it from the higher RH space to the lower RH space. The rate of vapor transport at that steady state is determined gravimetrically. From these data an average value for δ of the specimen for the range of relative humidity defined by the two spaces is calculated. ASTM Test Methods for Water Vapor Transmission of Materials (E96) prescribes two specific cases of this procedure. If the relative humidity in one of the spaces is 0 % RH and in the other is less than 100 % RH, the test method is called a desiccant method or a dry cup method; if the relative humidity in one of the spaces is 100 % RH and in the other is greater than 0 % RH, the test method is called a water method or a wet cup method.

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 ranges, and the test method can result in well-defined values for δ of the test specimens. Representative values for the δ of many common building and insulating materials [25] for the range of 0 to 50 % and at 23°C, as determined at the Institute for Research in Construction, NRC Canada, are given in Table 2.

In the wet cup method, however, part of the specimen, being in contact with the space at 100 % RH, is always above the hygroscopic range and below the saturation moisture content. Even though a steady state can be experimentally established, the measured permeability is a result of combined vapor and liquid transport. Albeit, as long as the surface of the test specimen that is in contact with the 100 % RH does not have any condensed water, the contribution due to the liquid water transport is very small. In such a situation, for a highly hygroscopic material, the upper value of permeability may approach the water vapor permeability of still air. For example, for a specimen of cellulose fiber insulation, measurements at the Institute gave an estimation of the upper limit of water vapor permeability equal to 1.93×10^{-10} kg m^{-1} s^{-1} Pa^{-1}, at 23°C. The water vapor permeability of still air at the same temperature is approximately 2×10^{-10} kg m^{-1} s^{-1} Pa^{-1} [34].

The principle of the measurement of δ is rather simple, as shown in Fig. 5. But the practical difficulties in the experiments are many [35]. Furthermore, several corrections are to be applied to estimate the true permeability of a test specimen [35–37]. These corrections include the resistances offered by the surfaces of the test specimen and the layer of still air as well as the edge imperfections that may be introduced by sealing the test specimen to the cup itself. ASTM E96 has been revised to highlight all precautions for the experiments and the data analyses. Standards by themselves will not yield reliable results. Highly skilled technicians alone can conduct the experiments reliably, as was evident from the discrepancies that were recently reported in a European round robin [38] series.

Direct measurement of δ can be very time consuming. For highly vapor resistant materials such as 12 mil polyethylene foils, it is not unusual that the measurements take up to 60 days. Therefore new indirect methods, based on tracer gas techniques [39] and simultaneous application of air pres-

TABLE 2—Water vapor permeability of common building and insulating materials determined using the dry cup method (0 % to 50 % RH).

Building Material	Density, kg m^{-3}	Specimen Thickness (approximate), mm	Permeability,[a] kg m^{-1} s^{-1} Pa^{-1}
Oriented Strand Board	650	12	2.5E−13
Plywood	445	18	4.0E−13
Wood Fiberboard	320	12	1.3E−11
Composite Wood Siding	740	11	4.2E−12
Extruded Clay Brick	1980	12	4.3E−12
Mortar Type N	1600	13	1.6E−11
Regular Portland Stucco	1985	13	1.1E−12
Fibre Cement Sheathing	1380	8	4.6E−13
Cement Board	1130	12.5	7.4E−12
Aerated Concrete	460	20	1.4E−11
Gypsum Board (with Paper Face)	625	12.5	3.3E−11
Georgian Bay Limestone	2500	20	2.6E−13
Low Density Glass Fiber Batt	11.5	88	1.7E−10
Cellulose Fiber (Blown)	30	65	1.3E−10
Expanded Polystyrene Board	15	25	3.2E−12
Extruded Polystyrene Board	28	25	1.2E−12
Polyurethane Foam (Spray)	39	25	2.5E−12
Polyisocyanurate Board	25.5	25	4.4E−12
Low Density Spray Foam	7.5	24	8.8E−11
#15 Felt Bituminous Paper	715	0.72	2.1E−13
10 minute Paper	850	0.20	7.4E−14
30 minute Paper	909	0.22	1.4E−13
60 minute Paper	823	0.34	6.1E−13
SBP Membrane	450	0.14	6.3E−13
Vinyl Wall Paper	830	0.21	2.5E−14

[a] To calculate the permeance (kg m^{-2} s^{-1} Pa^{-1}) at the given thickness, divide the permeability with the thickness expressed in metre.

sure difference and RH difference [40] have been suggested. The reliabilities of these methods need to be established.

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

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

In Eq (8) δ_T can be called a thermal vapor permeability. Traditionally, building physicists have disregarded this part of the vapor flux assuming that it is insignificant in relation to J_v in Eq (7). Galbraith et al. [41] have suggested an experimental procedure to directly measure this quantity. This needs further investigation. By an indirect method, for glass fiber insulation it is estimated [42] that δ_T is approximately 1×10^{-8} kg m^{-1} s^{-1} K^{-1}. Based on this value, much less than 10 % of the vapor flux through glass fiber insulation due to diffusion in typical building applications alone will be due to the thermal effect. Most of the flux is due to the vapor pressure difference across the insulation.

Equations (7) and (8) represent vapor transport due to diffusion only. In building applications another mode of vapor transport due to the flow of air that carries the vapor in it is often more significant [43,44]. Air permeances of building materials and the leakage characteristics of building components dictate this mode of vapor transport that is referred to as convective flow of vapor. The following example illustrates the significance of convective vapor flows in buildings.

Let us consider a typical 2 by 4 residential wall with an insulated cavity and that includes a Type II vapor retarder (permeance $\approx$60 ng m^{-2} s^{-1} Pa^{-1}). For indoor conditions equal to 21 °C and 48 % RH with an exterior condition equal to −15 °C and 60 % RH, moisture may condense within the cavity due to diffusion at a rate $\approx$4 g m^{-2} day^{-1}. Now suppose that the indoor air moves into the cavity at a rate equal to 1.4 L m^{-2} s^{-1} (this is roughly equivalent to an orifice flow that is induced by a pressure difference of 10 Pa through a hole that is approximately 2 cm in diameter). The rate of condensation then increases to $\approx$480 g m^{-2} day^{-1}, more than 100 times that due to diffusion alone. Therefore the control of air movement is key to the control of moisture management in buildings.

Liquid Transport

From an experimentalist's point of view, liquid transport through porous building materials is not as well defined as vapor transport; it is very difficult, if not impossible, to separate the processes such as liquid diffusion, capillary flow, and surface flow. Hence the total process is represented by one equation

$$J_l = -D_l \cdot grad\ c \qquad (9)$$

where J_l is the total moisture flux and c is the concentration of moisture. The total moisture flux includes the vapor flux, albeit negligibly small in comparison with the liquid flux, at concentrations that approach full saturation concentration. The transport coefficient D_l may be called "moisture diffusivity" and has the dimensions of (length^2/time). For all practical purposes D_l is treated as the liquid diffusivity and used to describe liquid transport through building materials. It is also customary to write Eq (9) as

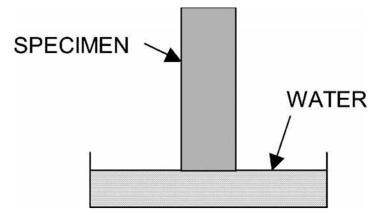


Fig. 6—Schematic drawing of the transient moisture transport process that is used to determine the liquid diffusivity of porous building materials. All four longitudinal surfaces of the test specimen are coated with water vapor resistant epoxy resin and one of the open-end surfaces is in contact with water while the other is open to the ambient air.

$$J_l = -\rho_0 D_l \cdot grad\ u \qquad (9a)$$

where ρ_0 is the density of the building material at dry state and u is called the moisture content, expressed as mass of moisture per unit mass of the dry material. Unlike the vapor permeability, the dependence of liquid diffusivity on moisture content for most materials is significant.

In principle Eq (9) can be directly used to determine the liquid diffusivity from a steady state experiment. But in practice it is not that straightforward. In a steady state experiment, one would establish a steady state moisture distribution within a test specimen through which liquid is transported with a balance of liquid water entry on one side and vaporization on the other side. If the steady state moisture distribution within the specimen can then be determined, Eq (9) can be used to calculate the liquid diffusivity at various moisture contents. There are few examples reported in literature where this technique was used to determine liquid diffusivities of building materials [45,46].

For practical reasons, most researchers are now using the following transient method to determine the liquid diffusivity and its dependence on the moisture content of porous building materials [47]. A transient moisture transport process, as schematically shown in Fig. 6, is the basis for the method. A rectangular test specimen (say 30 cm high, 5 cm wide, and an appropriate thickness that depends on the density of the material) is precisely cut with uniform thickness and dried at a temperature that is recommended for the material. The four longitudinal sides of the specimen are then coated with a thin film of epoxy resin that resists vapor and liquid transport across those surfaces. The two end surfaces are freshly cut and one of these open surfaces is placed in contact with water and the specimen is clamped in a vertical position. The time at which the surface just touches water is recorded as the "zero" time for the transport process. Liquid water starts to diffuse through the open surface of the specimen and then into the specimen upwards.

At regular intervals, the moisture distribution within the specimen is then determined. Techniques that use gamma-ray [48], nuclear magnetic resonance [49], or X-ray [50] are applied for this purpose without interfering with the transport process. The measurements are continued till the upward advancing moisture front enters the upper half of the test specimen. The data on the spatial and temporal distributions of moisture within the test specimen can be analyzed in two different ways to derive the liquid diffusivity of the material, as follows.

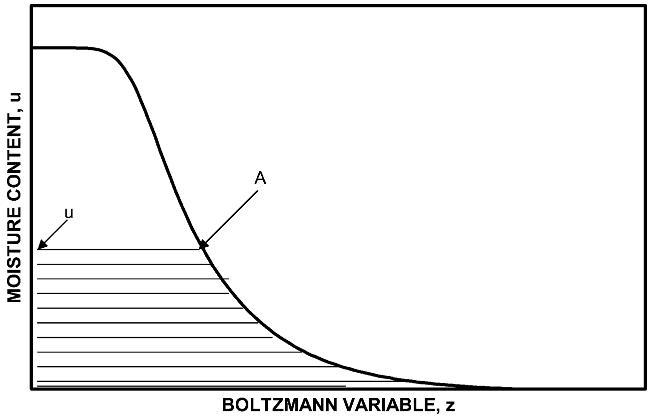


Fig. 7—Graphical interpretation of Eq (12). At a moisture content u, the liquid diffusivity is the ratio between the area under the line uA (as shaded) and the derivative of the curve at A, multiplied by −0.5.

For a one-dimensional transport process, as shown in Fig. 6, the transport Eq (9) yields the moisture (mass) conservation equation

$$\frac{du}{dt} = \frac{d}{dx}\left\{D_l \frac{du}{dx}\right\} \tag{10}$$

where t is time and x a distance along the direction of the transport.

The transient experiment generates a number of values for u at various t and x and all these shall be consistent with Eq (10). Then one can solve a number of simultaneous equations for various values of u, x, and t and optimize [51] the solutions to derive the values for D_l and its dependency on u to best fit the entire sets of data that have been generated from the transient experiment.

An alternative approach makes use of a technique called "Boltzmann Transformation" [52,53] for the data analysis. In this approach an amalgamated Boltzmann variable z is defined as

$$z = xt^{-1/2} \tag{11}$$

to combine x and t. For many porous materials the separate moisture distribution curves obtained at separate intervals during the process collapse into one characteristic curve. If this happens, then the conservation Equation (10) yields the following solution for D_l at any desired u.

$$D_l(u) = -0.5\frac{\int_0^u z du}{\left(\frac{du}{dz}\right)_u} \tag{12}$$

The typical shape of the characteristic curve of porous building materials is shown in Fig. 7. The graphical interpretation of Eq (12) is also illustrated in the figure. At any desired moisture content u, determine the integral as the shaded area that is shown in the figure. Then determine the derivative (du/dz) at the Point A on the characteristic curve. The value for D_l at u is then given by the ratio between the integral and the derivative at A multiplied with −0.5. This calculation can be done at any value for u between 0 and the maximum (saturation) moisture content and the functional dependence of D_l on u for the porous material can be derived.

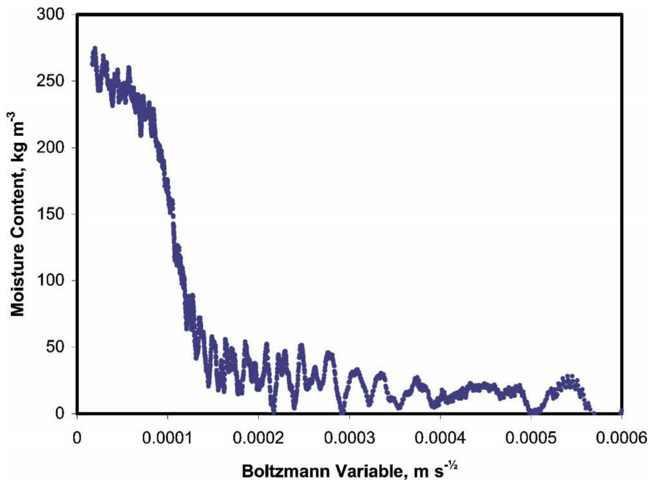


Fig. 8—The characteristic curve for a sample of aerated concrete as determined using the gamma-ray technique; the inhomogeneity of the material results in the scatter shown in the figure. There are well over a thousand data pairs in the curve. Therefore a smoothened characteristic curve can be drawn and the liquid diffusivity evaluated (see Table 3).

The experimental and analytical procedures that have been described above were recently applied to a sample of aerated concrete bock (density ≈460 kg m^{-3}) [25]. The characteristic curve for the sample is shown in Fig. 8 and the liquid diffusivity that has been derived from the characteristic curve is listed in Table 3.

Water Absorption Coefficient

The determination of liquid diffusivity has been very challenging. Round robin measurements and common exercises that involve leading international research groups [47,54,55] have been discouraging. The deviations in the results have been often more than 100 %. The reason for this is also not well understood. To date no standard procedure has been developed for the determination of liquid diffusivity.

Also, the driving potential that is associated with liquid diffusivity, viz. moisture content, though easily realizable in experiments, has been questioned, being not a true thermo-

TABLE 3—The dependence of the liquid diffusivity of an aerated concrete block on moisture content.

Moisture Content kg kg^{-1}	Diffusivity m^2 s^{-1}	Moisture Content kg kg^{-1}	Diffusivity m^2 s^{-1}
0.087	8.72E−09	0.326	3.44E−09
0.109	5.47E−09	0.348	3.64E−09
0.130	4.32E−09	0.370	3.91E−09
0.152	3.76E−09	0.391	4.29E−09
0.174	3.44E−09	0.413	4.81E−09
0.196	3.26E−09	0.435	5.56E−09
0.217	3.16E−09	0.457	6.71E−09
0.239	3.12E−09	0.478	8.71E−09
0.261	3.13E−09	0.500	1.30E−08
0.283	3.19E−09	0.522	2.89E−08
0.304	3.29E−09	0.543	5.15E−08

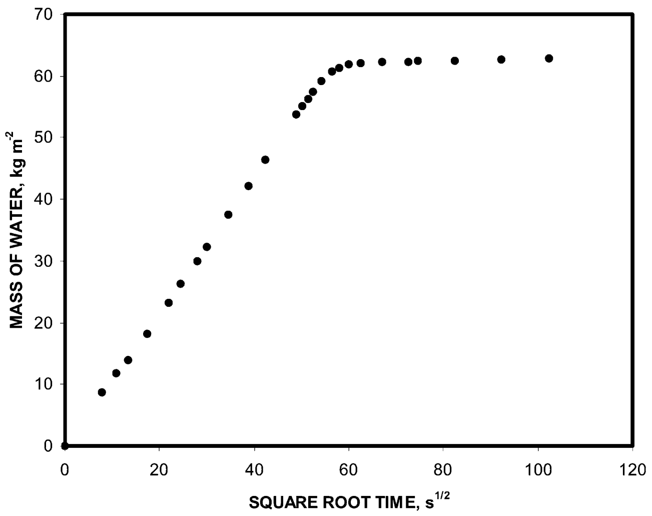


Fig. 9—Water absorption from a surface of a specimen of calcium silicate that is in contact with a water surface; the initial straight line corresponds to a water absorption coefficient ≈ 1.1 kg m^{-2} s$^{-1/2}$.

dynamic potential. Unlike temperature, there is no true continuity for moisture content in a multilayer building assembly. To overcome this discrepancy, suction, which is the magnitude of pore pressure (the negative of the excess air pressure that shall be applied to a porous body to maintain an equilibrium at any given moisture content), has been considered as the driving potential for liquid transport and liquid conductivity (or permeability) has been introduced as the corresponding transport coefficient. Mathematically, however, liquid diffusivity and conductivity are related through the first derivative of moisture content as defined by the sorption isotherm. A clear consensus is still not reached among the research community to establish the advantage of using liquid conductivity rather than liquid diffusivity in hygrothermal analyses.

As an engineering solution to define liquid transport, a quantity called "water absorption coefficient" has been discussed [56–58]. In an experiment, similar to that shown in Fig. 6, the mass of water that enters the porous body is determined at different intervals. For many building materials the plot of the mass of water versus the square root of time results in a straight line. The slope of the line that is calculated for unit area of cross section of the porous material is called the water absorption coefficient. An example of this for calcium silicate insulation is shown in Fig. 9.

The height of the test specimen in Fig. 9 is 0.1 m. All four longitudinal surfaces being coated with water vapor resistant epoxy resin and the open surface being in contact with air that is nearly saturated with water vapor, the point at which the two straight line parts in Fig. 9 intersect corresponds to the capillary saturation for the calcium silicate specimen. This corresponds to approximately 620 kg m^{-3}. It has been shown [56] that from the information on the water absorption coefficient, A, and the capillary saturation moisture concentration, c_{cap}, an average value for the liquid diffusivity can be estimated as

$$D_l \approx (A/c_{cap})^2 \tag{13}$$

TABLE 4—Thermal moisture diffusivity, D_T, of a specimen of wood fiberboard (density 270 kg m^{-3}) at a mean temperature of 20°C obtained from a steady state experiment [54].

Moisture Concentration, kg m^{-3}	D_T, m^2 s^{-1} K^{-1} $\times 10^{-10}$	Moisture Concentration, kg m^{-3}	D_T, m^2 s^{-1} K^{-1} $\times 10^{-10}$
27	0.18	270	1.65
54	0.38	297	1.85
81	0.39	324	2.06
108	0.39	351	2.26
135	0.42	378	1.65
162	0.62	405	0.64
189	0.82	432	0.39
216	1.11	459	0.14
243	1.42		

Also engineering models were introduced to derive values for liquid conductivity from the same information [58]. These approaches led to approximate information on the transport of liquid water through building materials.

Thermal Moisture Diffusivity

The transport Equation (9) is true only for an isothermal process. For nonisothermal processes a term that corresponds to a thermal gradient also has to be considered. Then

$$J_l = -\rho_0 D_l \cdot grad\ u - \rho_0 D_T \cdot grad\ T \tag{14}$$

The transport coefficient D_T may be called "thermal moisture diffusivity" [23]. Information on this property is very sparse in the scientific literature. Salonvaara [51] and Hokoi [59] have conducted nonisothermal moisture uptake experiments and derived approximate values for thermal moisture diffusivity by simultaneously measuring moisture and temperature distributions in the test specimen. Hokoi's results on wood fiberboard are given in Table 4. More investigations are necessary to better define the role of this transport coefficient on moisture transport through contemporary building materials.

Storage of Moisture and Energy Changes

As moisture is transported across a finite volume in a porous building material of a building assembly, the amount of moisture retained by the finite volume changes during the transient part of the transport process. The basic causes for this change are:

1. A change in local temperature within the finite volume.
2. A change in local vapor pressure within the finite volume.

Changes in local temperature and vapor pressure within the pore structure change the vapor concentration within the pores and also change the amount of moisture adsorbed by the solid matrix and the moisture condensed within the pores. All three quantities of moisture are governed by the vapor pressure Eqs (1) and (2) as well as the sorption-desorption-suction isotherm of the building material. As the local temperature and vapor pressure change, depending on where the material is on its sorption-desorption-suction isotherm, moisture may undergo any of the phase transitions that are shown in Fig. 3. These phase transitions are associated with significant latent heat transfers and thus affect the energy conservation equations that correspond to the finite volume under consideration. This in turn affects the thermal domain of the finite volume. Hence a proper analysis of the hygrothermal effects within a built environment shall consider the interaction between heat and moisture transfer. If air transport also coexists, the interaction between the three parallel transport processes becomes even more complex. The details of these interactions are further explained in the following chapter of this manual.

Modeling Heat, Air, and Moisture Transport

In recent years the fundamental knowledge that is summarized above, together with the knowledge on heat transfer and airflows in buildings has resulted in many computer based models that have been used to assess the hygrothermal performances of building envelope components, such as walls and roofs [9,10,14,60]. Further advances are soon expected in this area to include whole building hygrothermal analysis [7].

The generalized transport Eq (3) forms the fundamental basis for all models that are used for hygrothermal analyses. Fourier's equation for heat transfer, Fick's Law for mass transfer, Darcy's Law for air and liquid flows, and Navier-Stokes equation for convective flow are examples of transport equations that have been used in the development of computer models. When a transport process through a medium is modeled, the medium is treated as an ensemble of many finite volume elements. These volume elements are called control volumes. Each control volume, V, has to fulfill the axiom of conservation of any entity B during any stage of the transport process. The generalized conservation equation is [61].

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

The first step in modeling is then to write mathematical expressions for the three terms in the above conservation equation for each transport process under consideration. In building applications, this results in three simultaneous conservation equations.

1. Conservation of energy for heat transport.
2. Conservation of mass for air and moisture transport.
3. Conservation of momentum for air and water vapor transport.

The exactness of these equations depends on how exactly the two terms on the right hand side of the conservation equation represent the physical phenomena. This in turn depends largely on empirical knowledge. However, significant work has been carried out by a number of research groups in the past decade to update the empirical information. In the case of moisture conservation equations the European Union has even attempted a project [6] on standardization of the experimental and analytical procedures.

However detailed the conservation equation may be and however sophisticated the mathematical procedures that are used to solve those equations may be, the reliability of the results from the model calculations depends on the reliability of a number of inputs to the model. Information on the hygrothermal properties of various materials in the building assembly and the parameters that define the boundary conditions of the assemblies are two of the inputs that shall be reliably known. Significant advances were made in generating information on the hygrothermal properties of building materials [24–28] in recent years. ASHRAE SPC 160 is developing a standard procedure for weather data analyses in relation to hygrothermal modeling. Further advances are expected, based on the outcome of the IEA Annex 41 [62–65].

With the advances in the development of personal computers, mathematical tools and models for hygrothermal analyses are gaining popularity within building practitioners as well as the building industry. The procedures used by tools can be as simple as the steady state method developed by Glaser and illustrated in Appendix 2 and subsequently in Chapter 10 of this manual. Computer models can be as simple as a one-dimensional heat and moisture transfer model or as complex as a two- or three-dimensional heat, air, and moisture transfer model. Further details on modeling can be found elsewhere [9].

Concluding Remarks

The information on the hygrothermal behavior of building materials continues to be predominantly empirical. Various international research groups in this regard have generated a significant amount of information in the past decade on a number of building materials that are used in contemporary construction. This information includes many experimental and analytical procedures for the determination of the transport and storage properties of building materials as well as documents on building material properties. A theoretical approach to quantify various modes of moisture transport is still elusive. This has resulted in ambiguities in the empirical knowledge. Many of the currently used experimental procedures are very challenging and demand very specialized skills on the part of the experimentalist. Disagreement among the results even from well established laboratories are often alarming. Also, standard test procedures in several cases are yet to be agreed upon at an international level. Both these issues need attention from the international research community.

The advances made in recent years in the use of computer-based hygrothermal models have been remarkable. With reliable information on moisture storage and transport properties as well as detailed information on various boundary conditions, adequate agreement has been obtained between model calculations and controlled experimental results on hygrothermal processes, such as wetting and drying of building materials and assemblies. Commercially available computer models are gaining acceptance among building practitioners and researchers alike. Further advances in this field are expected within the next five years as the outcome of an international effort called the IEA Annex 41,–MOIST-ENG. These advances will address whole building hygrothermal analysis rather than the analysis of building components and rational approaches to select the boundary conditions for the analysis.

Appendix 1
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

$$pV = nRT \tag{A1}$$

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

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

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

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

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

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

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.

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

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

For temperatures below 273.16 K, A = 28.542, B = −5,869.9 K, and C = −2,882 $K^{1.5}$, and for temperatures above 273.16 K, A = 22.565, B = −2,337.1 K, and C = −33,623 $K^{1.5}$.

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 derived 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

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

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

$$W = \frac{\text{mass of water vapor}}{\text{mass of dry air}} \tag{A7}$$

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.

$$\text{RH} = 43\ \% = \frac{\text{partial pressure of water vapor}}{2{,}338.6\ \text{Pa}} \times 100$$

then, partial pressure of water vapor = 1,005.6 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 a 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.

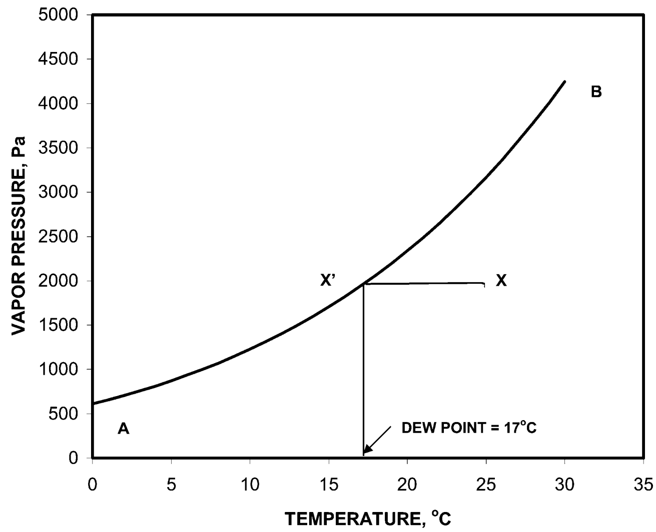


Fig. A1—Condensation of moist air during cooling.

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 then has 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.

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 psychrometric chart, a simple form that is illustrated in Fig. A2. Such

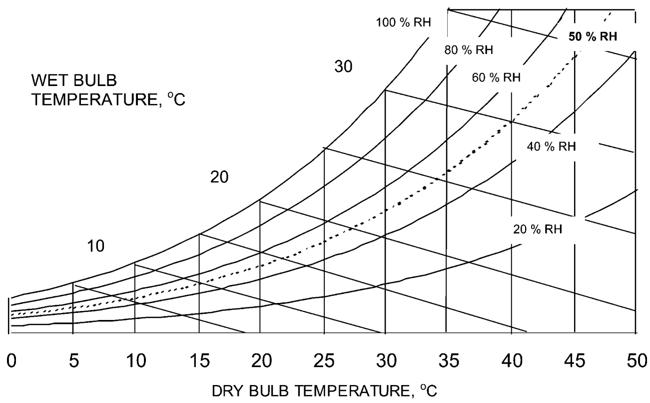


Fig. A2—A simple psychrometric chart.

a chart graphically approximates the properties of moist air. A psychrometric chart is basically generated from Fig. A1by 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 (see Example 5 below). 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.

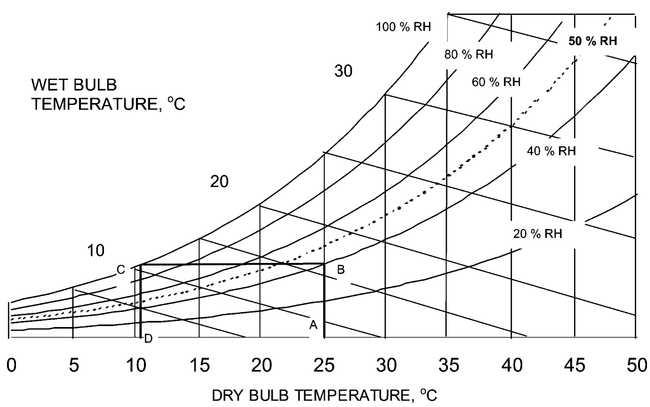


Fig. A3—Calculation of dew point temperature.

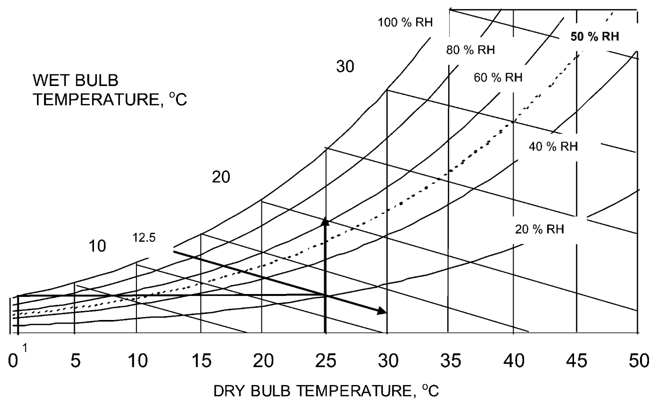


Fig. A4—Calculation of relative humidity and dew point temperature from psychrometric measurements.

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.

APPENDIX 2

Example 1. Surface Condensation on Windows; Psychrometric Calculations

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

TABLE 5—Material Properties

Material	Thermal Conductivity W/(m·K)	Vapor Permeability kg/(m·s·Pa)
Gypsum	0.17	1.7E−11
Insulation	0.036	1.3E−10
Wafer board	0.055	4.2E−13

20°C, the saturation vapor pressure, according to the approximate 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

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 is 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?

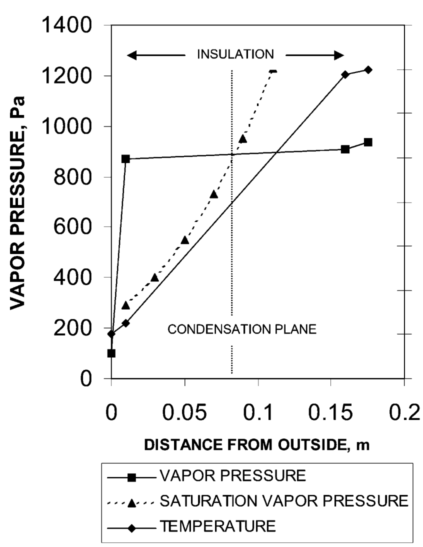


Fig. A5—Calculated results from vapor pressure-saturation vapor pressure method to Example 2; where the saturation vapor pressure curve intersects the vapor pressure distribution line, a condensation plane appears.

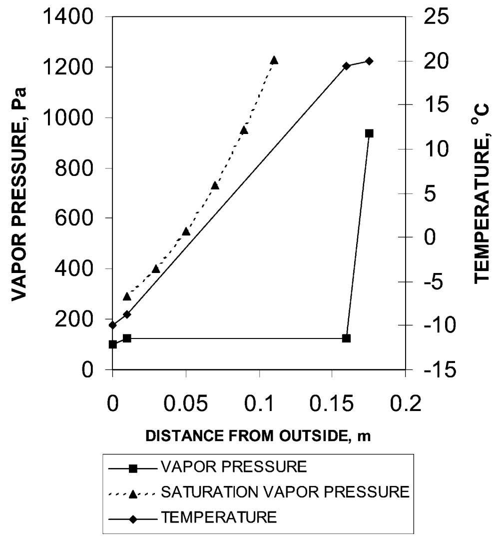


Fig. A6—Calculation shows that as the water vapor permeability of the gypsum board is reduced from 1.7E-11 kg/(m·s·Pa) to 1.7E-14 kg/(m·s·Pa), say by using a vapor retarder, the saturation vapor pressure curve does not intersect the vapor pressure lines and the condensation plane in Fig. vanishes.

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 plane from inside to outside, where this may happen, is referred to as the condensation plane.

The calculated temperature and vapor pressure distributions, at steady state, are shown in Fig. A5. 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 approximately through the center of the insulation layer 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. A6, 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 insulation and that the amount of condensed moisture at the condensation plane calculated above is negligible for several hundred hours.

References

[1] Phillip, J. R. and de Vries, D. A., "Moisture Movemnt in Porous Media Under Temperature Gradients," *EOS Trans. Am. Geophys. Union*, Vol. 38, 1957, pp. 222–232.

[2] De Vries, D. A., "The Theory of Heat and Moisture Transfer in Porous Media Revisited," *Int. J. Heat Mass Transfer*, Vol. 30, 1987, pp. 1343–1349.

[3] Luikov, A. V., "Systems of Differential Equations of Heat and Mass Transfer in Capillary Porous Bodies," *Int. J. Heat Mass Transfer*, Vol. 18, 1975, pp. 1–14.

[4] International Energy Agency Annex 14, "Condensation and Energy," 1986–1990.

[5] International Energy Agency Annex 24, "Heat, Air and Moisture Transfer in Insulated Envelope Parts," 1991–1995.

[6] European Union Research Project, "HAMSTAD," 2001–1004.

[7] International Energy Agency Annex 41, "MOIST-ENG," 2003–2008.

[8] Kohonen, R., "A Method to Analyze Transient Hygrothermal Behaviour of Building Materials and Components," Publication 21, Technical Research Center of Finland, Espoo, 1984.

[9] Hens, H., "Heat, Air and Moisture Transfer in Insulated Envelope Parts. Final Report, Volume 1, Task 1: Modeling," International Energy Agency Annex 24, Laboratorium Bouwfysica, K. U. Leuven, Belgium, 1996.

[10] Kumaran, M. K., Mukhopadhyaya, P., Cornick, S. M., Lacasse, M. A., Rousseau, M. Z., Maref, W., Nofal, M., Quirt, J. D., and Dalgliesh, W. A., "An Integrated Methodology to Develop Moisture Management Strategies for Exterior Wall Systems," *9th Canadian Conference on Building Science and Technology*, Vancouver, B.C., 27 February 2003, pp. 45–62, (NRCC-45987) URL: http://irc.nrc-cnrc.gc.ca/fulltext/nrcc45987/

[11] Kuenzel, H. M., "Simultaneous Heat and Moisture Transport in Building Components; One and Two Dimensional Calculation Using Simple Parameters," Ph.D. Thesis, Fraunhofer Instiue in Building Physics, 1994.

[12] Various Papers in the *Proceedings of 1st International Building Physics Conference*, Eindhoven, The Netherlands, 2000.

[13] Various Papers in the *Proceedings of 2nd International Building Physics Conference*, Antwerpen, Belgium, 2003.

[14] Janssens, A., "Reliable Control of Interstitial Condensation in Lightweight Roofing Systems," Ph.D. Thesis, K. U.-Leuven, Belgium, 1998.

[15] Kumaran, M. K., "ASHRAE RP-1018 Research Report: A Thermal and Moisture Transport Property Database for Common Building and Insulating Materials," 2002, pp. 161–165.

[16] Alberty, R. A., *Physical Chemistry*, 7th ed., John Wiley & Sons, 1987, p. 318.

[17] Tveit, A., "Measurements of Moisture Sorption and Moisture Permeability of Porous Materials," Rapport 45, Norwegian Building Research Institute, 1966, p. 39.

[18] Straube, J., Onysko, D., and Schumacher, C., "Methodology and Design of Field Experiments for Monitoring the Hygrothermal Performance of Wood Frame Enclosures," *Journal of Thermal Environment and Building Science*, Vol. 26, 2002, p. 137.

[19] Kumaran, M. K. and Normandin, N., Unpublished data, Institute for Research in Construction.

[20] Mukhopadhyaya, P., Kumaran, M. K., and Normandin, N., Unpublished data, Institute for Research in Construction.

[21] Hansen, M. H., "Retention Curves Measured Using Pressure Plate and Pressure Membrane," *Nordtest Technical Report* 367, Danish Building Research Institute, 1998, p. 63.

[22] Krus, M., "Moisture Transport and Storage Coefficients of Porous Building Materials," Ph.D. Thesis, Fraunhofer Institute in Building Physics, 1996.

[23] Kumaran, M. K., "Heat, Air and Moisture Transfer in Insulated Envelope Parts. Final Report, Volume 3, Task 3: Material Properties," International Energy Agency Annex 24, Laboratorium Bouwfysica, K. U.-Leuven, Belgium, 1996.

[24] Hansen, K. K., "Sorption Isotherm, A Catalogue," Technical Report 162/86, The Technical University of Denmark, Lyngby, Denmark, 1986.

[25] Kumaran, M. K., "ASHRAE RP-1018 Research Report: A Thermal and Moisture Transport Property Database for Common Building and Insulating Materials," 2002, p. 229.

[26] Kumaran, M. K., Lackey, J. C., Normandin, N., van Reenen, D., and Tariku, F., "Summary Report from Task 3 of MEWS Project at the Institute for Research in Construction—Hygrothermal Properties of Several Building Materials," 2002, (RR-110), p. 73.

[27] Richards, R. F., Burch, D. M., and Thomas, W. C., "Water Vapor Sorption Measurement of Common Building Materials," *ASHRAE Transactions*, Vol. 98, Pt. 2, 1992.

[28] Kumaran, M. K., Lackey, J. C., Normandin, N., Tariku, F., and van Reenen, D., "Variations in the Hygrothermal Properties of Several Wood-Based Building Products," *Proceedings, 2nd International Building Physics Conference*, Leuven, Belgium, 14 September 2003, pp. 35–42, (NRCC-46090), URL: http://irc.nrc-cnrc.gc.ca/fulltext/nrcc46090/

[29] Kumaran, M. K., Lackey, J. C., Normandin, N., Tariku, F., and van Reenen, D., "Heat, Air and Moisture Transport Properties of Several North American Bricks and Mortar Mixes," *J. Test. Eval.*, Vol. 32, No. 5, 2004.

[30] Prigogine, I., *Introduction to Thermodynamics of Irreversible Processes*, Interscience Publishers, New York, 1967.

[31] de Groot, S. R., *Non-Equilibrium Thermodynamics*, Dover Publications, New York, 1984.

[32] Kumaran, M. K. and Stephenson, D. G., "Heat Transport Through Thermal Insulation: An Application of Irreversible Thermodynamics," ASME Paper No. 86-WA/HT-70, ASME, New York, 1986, pp. 1–4.

[33] Kumaran, M. K. and Stephenson, D. G., "Heat Transport Through Fibrous Insulation Materials," *J. Therm. Insul.*, Vol. 11, 1988, pp. 263–269.

[34] Kumaran, M. K., "An Alternative Procedure for the Analysis of Data from the Cup Method Measurements for Determination of Water Vapor Transmission Properties," *J. Test. Eval.*, Vol. 26, 1998, pp. 575–581.

[35] Joy, F. A. and Wilson, A. G., "Standardization of the Dish Method for Measuring Water Vapor Transmission," *Proceedings of the International Symposium on Humidity and Moisture*, Washington, DC, Vol. 4, Chapter 31, 1963, pp. 259–270.

[36] Hansen, K. K. and Lund, H. B., "Cup Method for Determination of Water Vapor Transmission Properties of Building Materials. Sources of Uncertainty in the Method," *Proceedings of the 2nd Symposium, Building Physics in the Nordic Countries*, Trondheim, 1990, pp. 291–298.

[37] Lackey, J. C., Marchand, R. G., and Kumaran, M. K., "A Logical Extension of the ASTM Standard E96 to Determine the Dependence of Water Vapor Transmission on Relative Humidity," *Insulation Materials: Testing and Applications: 3rd Volume, ASTM STP 1320*, R. S. Graves and R. R. Zarr, Eds., ASTM International, West Conshohocken, PA, 1997, pp. 456–470.

[38] Roels, S., Adan, O., Brocken, H., Carmeliet, J., Cerny, R., Hall, C., Hens, H., Kumaran, M. K., Pavlik, Z., Pel, L., and Plagge, R., "Interlaboratory Comparison of the Measurement of Basic Hygric Properties of Porous Building Materials," *Journal of Thermal Envelope and Building Science*, Vol. 27, No. 4, 2004, pp. 307–324.

[39] Kjatan Gudmundsson, T., "An Approach to Determining the Water Vapour Transport Properties of Building Materials," *The Nordic Journal of Building Physics*, (*Electronic*), Vol. 3, 2002–2004, pp. 1–10.

[40] Galbraith, G. H., Kelly, D. J., and McLean, R. C., "Alternative Methods for Measuring Moisture Transfer Coefficients of Building Materials," *Proceedings of the 2nd International Building Physics Conference*, Antwerpen, Belgium, 2003, pp. 249–256.

[41] Galbraith, G. H., Kelly, D. J., McLean, R. C., Munsi, Y., and Baker, P., "Measurement Techniques for the Investigation of Non-isothermal Moisture Transport," *Proceedings of CIB W40 Meeting on Heat and Moisture Transfer in Buildings*, Wellington, New Zealand, 2001, pp. 22–28.

[42] Kumaran, M. K., "Moisture Transport Through Glass-Fibre Insulation in the Presence of a Thermal Gradient," *J. Therm. Insul.*, Vol. 10, 1987, pp. 243–255.

[43] Ojanen, T. and Kumaran, M. K., "Air Exfiltration and Moisture Accumulation in Residential Wall Cavities," *Thermal Performance of the Exteriour Envelopes of Buildings: Proceedings of the ASHRAE/DOE/BTECC Conference*, Clearwater Beach, FL, 7 December 1992, pp. 491–500.

[44] Ojanen, T. and Kumaran, M. K., "Effect of Exfiltration on the Hygrothermal Behaviour of a Residential Wall Assembly," *Journal of Thermal Insulation and Building Envelopes*, Vol. 19, 1996, pp. 215–227.

[45] Luikov, A. V., *Heat and Mass Transfer in Capillary Porous Bodies*, Oxford, Pergamon, 1964.

[46] Richards, R. F., "Measurements of Liquid Diffusivity in Porous Building Materials," *Proceedings of the Conference on the Thermal Performance of the Exterior Envelopes of Buildings V*, Clearwater Beach, FL, 1992, pp. 501–511.

[47] Carmeliet, J., Adan, O., Brocken, H., Cerny, R., Hall, C., Hens, H., Kumaran, M. K., Pavlik, Z., Pel, L., Plagge, R., and Roels, S., "Determination of the Liquid Water Diffusivity from Transient Moisture Transfer Experiments," *Journal of Thermal Envelope and Building Science*, Vol. 27, No. 4, 2004, pp. 277–305.

[48] Kumaran, M. K. and Bomberg, M. T., "A Gamma-Spectrometer for Determination of Density Distribution and Moisture Distribution in Building Materials," *Moisture and Humidity: Measurement and Control in Science and Industry: Proceedings of International Symposium*, Washington, DC, 1985, pp. 485–490.

[49] Pel, L., "Moisture Transport in Porous Building Materials," Ph.D. Thesis, Eindhoven University of Technology, The Netherlands, 1995, pp. 47–80.

[50] Carmeliet, J., van Besien, T., and Roels, S., "New Indirect Estimation Technique for the Determination of the Moisture Diffusivity from Transient Moisture Content Profiles Measured by means of X-ray Radiography," *Proceedings of the 2nd International Building Physics Conference*, Antwerpen, Belgium, 2003, pp. 159–167.

[51] Salonvaara, M., "A Transient Method to Determine Moisture and Heat Transfer Coefficients of Porous Materials," *Proceedings of the 2nd Symposium on Building Physics in Nordic Countries*, Tapir Publishers, Trondheim, Norway, 1990, pp. 355–360.

[52] Bruce, R. R., and Klute, A., "The Measurement of Soil Diffusivity," *Soil Sci. Soc. Am. Proc.*, Vol. 20, 1956, pp. 251–257.

[53] Kumaran, M. K., Mitalas, G. P., Kohonen, R., and Ojanen, T., "Moisture Transport Coefficient of Pine from Gamma Ray Absorption Measurements," *Collected Papers in Heat Transfer, 1989: Winter Annual Meeting of the ASME*, San Francisco, CA, 1989, pp. 179–183.

[54] Kumaran, M. K., "Heat, Air and Moisture Transfer in Insulated Envelope Parts. Final Report, Volume 3, Task 3: Material Properties," Appendix I, International Energy Agency Annex 24, Laboratorium Bouwfysica, K.U.-Leuven, Belgium, 1996, pp. 109–112.

[55] Kumaran, M. K., "Heat, Air and Moisture Transfer in Insulated Envelope Parts. Final Report, Volume 3, Task 3: Material Properties," Appendix II, International Energy Agency Annex 24, Laboratorium Bouwfysica, K. U.-Leuven, Belgium, 1996, pp. 113–122.

[56] Kumaran, M. K., "Moisture Diffusivity of Building Materials from Water Absorption Measurements," *Journal of Thermal Envelope and Building Science*, Vol. 22, 1999, pp. 349–355.

[57] Roels, S., Carmielet, J., Hens, H., Adan, O., Brocken, H., Cerny, R., Pavlik, Z., Hall, C., Kumaran, K., Pel, L., and Plagge, R., "Interlaboratory Comparison of Hygric Properties of Porous Building Materials," *Journal of Thermal Envelope and Building Science*, Vol. 27, 2004, pp. 307–325.

[58] Grunewald, J. and Bomberg, M., "Towards an Engineering Model of Material Characteristics for Input to HAM Transport Simulations," *Proceedings of the 2nd International Conference on Building Physics*, Antewerpen, Belgium, 2003, pp. 237–248.

[59] Hokoi, S., "Fundamentals Study on Thermal Properties of Moist Building Materials," 1986, Kobe University (in Japanese).

[60] Trechsel, H. R., Ed., *Moisture Analysis and Condensation Control in Building Envelopes, ASTM MNL40*, ASTM International, West Conshohocken, PA, 2001.

[61] Mikhailov, M. D. and Ozisik, M. N., *Unified Analysis and Solutions of Heat and Mass Diffusion*, Wiley-Interscience, New York, 1984, p. 2.

[62] Woloszyn, M. and Rode, C., "Modeling Principles and Common Exercises," International Energy Agency (Exco ECBCS) Annex 41 – Whole Building Heat, Air, Moisture Response, D/2008/0543/204, NUR 955, ISBN 978-90-334-7057-8, 2008, p. 234

[63] Roels, S., "Experimental Analysis of Moisture Buffering," International Energy Agency (Exco ECBCS) Annex 41 – Whole Building Heat, Air, Moisture Response, D/2008/0543/205, NUR 955, ISBN 978-90-334-7058-5, 2008, p. 173.

[64] Kumaran, K. and Sanders, C. "Boundary Conditions and Whole Building HAM Analysis," International Energy Agency (Exco ECBCS) Annex 41 – Whole Building Heat, Air, Moisture Response, D/2008/0543/206, NUR 955, ISBN 978-90-334-7059-2, 2008, p. 235.

[65] Holm, A. "Applications; Indoor Environment, Energy, Durability," International Energy Agency (Exco ECBCS) Annex 41 – Whole Building Heat, Air, Moisture Response, D/2008/0543/208, NUR 955, ISBN 978-90-334-7061-5, 2008, p. 177.

MNL18-EB/Oct. 2009

2

Hygrothermal Characteristics of Materials and Components Used in Building Enclosures

Mark T. Bomberg[1] and Clifford J. Shirtliffe[2]

Problem Statement

A BUILDING IS A RATHER COMPLEX AND LONG-lived system. Its shell, building enclosure (BE), "breathes," ages, expands, contracts, and is exposed to an ever-changing set of conditions induced by nature and man. Sometimes the people change the fabric from the original design; buildings are reinsulated, renovated, and rehabilitated. The designer must consider all aspects of the building's life during the design and yet keep the building affordable and competitive.

The design of the building enclosure aimed in addressing the set of interacting conditions in heat, air, moisture flows, and their effects on construction, is called "environmental control."

A Need for the Holistic Approach to Design of Environmental Control of Buildings

The discussion on environmental control function involves several types of barriers in the assembly. The barriers are given different names and acronyms. Material standards tend to follow the name and list all the tests necessary to meet that single function for which the barrier is named. For instance, the vapor barrier retards the passage of water vapor or the air barrier retards the passage of air. Building codes have the same approach; they simplify the process of design by relating control of each phenomenon to one particular material, e.g., thermal insulation is to control heat transfer; air barrier is to control air leakage. While this may be necessary to develop standards based on a minimum acceptable performance, this is far from the reality of buildings' performance. These "designated" materials actually perform many different functions and influence the overall system performance in many ways. For instance, by increasing temperature in the wall cavity, thermal insulating sheathing may also reduce the degree of condensation in the cavity. Similarly, while controlling air leakage, the air barrier system may also provide effective moisture control.

There is a fundamental difference between dealing with the environmental control of the building envelope and the structural design. In the structural design, once information on all the loads and forces has been collected, one can select materials and establish their cross sections and other dimensions. The design is completed. In the design of environmental control, such a situation marks the beginning of the process. The environmental performance of BE depends on the whole assembly not only performance of the selected "barriers." Once the primary barriers and materials have been selected to satisfy the building codes and standards (i.e., on the basis of separate functions), the designer must analyze the performance of the whole system. Since the process of environmental control depends on strong interactions between heat, air, and moisture transport, to ensure that all aspects of the building envelope perform effectively, one must deal with heat, air, and moisture transport collectively.

Bomberg and Brown [1] stated:

> "Accommodating environmental control in building design requires iterative analysis and a willingness to change not only minor details, but to alter the basic concept itself if information indicates that this is desirable. Thus, the design must remain as flexible as possible until all the consequences are fully examined.
>
> The design of an air barrier system offers an example of how the process of iterative design might work. The information flow may start with a search for suitable materials. Typical questions are asked about possible materials and their air permeability, they ability to be extended, about pliability, adhesion, and means of attachment, connection, and support. The review would address the long-term performance, material aging, stress, and deformations during service, as well as projected costs of repairs and maintenance. After making an initial selection, the designer then specifies the architectural details such as intersections and joints between building elements (for example foundations, walls, floors, windows, and doors). Then, to achieve satisfactory performance in these locations, the designer must ask further questions concerning the performance of the whole system, such as rate of air leakage, location of penetrations that may result in air leakage, risk of drafts, and impact on condensation. Throughout the design process, the designer consults with structural, electrical and mechanical experts to obtain answers to all these questions and to ensure that the selected materials will perform satisfactorily.

[1] *Research Professor, Syracuse University, Syracuse, NY 13244*
[2] *Previously Senior Research Officer with Institute for Research in Construction; National Research Council of Canada, Ottawa, Canada K1A 0R6.*

In addition, the designer reviews the buildability aspects such as material installation under different weather conditions, level of labor skill required for installation, and construction tolerance. Buildability, as the word suggests, reflects whether the design on paper can be constructed.

Finally, the complexity of heat, air, and moisture interactions demands redundancy in the design. For instance, the air barrier plan may be punctured, not connected to some elements of the envelope, or a rain leak may develop. The designer must evaluate if the moisture can be drained, or if not drained, whether it could be dried out. How long would the drying take? What effect would it have on other materials? Could the prolonged presence of moisture cause corrosion, mold growth, or rot?

The entire process of environmental control design must occur off-site, and never at the building site. Addressing only a specific design problem on the job site, without reviewing all the performance effects, courts disaster since integration of other requirements may not be achieved."

Advantages and Disadvantages of Models

Straube and Burnett [2], in their overview of hygrothermal analysis models, highlighted that models can be used to improve understanding of the problem and ways to avoid the potential problem. They can also be used for parametric study of climate or material characteristics; in other words, they are very useful in the first stage of design. Models are undoubtedly useful and a key tool in the designers toolbox, but they do not consider all the aspects of hygrothermal performance necessary in the design. For example, as discussed later in this chapter, a vapor barrier of 1 perm may represent sufficient retardation of water vapor flow for wood frame housing without an air barrier system, while 5 perms would be suitable for the same construction when provided with an air barrier.

While designers must conduct an overall qualitative assessment to determine whether the chosen barrier would actually function in the specific application, and for this must use analytical tools, this is only an input to their decision process. The final selection of the most appropriate barrier involves both analytical analysis and the professional judgment (conceptual logic).

In effect, modeling should be treated in a manner similar to material property testing: a necessary part of information needed for a judgment but not as information replacing the professional judgment.

Confusion in Concepts of Material Characteristics

Bomberg and Brown [1] highlighted that 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. On the analytical side is a complex array of tools (see Chapter 10 of this manual), models and data that 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.

Two previous sections showed the problems of an emerging science (building science). There are contradictions between material-based system of codes and standards and system-based evaluation of building science. Hygrothermal models that may provide holistic information need to be verified with independent tests if they are to be used in the decision making.

Writing the chapter on material characterization, authors faced a dilemma as to whether to report methods used for testing for input data to models or for input data to ASTM standards that are used by the building code (generally quite different) or focus on the building science view point. There is an ASTM manual No. 40) on hygrothermal models, there are many descriptions of ASTM standard test methods but there is no review of needs as seen from building physics point of view. Therefore, we selected the latter even though some of the building science concepts are still not developed into complete test procedures.

Characteristics of Materials Used in Airflow Control

One needs to ensure airtightness of the building enclosure for the following reasons:

- Reduce the amount of moisture carried by the moist air (indoor in cold climates, outdoor in warm and humid climates) and thereby increase durability of the construction.
- Reduce the amount of VOC or particulate carried from the outdoor or from construction materials into the indoor space.
- Reduce the amount of uncontrolled ventilation (air infiltration) that is driven by wind and temperature differences and not by the needs of the occupant.
- Reduce the amount of heat gain or loss caused by the air entry with temperature different than that of conditioned space.

The required level of air tightness depends on outdoor climate as well as on the indoor conditions (e.g., pressure fields created by mechanical ventilation, and heating or cooling systems). While the effects of uncontrolled airflows (UAFs) on energy or ventilation relate to an overall airtightness of the building enclosure, the moisture-originated durability depends on size and location of air leakage openings. The effects of moisture carried by the air require distinguishing between the requirements for local airflows and the overall tightness of the wall.

One has to address these issues during design of the building enclosure. The design of the building enclosure provides a basis for design of the heating, ventilating, and air conditioning (HVAC) systems. At the same time, the design, installation, and operation of the HVAC system affect all aspects of indoor climate and building enclosure (BE) durability. Air movements induced by HVAC may affect pollutant migration, rain penetration, condensation, drying of moisture within building cavities, and durability of building components.

While airflow control is recognized as critical to the proper functioning of building enclosures, the path from recognition to achieving it in practice is not an easy one. For instance, some building codes (e.g., Canada, Massachusetts) introduced requirements of the air barrier systems. Yet, as with all new concepts, a lot of details remain to be improved.

Air Barrier Systems

Earlier, and independently of each other, two alternate approaches to air leakage control were introduced: the Airtight Drywall Approach (ADA) and the External Airtight Sheathing Element (EASE). Using gaskets and controlling terminations of the drywall sheets, Lstiburek and Lischkoff [3] achieved relatively airtight buildings. To achieve continuity of airflow control at the wall /window interface both polyurethane foam and neoprene gaskets were placed at the terminations of the drywall. With ensuring control of airflow, one was able to reduce the requirement for water vapor resistance. Paint applied on the drywall provided the necessary vapor resistance and the polyethylene films were eliminated.

While the Airtight Drywall Approach system was shown to work well in a single-family house, to minimize flanking sound transmission in row housing and apartment blocks, one had to consider an alternate approach, namely, that of external insulating sheathing (EASE). Application of an External Airtight Sheathing Element was beneficial for several additional reasons. Firstly, by providing a continuous layer of thermal insulation on the outside of the framing, it reduced thermal bridging. Second, by increasing the temperature of the surface of the sheathing facing the wall cavities it reduced the risk for condensation in the cavities of wood-frame walls.

Later, with more stringent requirements listed in the model code—National Building Code of Canada [4] peel and stick or torch applied membranes became more popularly used, particularly in rehabilitation of old or damaged walls. Today, there is a number of membranes and liquid applied coatings that satisfy these requirements. For clarity of this presentation, we will only discuss requirements for airtightness of wall assemblies.

Air barriers are systems of materials designed and constructed to control airflow between a conditioned space and an unconditioned space. The air barrier system is the primary air enclosure boundary that separates indoor (conditioned) air and outdoor (unconditioned) air. In multi-unit, townhouse, or apartment construction, the air barrier system also separates the conditioned air from any given unit and adjacent units. Air barrier systems also typically define the location of the pressure boundary of the building enclosure. In multi-unit, townhouse, and apartment construction, the air barrier system is also the fire barrier and smoke barrier in inter-unit separations. In such an assembly, the air barrier system must also meet the specific fire resistance rating requirement for the given separation.

Air barrier systems typically are assembled from *materials* incorporated in *assemblies* that are interconnected to create *enclosures*. Each of these three elements has measurable resistance to airflow (see later text). Materials and assemblies that meet these performance requirements are said to be air barrier materials and air barrier assemblies. Air barrier materials incorporated in air barrier assemblies that in turn are interconnected to create continuous enclosure are called air barrier systems.

In the 1995 edition of the NBCC, the air barrier system was required to satisfy the following requirements:

- There should be a material layer intended to provide the principal resistance to air leakage with an air permeance not greater than 0.02 $L/(s \cdot m^2)$ measured at a 75 Pa difference.
- All components of the air barrier system shall comply with durability requirements specified by respective material standards.
- The system shall be continuous across joints, junctions and penetrations.
- The system shall be capable of transferring design wind loads.
- The system shall be evaluated with deflections reached at 1.5 times of the specified wind load.

Reviewing issues in airflow control, Bomberg et al. [5] stated:

> "Now we recognize that the performance of the air barrier must be considered in light of its performance as a system. Yet assuming that air barriers are employed mainly for the sake of energy conservation is a mistake. We have come to depend on air barriers for several stated and unstated benefits. Besides the obvious economic benefit of minimizing loss of energy used for conditioning air, we have long recognized that airflow through wall assemblies, may lead to deposition of moisture, whether the buildings are heated or cooled. To a lesser degree, we recognize that contamination of wall cavities in the building assemblies by organic materials from inside or outside provides both the nutrients and the inoculation potential for mold growth. Moisture carried by air may also increase the rate of emission of volatile organic compounds from these materials. While keeping rain out of building enclosures is a primary consideration in design, controlling airflow through the building enclosure comes a close second in importance to allow environmental control within buildings. A complete overview of this topic would consider airflow through foundations, walls and roofs."

Concepts of air barrier systems are intrinsically associated with wall airtightness. In this context, Bomberg et al. [5] listed five different concepts of airtightness. Some of them have little practical significance, for instance the concept of material airtightness as defined by the NBCC 1995 [4]. As shown in the next section there is a number of materials that are impermeable for air and many of wood or thermal insulating sheathing boards are tighter than the benchmark in NBCC 1995 [4]; namely, 1/2-in. gypsum board. The second concept of no practical value is that of plain wall assembly without a window or penetrations. While it might have been interesting during the development work, this type of test does not address the most important issue of AB systems, i.e., continuity of airflow control.

Three remaining concepts have a significant impact on construction trade and should be carefully defined:

- overall enclosure airtightness
- laboratory assembly airtightness
- field assembly airtightness

Overall enclosure airtightness is tested under field conditions using HVAC or blower door apparatus to pressurize or depressurize the whole building. This test provides information about airtightness of the building enclosure to enable the HVAC system to function properly (Desmarais et al. [6]) and for modeling of energy use. The overall enclosure airtightness is a product of enclosure airtightness, connectivity with other partitions and spaces, and interzonal airflows. In this sense, overall enclosure airtightness may be used as a benchmark with one value proposed for different constructions and different climates.

Laboratory tests of wall assemblies provide information that can lead to improvements in construction details [7–9]. While the above laboratory tests are important for material and component manufacturers, they will not necessarily predict field performance of the enclosure. The situation in the field involves more complicated pathways, including those between different zones and through interior partitions.

Quirouette [7] proposed a target for wall airtightness with the provision that "*these numbers are for discussion only*." The starting point was taken from recommendations used by the metal and glass curtain wall industry that had adopted a limit of 0.3 $L/(s \cdot m^2)$ at 75 Pa as the maximum allowable air leakage rate. In later CCMC publications, this value was replaced by a range related to the average operating interior relative humidity but independent of climate and the nature of materials used in the assembly. This means that the same criterion would apply equally to a wood frame wall in the mixed climate of Vancouver, BC or severely cold climate of North Bay, ON. Yet, Ojanen et al. [10] showed that, under the same airflow conditions, in those two locations moisture accumulation would be about 100 times different. Furthermore, the limit for enclosure airtightness depends on a wall construction and, in particular, to the use of thermal insulating sheathings. Ojanen and Kumaran [11] highlighted the importance of using the thermal insulating sheathing in a cold climate.

While the overall enclosure airtightness is a general benchmark, the field airtightness of assembly must relate to the actual hygrothermal performance of the assembly and specifically to the durability and risk for mold growth. No general statement in codes is recommended because this is an effect of hygrothermal design and proper construction techniques rather the arbitrary goal. In residential construction, it would be of great benefit to require air tightness testing during construction for identification of faults at a time when they are most easily fixed. Such a test may assure good performance of the assembly. This would be more effective than specifying specific enclosure airtightness criteria in codes or standards.

In a nutshell, we need the AB systems. Understanding of the building science principles involved provides us with a possibility of "designing out" potential problems. The authors claim that enforcing AB continuity is much more important than providing requirements for material or laboratory wall airtightness. The airtightness criterion introduced by the Canadian model code is useful to define acceptable materials. Performance of the system, however, depends on decisions as to where the airtightness plane is located (interior, exterior, or in the middle of the assembly) and how the airtightness plane is made continuous over junctions, joints, and interfaces.

TABLE 1—Air permeability of selected building materials where rate = $L/s \cdot m^2$ at 75 Pa and Nml = No measurable leakage.

Material	Rate
Modified torch-on membrane (glass matt)	Nml
Modified torch-on membrane (polyester matt)	Nml
Modified peel and stick membrane, 1.3 mm	Nml
Polyethylene film, 1.5 mm (6 mil)	Nml
Plywood sheathing, 9.5 mm (3/8 in.)	Nml
Foil backed gypsum board	Nml
Extruded polystyrene insulation, 38 mm	Nml
Cement board, 12.7 mm	Nml
TYVEK® Home Wrap	0.004
Plywood sheathing, 8.0 mm	0.007
Waferboard, 16 mm	0.007
Gypsum board, (MR), 12.7 mm	0.009
Waferboard, 11 mm	0.011
Particle board, 12.7 mm	0.016
Gypsum board, 12.7 mm	**0.020**
Particle board, 15.9 mm	0.026
Tempered hardboard, 3.2 mm	0.027
TYVEK® Commercial Wrap	0.04
Expanded polystyrene insulation, 1.25 lb/ft^3	0.12
Roofing felt, 30 lb.	0.19
Nonperforated asphalt felt, 15 lb.	0.27
Perforated asphalt felt, 15 lb.	0.40
Fiber board, 11 mm	0.82
Perforated polyethylene #1	3.23
Expanded polystyrene insulation, 0.9 lb/ft^3	12.2
Tongue and groove planks	19.1

Air Leakage Characteristics for Building Enclosure, Assembly, and Materials

To give a few examples of material airtightness as tested in the lab we reproduce Table 1 from Quiroette et al. [7]. (For discussion of test methods, see "Methods Uses for Measuring Hygrothermal Characteristics" "Laboratory Tests of Airtightness".)

Table 2 shows an air leakage test performed by the National Research Council of Canada (NRCC) on wall assemblies [12]. To simulate sustained wind loading, the test walls were subjected to test pressures of 250, 500, and 1000 Pa for 1 h each. Gust loading was simulated by subjecting the walls to pressure differentials of 1500, 2000, and 2500 Pa for 5 to 10 s. Following each structural performance test, the wall was examined for visual signs of structural damage, and the air leakage rate was measured at approximately 75 Pa for verification of nonvisible damage.

Table 2 describes each of the air barrier systems tested and the air leakage rate obtained at a pressure differential of 75 Pa. The table also provides the maximum pressure differentials, for both sustained load and gust load, to which the wall was exposed without exhibiting a significant loss in airtightness. Finally, it includes observations on the results of the structural wind load tests. Except for test 1, other tests reported in Table 2 passed the proposed criterion.

Comparing Tables 1 and 2 one can observe that the difference between material and assembly airtightness is one order of magnitude (about 10 times) and between Tables 2 and 3, i.e., the difference and between laboratory test and field test is similar. A limit of material permeance of 0.02 $L/(s \cdot m^2)$ @ 75 Pa proposed by NRCC [13] is generally

TABLE 2—Results of Air Leakage and Structural Load Tests [12]

Wall #	System Description	Air Leakage Rate L/s·m²@75 Pa	Sustained Load		Gust Load	
1	Fiberboard/Tyvek®/Strapping Fiberboard sheathing nailed to the wood structure with 1 3/4-in. galvanized roofing nails at 6 in. o.c., Tyvek paper (1990 version) stapled to the fiberboard every 4 ft, vertical wood strapping nailed to the perimeter and face of the studs with spiral nails at 12 in. o.c.	**0.488** There was no change to the air leakage rate after the structural tests. However, the wall was too leaky to obtain either positive or negative test pressures at 2000 Pa and 2500 Pa: under positive pressure, the Tyvek ballooned outward between the wood strapping and after the +1000 Pa sustained load test, the Tyvek paper remained loose on the surface of the fiberboard sheathing.	–1000 Pa	+1000 Pa	–1500 Pa	+1500 Pa
3	Exterior gypsum/Perm-A-Barrier tape Two exterior gypsum boards nailed horizontally to the wood structure using 1 3/4-in. galvanized roofing nails at 6 in. o.c., primed with "Primer P-3000" and sealed with Perm-A-Barrier wall seam tape.	**0.015** There was no change in the air leakage rate after structural tests. However, structural failure occurred during the +2500 Pa test: the top gypsum board pulled off from the nails along the intermediate supports, after which the air leakage rate increased to 1540 L/s·m².	–1000 Pa	+1000 Pa	–2500 Pa	+2300 Pa
4	Extruded Polystyrene/3M tape Shiplapped, extruded polystyrene insulation boards nailed to the structure with 2 1/2-in. spiral nails with 1-in. diameter metal washers every 6 in. along the edges and 12 in. along the intermediate supports, with 3M construction tape over joints.	**0.002** Because of the airtightness of this assembly, the reference air leakage was taken at 185 Pa instead of 75 Pa. Two air leakage tests were performed under both negative and positive pressure differentials: first, with untaped nails at the center of the insulation boards; then, with nails taped with 3M construction tape. No difference was noted with nails taped or untaped. The system failed structurally at some nail locations at +2500 Pa gust load test, but the air leakage after the test was only 0.005 at 180 Pa.	–1000 Pa	+1000	–2500 Pa	+2500 Pa
6	Dryvit Wall Panel Prefabricated wall panel supplied by Dryvit, consisting of steel stud structure, exterior gypsum board, expanded polystyrene insulation and a synthetic exterior finish.	**0.003** The air barrier system performed structurally through all the sustained load and gust load tests with no visible physical change of the assembly components. The gypsum board layer was made up of various differently sized pieces screwed to the steel stud structure about every 4 in.. The use of full-size gypsum boards might lead to a different performance than the one obtained.	–1000 Pa	+1000 Pa	–2500 Pa	+2500 Pa
7	Gypsum/Joint Compound Gypsum board (1/2-in.) attached horizontally to the wood structure with 1 1/4-in. drywall screws every 8 in. along edge supports and 12 in. along the intermediate supports, with drywall joint compound (two coats) and paper tape and surface-painted with two coats of latex paint.	**0.002** No change in air leakage was observed after negative pressure tests. Air leakage increased to 0.006 L/s·m² after reaching +1800 Pa: the gypsum board pulled off somescrews but did not cause a complete break of the air seal. Because of the increased air leakage, a second +2000 Pa test was attempted. Structural failure occurred during this test at approximately +1600 Pa: the top gypsum board pulled away from all the screws along the intermediate supports, and the gypsum board joint broke along the whole length.	–1000 Pa	+1000 Pa	–2500 Pa	+1800 Pa
8	Plywood Skin Panel Plywood skin glued with subfloor adhesive to a frame of 2×4 wood studs at 2 ft o.c. with a single top and bottom plate and 1 1/4-in. drywall screws at 6 in. o.c. The 2 1/2-in. glass fiber batt insulation against the inner plywood in the cavities left a 1-in. air space between it and the outer plywood.	**0.004** No change in air leakage rate nor any physical change was noted after all sustained load and gust load tests. To determine if a single plywood skin subject to the same attachment techniques would perform as well, 2-in. diameter holes were drilled in the exposed plywood skin at the top and bottom of each stud space, and the air leakage testwas repeated at intervals of from 10 Pa to 500 Pa. The air leakage rate was measured as 0.005 L/s·m² at 75 Pa. The 1000 Pa sustained load test and the 2500 Pa gust test were also repeated with no change in air leakage rate being observed.	–1000 Pa	+1000 Pa	–2500 Pa	+2500 Pa

TABLE 2— *(Continued.)*

Wall #	System Description	Air Leakage Rate L/s·m²@75 Pa	Sustained Load		Gust Load	
9	Fiberboard/Polyurethane Foam Asphalt impregnated fiberboard (7/16-in.) nailed to the wood structure with 1 3/4-in. galvanized roofing nails at6 in. o.c. on edges and 12 in.o.c. on the intermediate supports, and stud cavities filled spray-applied polyurethane foam insulation cut flush	**0.019**	−1000 Pa	+1000 Pa	−2500 Pa	+2500 Pa
		The system performed structurally through all the sustained load and gust load tests with no change in air leakage rate being observed and no significant physical change to the assembly components. During the +500 Pa sustained load test, several nail heads became partially embedded in the fiberboard.				

accepted as division between air impermeable (i.e., suitable for AB systems) and air permeable materials.

The ten-fold difference between airtightness of material and assembly highlights that the critical issue in assembly airtightness is the continuity of AB plane over joints, junctions, and penetrations. Therefore, errors in determination of material properties make a small effect on the performance of the assembly.

For laboratory testing of assembly airtightness Lstiburek [14] proposes use of the criterion of 0.20 L/(s·m^2) @ 75 Pa. It is slightly less than the limit proposed by Quiroette [7] but slightly more than the subsequent numbers produced by CCMC and related to relative humidity of the indoor air. To appreciate the requirements for airtightness one must step back and review the purpose of the AB systems. One must recognize need for separation between two different effects. One related to energy performance and designing HVAC equipment. A mechanical engineer cannot assume that the building enclosure is impermeable and if so there must be guidance (benchmark) for the HVAC design process. The benchmark of 0.20 L/(s·m^2) @ 75 Pa appears easy to satisfy in the construction of curtain walls or residential wall assemblies.

Finally, similar benchmark for the overall building envelope is proposed by Lstiburek [14] as 2.0 L/(s·m^2) @ 75 Pa. This proposal goes across the border between commercial and residential buildings and different climates. It means that the mechanical systems should be designed so that multizonal air flows and uncontrolled air flows caused by the connectivity of hidden connections, staircases, leaky ducts, return plenum and other means of interzonal flow that counteract the operation of air distribution systems be controlled. Furthermore, they should be controlled to the same level as the best homes or schools (note that Table 3 shows New York schools being five times more airtight than Florida schools).

Effectively we have selected somewhat idealized sequence of acceptance limits: 0.02 L/(s·m^2) @ 75 Pa for laboratory tests on materials; 0.20 L/(s·m^2) @ 75 Pa for laboratory tests on assemblies; and 2.0 L/(s·m^2) @ 75 Pa for field tests on the whole building enclosure. Yet it is important to bear in mind that these are design benchmarks rather than values of a critical significance.

We have stated that AB systems perform a dual role. On one side, airtightness is linked to energy use and HVAC design; on the other side the airtightness is linked with the amount of moisture and pollutants transported by air. Nevertheless, the above-discussed benchmarks do not address issues of durability and indoor environment. In principle, one cannot analyze effects of airflows on durability and indoor environment without information about the outdoor and indoor climates and the construction of the assembly. The level of permissible airflow depends on presence of moisture sensitive materials (moisture tolerance of the building assembly). Environmental control design of building enclosure should not be simplified to the consideration of one (e.g., RH of indoor air) only out of the many parameters affecting moisture flow through the assembly.

Characteristics of Materials Used in Rain and Ground Water Control

Prior to addressing performance of the building enclosure one must review architectural design of the building site. This examination includes building orientation and shape, consideration of wind and deflection of the driving rain. In particular, the review includes issues such as orientation of prevailing wind during rain periods, size of the roof-overhang, design of roof parapet walls, presence of adjacent buildings and their effect on local aerodynamics, etc.

The next stage involves the review of main components in moisture control system, such as

TABLE 3—Overall enclosure leakage measured in different buildings

Building Description	EA— L/(s·m²)@75 Pa	Mean EA— L/(s·m²)@75 Pa	Source
200 new tract-built homes, 1989	1.18 to 3.55		NRC [13]
Tract-built homes	2.23 to 3.6		CMHC [14]
NIST offices	3.9 to 43.3	15.3	Persily [15]
Florida offices	5.8 to 124.5	36.0	Persily [15]
N.Y. schools	2.7 to 14.7	8.5	Persily [15]
Florida schools	10.9 to 53.9	24.5	Persily [15]

1. Water resistive barrier (WRB)
2. Wall drainage systems
3. Weeping holes and flashings
4. Capillary breaking layer, sometimes also called floor drainage layer
5. Basement wall drainage systems, waterproofing and dampproofing of underground constructions
6. Material characteristics in context of rain or ground water entry into the material
   6.1 Water absorption coefficient
   6.2 Capillary moisture content

Water Resistive Barrier (WRB)

In the past decade, a significant number of papers published in U.S. and Canada have discussed the increase in the frequency of the occurrence of moisture-originated failures. Some of these failures have had significant economic repercussions (e.g., cost of repairs in the "leaky condo" failure in the main delta area of BC has been estimated in billions of dollars [15,16]. Several field surveys, performed in United States and Canada showed that similar increases of moisture-originated problems in other locations. As many as 95 % of residential building defects occurred during the first seven years of occupancy and it was found that rain penetration was the primary source of moisture. Many of the constructions lacked a water resistive barrier or had defects in the barrier.

Use of a water resistive barrier (WRB) in the construction is, therefore, required by many codes and standards. Several terms are used to describe the barrier, such as the water resistive barrier or weather resistive barrier, wind barrier, building paper, drainage plane, protective wrap or house wrap to denote that a coating or a membrane that is placed to the exterior of the sheathing board (OSB, plywood, exterior drywall, or even an exterior insulation board). To unify the terminology, an ASTM group postulated the term "water resistive barrier" (WRB) to describe all these components.

WRB materials perform several essential functions within a building envelope [17]. The primary function has always been to shed any water that penetrates the cladding. While building professionals could design a perfect structure with each barrier functioning perfectly, experience shows that defects created during construction or subsequent to it can lead to the entry of water past the outer cladding, especially when defects in the different barriers are in close proximity. Ideally, The WRB is a second line of defense. This second line of defense allows drainage and drying of the penetrating moisture in a time that does not allow water vapor related problems to occur.

WRB products can also contribute to the control of the flow of air through the construction. Energy efficiency and the resulting economic benefits through the restriction airflow are well known. Furthermore, an WRB can reduce the flow of water vapor transport through the wall. This means that the moisture characteristics of materials adjacent to a WRB material can strongly affect the thermally driven water vapor flow, which varies depending on the outdoor conditions, i.e., temperature gradients and solar radiation. For example, in a cold climate, a WRB must have a high enough permeance to allow an outward diffusion of water vapor, yet the permeance should not be too high to allow an excessive inward flow at times when the thermal gradient is reversed or in periods of intense solar radiation in winter or even during certain summer conditions. Thus, depending on the climate and the service conditions, different types of the WRB may need to be used in a given wall assembly to optimize its performance and to ensure its durability. The evaluation of WRB products must quantify their contribution to the performance of the overall wall system. The WRB must have resistance to transfer water, water vapour and air in the range suitable for the specific climate and use conditions to be encountered and any changes in these that could occur.

A Uniform Classification of Water Resistive Barriers

A uniform classification of water resistive barriers can be of considerable use in helping designers realize that all WRB products, independent of their structure, can and must be evaluated in a consistent and similar manner. Those intended for WRB applications vary in manufacture and basic materials. Baker and Bomberg [18] introduced the following classification for WRB products:

Class C

Asphalt-impregnated cellulose fibers; the asphalt or other component imparts water resistance to the cellulose fibers.

Sub-Class CF—asphalt impregnated cellulose felt.

Class P

Polymeric fibers; these include sheet materials manufactured from spun-bonded polyolefin fibers that are hydrophobic and form a mat that repels water.

Class PP

Perforated polymeric film; these sheet materials are monolithic films, mechanically perforated to permit vapor to pass and to provide some resistance to water penetration.

Class M

Micro-porous film; these sheet materials are monolithic films that have particles incorporated into the material. When the film is stretched, some of the particles fall away, leaving a film with micro-pores.

Class ML

Multiple-layered WRB; consisting of a combination of two classes.

Class LA

Liquid (trowel) applied WRB; these films are formed by applying one or two coats of a base-coat material to wood-based or gypsum sheathing. When cured, the films provide a water resistive coating on the sheathing and continuity at joints.

Understanding Performance of WRB

These pictures illustrate the nature of WRB products. They consist of a fine porous structure, created by fibrous matrix that possesses a negative wetting angle. WRB acts as the filter separating water molecules in the liquid, from those in vapor phase in the air. Vapor transport is not affected significantly by water surface tension and can move freely through a fibrous network. (Note materials artificially perforated are not included in this discussion, because changes in physical and chemical conditions on the surface of such materials during the service life can be completely different from such

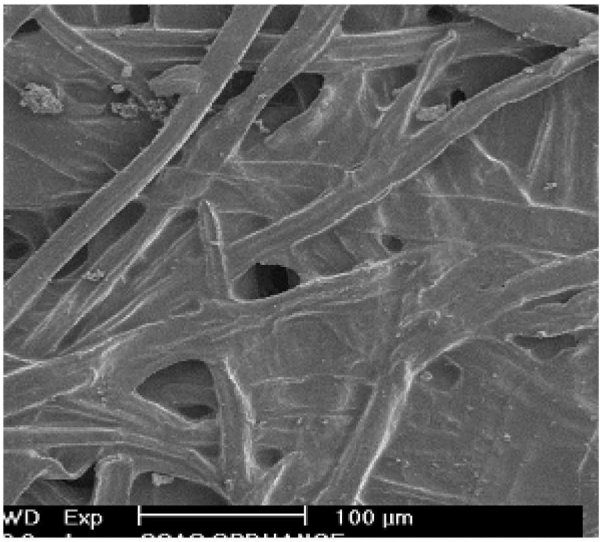


Fig. 1—Scanning electron microscope (SEM) picture of WRB Class C (Asphalt impregnated cellulose fibers; with 30 min rating, grade D product). Courtesy of Du Pont Corporation, USA.

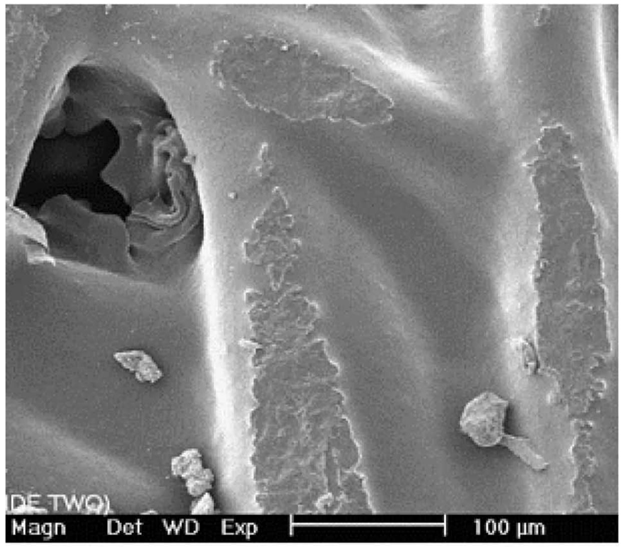


Fig. 3—SEM picture of Class PP (perforated film supported on cross-woven film). Courtesy of Du Pont Corporation, USA.

changes in fibrous materials.) It is evident from Figs. 1–3 that conditions affecting the evaporation and vapor diffusion from the water menisci in the wetted material will strongly affect the rate of total moisture transfer (i.e., transport in both vapor and absorbed liquid phase) through the material.

The capability of resisting water by the WRB fibrous products is provided by two elements: on one side, by the pore size and pore size distribution and on the other, by a negative wetting angle of fibers or material modifiers (asphalt, wax, or other surface coating agents). While the first two tests yield the minimum (ASTM E96—Dry Cup) and maximum water vapor permeance (Modified Inverted Cup—see below) these tests measure resistance to passage of gas [19]. These tests are not affected by aging or other changes in surface chemistry that may affect the affinity of the WRB to water [20]. In some preliminary test, under a combination of chemical agents and dust particles, the hydrophobic nature of WRB was changed into hydrophilic, allowing water passage in several spots. Therefore, an LPR test (see below) is necessary to address the aging and weathering resistance of WRB.

These three tests, together with measurements of moisture transport from water through WRB to an OSB substrate, improved our understanding of factors affecting moisture transfer through WRB (Table 4).

Line 4 in Table 4 provides the water vapor permeance measured with a double-cup method. Water vapor transmission was measured between two environments, one near 100 % RH and the other near 0 % RH. It is noted that moisture flux determined with the MIC method (line 2) was about 100 % higher than that represented by the water vapor diffusion test. The difference can be attributed to the resistance offered by the still air layer under the material surface, and the effect of water on cellulose fibers (while the upper surface was exposed to the hydrostatic pressure of 50 Pa). In effect, the MIC test represented the worst conditions for water vapor dominant moisture transport. The water transfer obtained by the MIC test of 5.0×10^{-6} kg/(m$^2\cdot$s) represents the

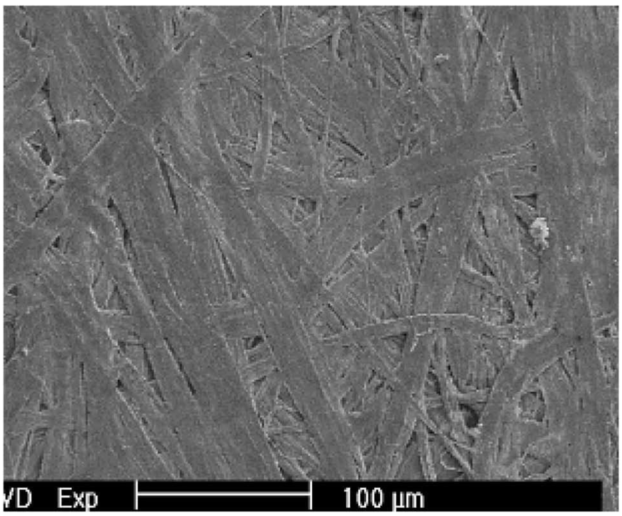


Fig. 2—SEM picture of Class P (Flash Spun Bonded Polyolefin). Courtesy of Du Pont Corporation, USA.

TABLE 4—Comparison of flow rates for a selected Type C product.

Line number	Description of transport conditions	Moisture flux, kg/m$^2\cdot$s	Permeance, perms
1	Liquid flux measured in LPR	5.0×10^{-5}	
2	Modified Inverted Cup (MIC)	4.0×10^{-6}	22.1
3	Moisture flux OSB+staple (MF)	3.3×10^{-6}	—
4	Double Cup (0 to 100 % RH)	2.1×10^{-6}	11.6

most permeable product among all tests performed on type C, P, and LA-WRB products [19,21]. This value is still one order of magnitude lower than the moisture flux resulting from water filtration that was measured with the LPR test method.

Implications of Research on WRB

CMHC [22] states:

> This research has shown that the performance of class C and P membranes used for WRB applications is quite different from many other porous materials used in construction.
>
> In practice, WRB materials are intended to block rainwater from passing through them to the inner wall. To this end, two physical phenomena explain how they achieve that aim—they have sufficiently small pore sizes and a negative wetting angle. In these tests, the pore size was not much affected by aging, by weathering or even by mechanical stretching of the WRB products. The air or vapor permeability was not much affected by weathering conditions expected during construction. The use of soap or wood extracts solutions also did not affect the air or vapor permeability (at least for a one-time wetting) because moisture transport through the WRB was dominated by the vapor transfer phase.
>
> Despite this, under some combinations of weathering in the presence of wood extracts and other solutes, significant increases in water transmission resulted—one could observe water droplets passing through some membranes in a time span measured in minutes instead of days. Use of the liquid penetration tests (water contact on both sides of the WRB) was found to discriminate between materials with local deficiencies and those materials where the negative wetting angle was neutralized by weathering. Some WRB products, which performed sufficiently well when assessed using existing test methods in product standards (for example, some types of PP products), experienced onset of liquid flow within a few minutes. The lesson for designers is a simple one. To reduce the risk of water penetration the designer must eliminate the possibility for water contact on both sides of the WRB for prolonged periods. This is achieved by specifying assemblies that incorporate an air cavity on one side of the WRB. This measure is recommended for climatic conditions where the probability of water penetration is high. Under moderate climatic conditions a small air gap of a magnitude 1 to 3 mm may be sufficient, if it can be maintained.

Such a narrow air gap (capillary break) may be sufficient to enhance diffusion and some local water drainage, which in combination with other measures may provide a substantial reduction in moisture loads. To be on the safe side, the builder may select two layers of WRB. Because all interfaces in construction are hydraulically imperfect [23] the use of two WRB layers in loose contact is much superior to the use of a single layer with the same water vapor resistance [22]. Two layers and cladding attached with mechanical fasteners provide a degree of drainage, which is quite substantial. This is not a free water drainage—for free drainage, one needs more than 3 mm—but a combination of gravity component and diffusion helps to move the moisture downward. This is transient movement because the variable thermal gradient pushes the moisture in different directions, sometimes toward the inside and sometimes toward the outside. If water comes from small holes or penetrations, there is also a hydrostatic pressure, which pushes water, despite a narrow gap. The bottom of a WRB should terminate in a manner that provides water outflow and the access to exterior air. One needs to provide free drainage at the bottom of the wall with a good flashing and a few openings or holes to ensure connection to the exterior air.

Effectively, this research showed that two layers of WRB—whatever the membrane, as long as it is not perforated—are better than one layer of any product, even a highly rated product, because it increases the moisture removal potential, i.e., the local drainage plus drying potential. It also reduces the risk of the reverse moisture drive.

Another important point is to make a proper connection between the WRB and the flashing around windows and other penetrations.

Wall Drainage Systems

One of the most common wall drainage systems is the cavity between a brick veneer and back-up wall. With the incorporation of regularly spaced, open head joints, in the bottom part of the brick veneer, this is a traditional way of drainage in masonry walls (although quite inefficient). Weeping holes at the bottom of the wall provide venting of the air space behind the brick veneer and serve to reduce the humidity if the air space. Sometimes combined with openings at a higher level, in favorable conditions, ventilation of this cavity could have even more rapid effect on drying. The air cavity, when relatively free of mortar droppings, is an effective way of providing capillary break (see later section) and some drainage of the wall systems.

An air cavity that faces the masonry on one side and wood-based products on the other side, does not provide efficient drainage because most of the available water could become absorbed in the surfaces of this cavity. It is therefore common practice to place a WRB layer on the outer surface of the inner wall. The membrane must provide a more suitable surface for drainage. Because the provision of an air cavity may not be necessary a number of drainage systems use draining mats (typically 3–5 mm thick) and rib-formed adhesive used in exterior insulation finish systems (EIFS). In exterior insulation finish systems, an adhesive or a coating is applied to the outer surface of the substrate and vertical (not slanted, but vertical) ribs of adhesive provide the drainage space and rely on the resistance to absorption of water in the insulation to prevent extended periods of high humidity.

The drainage system must have efficient flashings and an adequate venting; see the next section.

Weeping Holes and Flashings

The weep holes in brick veneer are meant to provide a means of water removal and some degree of connectivity for drying of the air cavity by means of vapor diffusion and air flow, even if intermittent. It is generally recognized that window to wall and wall to floor connections require use of flashings

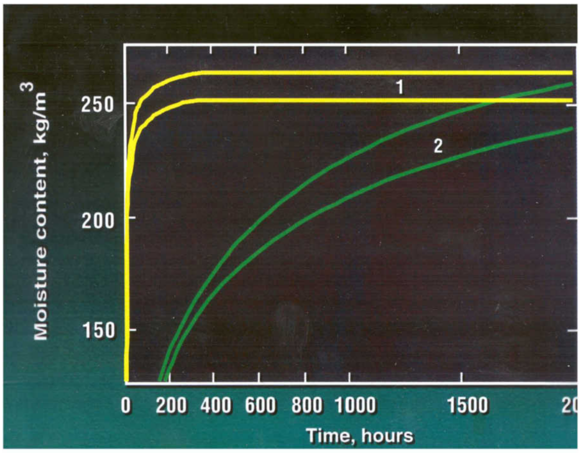


Fig. 4—The rate of moisture flow from a wet, reference material to dry test specimen (for two different initial moisture contents in the reference material) and two types of contact (1) direct contact, (2) 1.5 mm air gap. From Bomberg [25].

to remove or divert any water that may enter into the wall. Flashing materials must protect against water ingress into the adjacent construction materials, as well as lead water to the outer surface of the wall. Water must be led past the outside surface of the wall and be removed from a properly designed drip so that it does not drip on the wall or flow back into the construction below the drip. The design of flashing should be given a careful consideration. Wall failures in Brish Columbia and North Carolina have resulted in significant improvements in flashing techniques and several publications have been issued on specific constructions, e.g., ASTM standard on window installation (E2112) and best practice guide of CMHC [24].

Capillary Breaking Layer

Traditionally, a capillary breaking layer under basement floors is composed of crushed stone or large-sized gravel layer. As the name indicates, the function of this layer is to interrupt liquid flow of water conducted through the small pores and capillaries of porous materials and reduce the possibility of the contact of water with the floor except in extreme conditions. As this layer is always required under floor-slabs (in basement or ground-slabs) it is also called a floor drainage layer, implying that the excess water entering the layer is drained and removed by a drainage system.

One must realize, however, that unless there is a temperature difference across the capillary breaking layer this layer will only slow the rate but does not eliminate the moisture transport. The relative humidity in the wet soil environment is nearly 100 % RH and without a temperature difference the same RH will be on both sides of the capillary break. Without the heat flow, i.e., without the outer surface being cooler than the surface we want to protect, the use of capillary breaking layer (air gap) is very limited. In such a case one needs to use water and vapor barriers, e.g., polyethylene film.

Figure 4 illustrates an example of moisture exchange between two materials being in direct contact or separated by 1–2 mm thick air layer. Figure 4 shows that placing a dry piece of test material with the wet reference material and sealing the system so that we have no losses of moisture, one may compare the rate of moisture flow from wet to dry material. Two tests, with different initial moisture content of the reference material were performed. One may observe that within a few hours of a direct contact moisture content of the test material reached the same level as after a few weeks of water vapor diffusion through the air gap. One may also observe that given a long time for moisture equalization, the same equilibrium moisture content will be achieved. This figure highlights the fact that integrated moisture potential in vapor or liquid phase are identical so the equilibrium moisture content is also identical—yet the rate of moisture flow over a short period varies by the order of magnitudes.

Figure 4 permits drawing an important conclusion. To break the capillary flow we do not need a 10 mm thick air gap; significant retardation of moisture flux is achieved by the process of evaporation and diffusion through an air cavity. (An air cavity is advantageous over the drainage mat because the moisture storage on surfaces of the air cavity is smaller than moisture retained on the drainage mat.)

Basement Wall and Below Grade Drainage Systems

Significant amount of research has been done on performance of basement insulation systems [26–29]. Some research has dealt with exterior insulation [30–32] and highlighted two different principles of moisture control. One can either provide a drainage of water next to the wall, by use of a drainage mats, porous insulation (e.g., mineral fiber insulation boards) or by incorporating channels in insulation. Another principle involves moisture protection by use of appropriate insulations (extruded polystyrene boards or spray-on polyurethane foam). Even insulation that does not qualify as water resistant, namely, expanded polystyrene (EPS) boards has been successful [30] as long as there was presence of a sufficient temperature gradient (predominantly outward directed). The latter highlights the significance of being able to understand the interaction between heat and moisture transfers.

In designing a successful moisture protection for basements walls, both surface run-off and foundation drainage are necessary to reduce the potential moisture loads. This means an appropriate outward slope of the grade the 3 m (10 ft) distance around the building to ensure the surface run-off water and the drainage tile placed at the foundation of the wall. Without removal of excessive water, no basement drainage system will be successful.

Concrete with high water-cement ratio poured in forms or concrete block foundation walls may not perform adequately if they do not have some sort of moisture protective layer on the outer surface. Typically, a dampproofing is applied on the outside surface. Two methods for providing the protection are often confused, namely dampproofing and waterproofing layers. Dampproofing (ASTM D1079) layer is sprayed, or brushed onto the surface, to reduce the walls ability to absorb moisture from the soil (either as water or as vapor). Typically, it consists of asphalt emulsion.

Some foundation walls are made of modular blocks of cellular plastic (extruded or expanded polystyrene) that have reinforcing bars inserted in some cavities and then filled with a structural concrete. The outer and inner foam layers are connected with series of plastic or metal ties. This con-

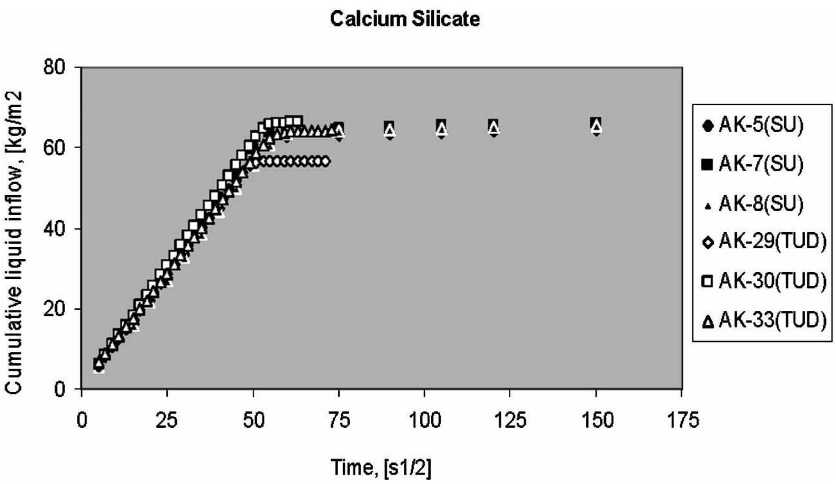


Fig. 5—Cumulative liquid inflow in calcium silicate measured manually (Syracuse U) and automatically (Technical U of Dresden).

struction system is called "insulated form concrete." Typically, the outer surface of the foam is protected with a thin membrane to reduce soil adfreezing. This combination of foam and surface layer acts as the water resistive barrier.

Waterproofing involves a thicker layer of coating or a membrane that will withstand water and vapour flows under conditions of hydrostatic pressure. A waterproofing membrane and ballast for the membrane is necessary to counteract expected water pressure (unless the layer is fused to the surface of the wall).

Membranes that are used in waterproofing are similar to those used in low-sloped roofing systems. There are many products with the principle constituent being:

- ethylene propylene diene terpolymer membrane
- a single ply sheet composed of a synthetic rubber, similar to butyl rubber, but with better weathering resistance achieved by addition of extenders and oils)
- modified bitumen composite (self-adhering)
- polychloroprene (neoprene)
- PVC (polyvinyl chloride)
- butyl rubber membranes.

Furthermore dimpled plastic (that runs full height and provides drainage between the concrete and the plastic). The dimpled plastic provides an air space for drainage and prevents adfreezing of the soil to the surface. Unless there is a hydraulic head, or the foundation drainage is not functional, water will be drained before it can reach the basement wall.

Characteristics Used for Control of Rain or Ground Water Entry

The principle of modern moisture management of building is a comparison between wetting and drying rates of construction or specific materials in the construction. The drying process is difficult to describe because during the first drying stage, the rate depends almost entirely on the environmental conditions, in the second stage it reverses to be almost independent on exterior conditions with the material properties governing the rate. For wetting, the rate of wetting from rain or other contact with water can be described by a single material characteristic. The characteristic is the water absorption coefficient (*A*-coefficient) of the material.

Water Absorption Coefficient

Bomberg et al. [33] reviewed the measurements of water absorption coefficient (*A*-coefficient). Figure 5, quoted from this paper shows, the traditional way of plotting cumulative water intake in a free water intake test against square root of elapsed time. Incidentally, this figure shows that manual measurements performed at one laboratory and those performed on the same material with an automatic balance in another laboratory can be equally precise.

Table 5 shows several values of water absorption coefficients and capillary moisture content for one series of tests performed on one batch of clay bricks. For nine measurement points and 95 % probability level, with a mean value of *A*-coeffcient equal to 0.149 and the standard deviation as shown above, the lowest probable *A*-coefficient is 0.125.

While a better way of presenting test results is discussed in the section dealing with measurement techniques, Fig. 5 shows that for some materials the slope of cumulative liquid inflow is almost constant until the end of the first stage of free water intake process. In Fig. 5, the first stage is completed when the upper surface of the specimen is reached. After some redistribution of moisture takes place and the whole specimen volume is filled, one achieves the so-called capillary moisture content (see the next section).

TABLE 5—*A*-coefficient and capillary moisture content for one batch of clay bricks.

Specimen	A-Coefficient ($kg/m^2 \cdot s^{0.5}$)	Water Content (m^3/m^3)
HS-B 26	0.1559	0.1422
HS-B 27	0.1348	0.1559
HS-B 28	0.1337	0.1565
HS-B 29	0.1639	0.1525
HS-B 30	0.1342	0.1646
HS-B 31	0.1535	0.1705
HS-B 32	0.1558	0.1809
HS-B 33	0.1650	0.1607
HS-B 34	0.1415	0.1521
Mean	0.1490	0.1595
Stdev	0.0130	0.0114

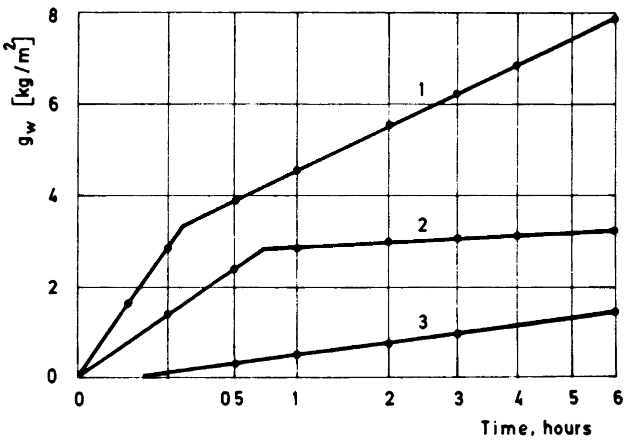


Fig. 6—Cumulative water flow g_w to the clay brick through rendering, plotted against the square root of time in hours. Curve 1 represents lime rendering (A=0.07 kg/m^2·s$^{1/2}$),-curve 2 lime rendering on cement splattered surface, and curve 3 a cement rendering (A=0.01 kg/m^2·s$^{1/2}$).

Kruger and Eriksson [34] (see [35]) showed that lime-cement mortar moves water faster than the cement mix, though both are significantly slower than the clay brick alone.

While a better way of presenting test results is discussed in the section dealing with measurement techniques, Fig. 5 shows that for some materials the slope of cumulative liquid inflow is almost constant until the end of the first stage of free water intake process. Incidentally the water absorption coefficient of calcium silicate and capillary moisture content of this material are very high $A = 1.2$ kg/m^2·s$^{0.5}$ and $w_{cap} = 0.82$ m^3/m^3.

The water absorption coefficient is used to compare performance of stucco, and other water protective coatings. Figure 6 quoted from Kruger and Ericson [34] shows that replacing lime mix with cement mix makes a dramatic difference in wetting and drying rate of stucco. Introduction of latex admixtures to cement stucco has further reduced the wetting/ drying rate of the stucco. Bomberg et al. [36] discussing failures of modern stucco in Northern regions of the United States and Canada showed that some finishing layers of this type had the water absorption coefficient as low as $A = 0.001$ kg/m^2·s$^{0.5}$. This is one order of magnitude lower than the cement stucco and two orders of magnitude (100×) lower than the best mixes designed for a good and moisture tolerant stucco in Europe and the United States.

Capillary Moisture Content

Capillary moisture content represents the maximum moisture content reached in the free water intake into the material. This value is often compared with moisture content reached by exposure to rain (water immersion) over 1, 2, or 3 days (see Chapter 27 of this manual) to gain a quick estimate of the risk for freeze-thaw damage.

Capillary saturation is an important information for modeling as it represents the maximum degree of material saturation caused by the capillary forces. Moisture content higher than the capillary moisture content can be reached only when a different wetting process is used, e.g., by removal of air entrapped in the water phase or water vapor condensation under thermal gradients.

Characteristics Used in Control of Moisture Transport

The concern with vapor diffusion aims at avoiding water vapor condensation inside of the building enclosure. Actually, the concern does not relate to the condensation itself, but to its harmful effects such as material degradation or dimensional changes. Yet, the same amount of interstitial condensation in masonry wall does not have the same consequences as one inside of a wood frame wall. The significance of condensed water depends on presence and type of moisture sensitive materials in the construction.

Furthermore, the amount of water vapor transferred by air leakage (moving air) is much higher than that carried by water vapor diffusion. Therefore, the required level of diffusion control actually depends on the degree of airtightness of the building enclosure, though not on the overall airtightness of a building envelope, but on the local airflows.

As previously stated, one needs to know the distribution of the airflows in the assembly. If a large localized airflow takes place in otherwise airtight assembly, and if the airflow path is long enough, the amount of condensation deposited may be sufficient to cause a local damage. An air leakage test identifies localized air leaks and simplifies the planning of procedure for the elimination of these large holes during the construction process.

When an air barrier system has been installed, and particularly when its overall quality has been assured during installation by performing of the field assembly airtightness test, the requirements for vapor diffusion control are significantly lower. In such a case, the traditional criterion of 1 perm for vapor barrier may be replaced a vapor retarder such as a layer of paint with a permeance between 3 to 7 perms [37].

The main components of an assembly and material characteristics used in the control of water vapor (or moisture) are:

1. water vapor retarder (permeable, semi-permeable, semi-impermeable, and impermeable) and adaptable protective retarders (varying rate with the level of moisture content)
2. material with low water vapor permeability (material layer providing resistance to vapor flow)
3. exterior thermal insulation (material layer modifying a dew point inside the wall cavity)
4. material with high hygroscopicity, i.e., material with high equilibrium
5. high moisture content in above-hygroscopic region
6. moisture diffusivity coefficient (ability of material to redistribute high moisture).

Water Vapor Retarder

In a review of the historic basis for current practice [38] observed that both water vapor barrier and retarder are used today to denote the same concept, namely an element that is designed and installed in an assembly to retard the movement of water by vapor diffusion. Two levels specified by codes and standards are 1 perm (57.2 ng/m^2·s·Pa) for buildings and 0.1 perm for freezers and industrial applications. As we stated previously, with introduction of air barrier systems the requirement of 1 perm may be relaxed. The use of the term "retarder" is preferred in the USA. Using the water vapor permeance established by the ASTM E96 Test Method A (the desiccant or dry cup method), the following classification has been proposed [39] for water vapor retarders:

- Class 4: Vapor permeable more than 10 perms
- Class 3: Vapor semi permeable between 1 and 10 perms
- Class 2: Vapor semi impermeable between 0.1 and 1 perm
- Class 1: Vapor impermeable less than 0.1 perm
  Note: Class 1 water vapor retarder may also be called a vapor barrier.

The class 4, permeable vapor retarders must also have limitation on the maximum value of water vapor permeance, because as shown by Bomberg et al. [33] in examination of stucco systems, values of WRB permeance of 50 to 70 are far too high to protect the OSB from moisture reversal under solar radiation in winter of cold climates. Typically, values of 15 to 25 perms will represent class 4 of materials. Semi-permeable coatings, paints, membranes or water vapor retarders have rating between 3 and 7 perms and semi-impermeable WVR one magnitude lower.

Adaptable or smart vapor retarders represent a special class of vapor retarders because of varying rate of moisture transmission in effect of changes in moisture content. They generally change the water vapor permeance by factor of 10 from low to high relative humidity range. At the time of writing this manual (2005), two types of polymeric materials are on the American market, one more suitable for industrial insulations, e.g., pipes, and the other designed for building applications. In principle, some traditional wood-based products, e.g., plywood or building papers belong to the same category because they change water vapor permeance by a factor of 5 or more between dry cup and high-humidity, spot, vapor permeability.

The main advantage of these products is that they allow good drying of the construction, when exposed to high moisture content or water presence (hydro-diode), while providing retardation of water vapor in low range of relative humidity.

Water Vapor Permeance (Layers) and Permeability (Materials)

We have a problem with terminology. Pure water vapor diffusion exists only at low moisture contents in the material while most of the durability problems and indoor air quality problems involve materials at humidity higher than 70 % RH. Typically, at this level of equilibrium moisture content, the moisture flow includes a combination of water vapor and liquid phases. It is not any more water vapor diffusion but a moisture transfer. Therefore, instead talking about the rate of diffusion (as it was for the dry cup test, see next section) one uses a special term "water vapor transmission" (WVT). In practice, however, one uses water vapor permeability for all types of moisture transports if they are related to partial pressure of water vapor. This quantity expresses the density rate of flow, and when divided by the driving force (the difference of water vapor partial pressures on both sides of the membrane) one obtains water vapor permeance through the layer.

The concept of permeance express an ability of a layer of material, membrane or coating to transmit water vapor in proportion to the difference in concentration across the layer, surface area and time. It is concept related to a layer.

If the test material is homogeneous and its thickness is known, one can calculate the water vapor permeability of this material. Water vapor permeability relates to a unit of thickness i.e., is a material property. We use the unit of permeance of 1 perm (in the in./lb system) that corresponds to 57.2 $ng/(m^2 \cdot s \cdot Pa)$ in the metric system. Permeability is expressed as perm·in. or in SI units as ng/(m·s·Pa). Since calculating water vapor transmission through multilayer structures requires one to add the flow resistance of each layer: the inverse of permeance called water vapor resistance is used.

Section 5 describes several measurement methods for determining water vapor transmission. The term "water vapor transmission" (WVT) avoids confusion with water vapor diffusion that is measured only at the lower end of relative humidity spectrum. In terms of physics, the best description of was given in paper of Joy and Wilson [40] who introduced the concept of spot permeability. To measure the spot permeability one must apply a narrow range of RH difference to both sides of the test specimen.

The traditionally used wet cup permeability test uses such a wide range of boundary conditions, i.e., 50 % RH and 100 % RH that relation between the measured permeance and the mean value of 75 % RH is lost. Instead, a spot permeability at 80 or 85 % RH (75 % RH to 85 or 95 % RH) measurements are used for moisture modeling. Yet, many material standards insist on measuring the wet cup values. In such a case, the dry cup should always be reported for the comparison.

Finally, in those applications, where materials are in contact with water a modified inverse cup, as described in the next section is recommended rather than wet cup. It is a comparative test but more precise and easier to perform than the wet cup test.

Since ASHRAE provides considerable data for water vapor permeance of materials and membranes[2], we show permeability (WVT) for special membranes such as smart retarders (Table 6). Disusing smart retarders Kiessl et al. [41] stated:

> "The hygrodiode has the lowest permeability under dry conditions. During the normal wet-cup test with pure water some condensation occurs but apparently not enough to get a continuous water film in the fabric. Therefore, the permeability stays rather low but it increases over a period of several weeks from 0.4 perm to 1.8 perm. During the condensation-cup test, the capillary transport started within 24 h and led to an apparent vapor permeability of 11 perm. The smart retarder already becomes very permeable under normal wet-cup conditions (a factor of 15 compared to dry cup value). But also here the condensation-cup increases the permeability to a peak of 22 perm. The

[2] The path is as follows: http://bookstore@ashrae.org than follow to papers & articles and search for RP-1018 the second position is database.

TABLE 6—Vapor permeability measured by cup methods, climatic chamber at 23 °C, 50% RH. Reprinted with permission from IBP, Hozkirchen, Germany.

	Vapor Permeability (perm)			
Vapor retarder type	Dry Cup 23 °C/3% RH	Wet Cup 23 °C/100% RH	Condensation Cup 25 °C/100% RH on Both Sides	Dry Cup (repetition)
Hygrodiode	0.25	0.4-1.8	11	—
Smart retarder	0.85	13	22	—
Kraft paper (no asphalt impregnation)	1.1	2.2	16	2.7

Kraft paper barely doubles its permeability from dry cup to wet cup but in the condensation cup the permeability sharply rises to 16 perm."

The concept of condensation cup is different from the methods discussed in this chapter. Although we recommend the use of modified inverted cup, where water is placed on one side and desiccant on the other side, in this test the relative humidity was near 100 % on both sides and the driving force was a 2 °C temperature differnctial acting across the membrane. Nevertheless, one can observe a dramatic difference between the wet cup and condensation cup. This explains why we have recommended using the modified inverted cup as a comparison to dry cup instead of wet cup.

Table 7 lists data on water vapor permeability of selected water resistive barriers from the manufacturers technical data sheets. Disregarding some probable errors or unexpected large difference between dry and wet cup on a "wrap," i.e., polymeric fiber product, the variation in water vapor permeance of these products is ten fold from 6 to 60 perms.

Exterior Thermal Insulation

One of the very significant measures to reduce the risk of water vapor condensation in the cavity of frame wall is to place an exterior thermal insulation. The amount of condensation calculated in glass fiber insulation installed in word frame walls by Ojnanen and Kumaran [11] was dramatically reduced when using an exterior insulation. In cold climate, the exterior thermal insulation almost eliminated condensation in the cavity even though air leakage of moist air to the cavity was significant. This is not a traditional method of moisture control, yet we have listed it here, because it is a very effective measure for reducing risk of condensation in any type of frame wall. Typically, the thermal resistance of the exterior insulation is at least 1/3 of the thermal resistance of the cavity insulation.

In steel frame walls, the use of exterior insulation is necessary to reduce the effect of thermal bridges caused by the steel studs, in wood frame wall it is recommended for all moderate to cold climate applications.

Sorption Isotherm (Equilibrium Moisture Content in the Hygroscopic Range)

The equilibrium moisture content plotted against RH is called the sorption isotherm. For most of inorganic materials the effect of temperature on the sorption isotherm is small; i.e., the same curve can be used in a range of temperatures. This is not the case for most organic materials where both RH and temperature affects the equilibrium moisture content. There are also materials that change dimensions during the water vapor sorption; typically, the initial volume and mass are used for calculation of the sorption isotherm. The character of the sorption isotherm is closely related to

TABLE 7—Water vapor permeability of selected polymeric water resistive barriers according to manufacturers.

Code	1 Black	2 White	3 White	4 White	5 Woven	6 Nonwoven	7 Woven	8 Wrap
Description	Coated Nonwoven Polymeric	Nonwoven Polymeric	Nonwoven Polymeric	Nonwoven Polymeric	Polyolefin perforated	Polyolefin Nonperforated	Polyolefin fabric	Woven nonperf
ASTM E-96 dry cup	13.7 perms				54 g/m^2/day	46.6 g/m^2/day	14 perms	10 perms
ASTM E-96 wet cup		58 perms	50 perms	28 perms				

Code	9 Wrap	10 Wrap	11 Wrap	12 Nonwoven	13 Perf woven	14 Micro perf	15 Perf woven	16 Cross lamin
Description	NR			PE, Nonperf	Polyolefin	Nonwoven Polyolefin	Polyolefin	Microporous PE
ASTM E-96 dry cup	15 perms	15 perms	48 perms	59 perms	63 g/sm/day	94 g/sm/day	63 g/sm/days	6.5 perms
ASTM E-96 wet cup			59 perms					

TABLE 8—A magnitude of moisture content in kg/m^3 in equilibrium at the specified relative humidity in the ambient air for different materials (to find volume % divide by 10).

Material	Density kg/m^3	Relative humidity in the air 30 %	50 %	70 %	90 %
Concrete	2300	19	28	39	56
Clay brick	1500	18	20	22	25
Lime-cement mortar	1800	20	30	42	70
Sandstone	1800	6	9	15	45
Mineral fiber insulation	Varies	2	2	2	4
Interior gypsum board	900	15	17	20	100
Wood-pine	500	40	50	70	140
Oriented strand board	650	55	84	117	246

the pore size and pore-size distribution so that this technique is also used for material characterization. Table 8 presents water vapor sorption isotherms for selected materials.

Moisture Retention Curve (Equilibrium Over the Whole Range of Moisture Contents)

Moisture storage (specific moisture content) is expressed as the relationship between the volumetric water content and a descriptor of the moisture potential. In the hygroscopic region (below 95 % RH), such a descriptor is the relative humidity of air. In the above-hygroscopic region, the descriptor is a capillary suction (the difference between pore-water pressure and air pressure acting on the water meniscus in the equilibrium state). The relation between moisture content and capillary suction is called the moisture retention curve (MRC).

To this end, one uses pressure plates (see next section). Figure 6 shows in a schematic manner combined information from the sorption isotherms and pressure plates.

Figure 7 shows that the maximum moisture content accessible by capillary forces is that of capillary moisture content (see above). To reach any higher moisture content higher than W_{cap} can be reached only when some air entrapped in the pore water is removed or when other forces interact with the capillary forces; e.g., heating and cooling of the material. The vertical shift in the maximum moisture content represents one of the two different types of hystereses. The other type of moisture hystereses is shown by horizontal arrows and highlight differences in pore filling and pore emptying under wetting and drying conditions. The preferential character of the pore-filling process is also related to the fraction of vapor transport; i.e., condensation of thermally driven moisture may have different prefilling pattern than that of liquid water intake.

Significance of Capillary Transport

Whether selecting materials for assembly design or doing simplified calculations one must bear in mind that moisture transport is caused by two different driving forces. One is the thermal gradient that moves water vapor always toward the lower temperature. The other is a gradient of moisture potential that, in a somewhat simplified manner, can be replaced by the gradient of moisture content. Thus, the moisture diffusivity describes the propensity for moisture equalization process in the material.

To provide an illustration of capillary transport signifi-

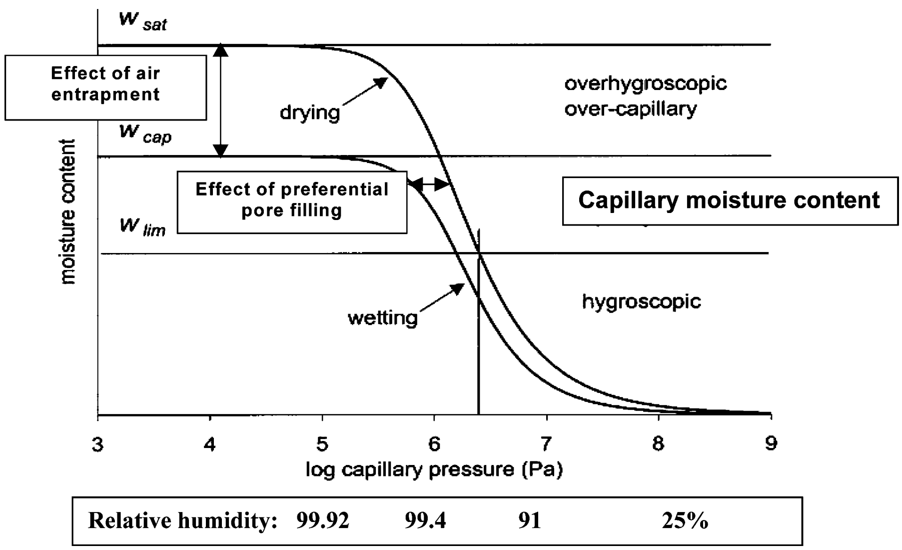


Fig. 7—Schematic representation of extreme wetting and drying branches of the moisture retention curves. Shown are two types of moisture hystereses and division between hygroscopic and above-hygroscopic fields. W_{sat}=maximum saturation (open porosity); W_{cap}=capillary saturation; W_{lim}=an arbitrary parameter used in modeling of MRC.

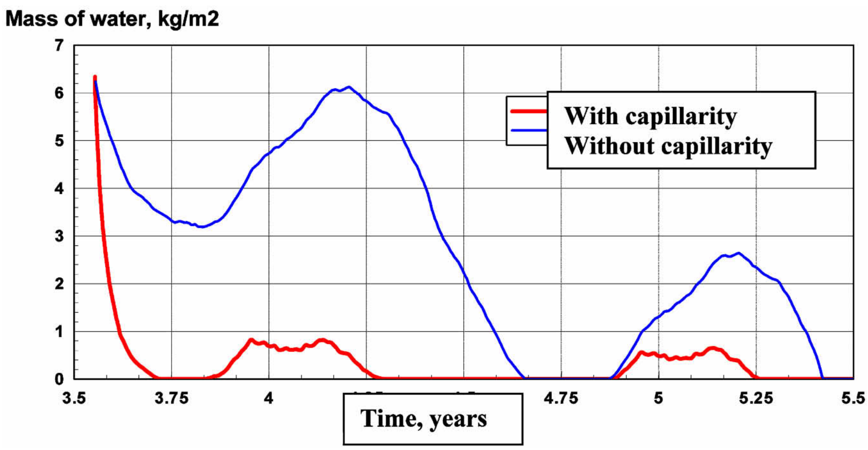


Fig. 8—Calculation of moisture content in the loam plaster that is a filling material in the framework-house in Ebersbach / Sachsen, with the initial moisture content equal to construction moisture. Calulations performed for the period from 21.7.98 to 1.9.99 in two cases: (a) (red line) calculated with contribution of capillarity and (b) (blue line) without contribution of capillarity, only water vapor diffusion. (See Haeupl [42]).

cance, Fig. 8 shows calculations of Haeupl [42] comparing water intake (kg/m^2) in two cases:

(1) calculations performed according to European standards but involving only the water vapor transport
(2) the same calculation but involving both vapor and liquid transports.

Case 1 resulted in an excessive moisture accumulation and the rejection of the wall assembly. Case 2, on the contrary, indicated that wall will perform well in the same conditions. In reality, this wall has been constructed and shown to perform well.

Methods Used for Measuring Hygrothermal Characteristics

Laboratory Tests of Airtightness

After a careful comparison of repeatability and reproducibility between the small scale tests [43] and full scale testing CMHC [12] the appropriate standards were developed. ASTM standard E2178 for testing materials [44] presents a method for determination of the air permeance through flexible sheets or rigid materials, using a 1 m^2 specimen, and various pressure differentials with the intent to establish air permeance at the reference pressure difference of 75 Pa.

Testing assemblies is based on about a decade of learning [12,14]. If one disregards those requirements that have mostly historic value and were used to improve the assemblies, such as testing plain wall without window and penetrations and using very low temperatures to accelerate the aging of some components, the basic methodology is good. This methodology involves combining static and dynamic wind loads and checking air tightness as the environmental and mechanical loads make their effect on the assembly.

In some instances the methodology was used in a creative manner e.g., when testing sealant foams as the component of air barrier systems. Bomberg and Onysko [46] reviewed testing of polyurethane sealing foam to provide continuity of air barriers. This procedure requires inserting a PVC window, e.g., 600 mm by 1220 mm, in the test wall that in turn is placed as a divider between two room chambers (one is held at 24±2°C and 50±10 % RH and the other is an environmental chamber). The environmental chamber undergoes the following sequence of conditions:

1. *Initial air leakage*.
   One starts with the room conditions (24±2°C and 50 +10 % RH) to perform an initial air leakage test. This test is performed as specified by ASTM E283 with a minimum of five measuring points over the range of pressure differences from 50 to 250 Pa.
2. *Environmental cycling*.
   (a) Environmental cycling starts by heating until reaching a temperature plateau at 66°C. When intended for use in low-rise buildings, a positive air pressure of 1000 Pa is applied and water spray with an intensity of 2.3 L/(min·m^2) at a temperature of 15±10°C applied for 60±2 min.
   (b) While maintaining air temperature at 66±3°C for another hour, the air pressure is switched to negative 1000 Pa.
   (c) Initiate the cooling transition to reach the chamber temperature of −20±2°C within a 1.5 h period. After reaching the low temperature plateau, apply a positive air pressure of 1000 Pa for 1 h followed by a negative air pressure of 1000 Pa for another hour.
   (d) Initiate a heating transition. The period of heating to 66°C may not last more than 30 min. This brings the total environmental cycling time to 6 h.
   Note: During weekends the environmental chamber is maintained at 66°C without application of air pressure or water spray.
3. *Interim examination and final testing*
   At the end of every 7-day period, a visual examination shall be performed and results reported. After completion of 60 cycles (3-week test period) an air leakage test is performed as described above. The overall leakage rate should not exceed the requirement from Table 1 CSA standard A440-98 for fixed windows, which for the joint length of 3.65 m, become 0.25 L/s for the foam sealant.
   To qualify foam sealants for use as a component of air barrier systems in Canada, the foam must be qualified

by this test. Desmarais and Bomberg [47] discuss details of foam sealant application in the wall /window interfaces.

Field Tests of Airtightness

There are several ASTM standards dealing with the use of blower door or mechanical equipment for pressurization/ depressurization of the indoor space. We shall not discuss them in this chapter because Chapter 8 deals with them in detail.

What is probably not addressed there is the evaluation of the assembly airtightness under the field conditions. Lstiburek [48], and Lstiburek et al. [49,50] presented a method of simultaneous testing of flows from a tested room through all adjacent partitions while opening and closing one of the doors or windows at the time in all adjacent compartments. This procedure gives n equations with n known perturbations of the pressure field (we know both outdoor and corridor pressures) that solved simultaneously gives also the leakage area of the tested exterior wall(s).

Two blower technique introduced by Proskiw [51] allow even checking the effect of connectivity with internal partitions and using a sequence of two blower door to pressurize / depressurize the room one may estimate the leakage area of the exterior wall(s).

Testing of Water Resistive Barriers

None of the existing test methods for testing water resistive barriers (WRBs) such as dry indicator test, boat test or water pounding test [19,20,22] have been found suitable for evaluation of WRB products. While these tests assumed the dominance of the liquid transport, actually the vapor transport was dominating while the contribution of liquid phase varied depending on the material. Generally, their precision needed to be improved. In effect, a testing methodology was proposed [33], that includes:

- Modified Inverted Cup water vapor transmission test (vapor and liquid) transport from water with 50 Pa pressure through the WRB to desiccant (this is modification to inverted cup procedure from ASTM E96 test method that is now under ballot as a separate standard)
- Liquid penetration resistance (LPR), the method is still under development (see text below).

Maximum Water Vapor Transmission Measured with Modified Inverted Cup (MIC)

The current ASTM E96 inverted cup method does not have a standardized thickness of water layer on top of the specimen. To ensure the repeatability and the reproducibility of the test method, constant conditions must be maintained on both sides of the test specimen. Placement of 5 mm thick water head on the specimen's upper surface provided a low, but practical level of hydrostatic pressure. Use of a frequently regenerated desiccant near at the bottom surface of the specimen provides near 0 % RH This creates the highest possible driving force for diffusion of water vapor. Earlier work [19] showed that using higher water head (e.g., 25 mm) had no significant effect on the results.

MIC test represents the most severe conditions resulting in a maximum moisture transfer. Table 9 shows comparison of MIC value with moisture transmission from water layer to OSB and plywood through WRB perforated with staples and nails [19].

TABLE 9—Moisture transmission rate, $kg/m^2 \cdot s$, for WRB class C or P, without or having perforations. Transfer takes place from water through WRB to the OSB substrate or to the desiccant (MIC).

Test	Class C Material 1	Class C Material 2	Class P Material 1	Class P Material 2
OSB (no perforations)	0.70×10^{-6}	1.00×10^{-6}	0.38×10^{-6}	0.50×10^{-6}
OSB+nail	3.74×10^{-6}	3.01×10^{-6}	0.64×10^{-6}	2.43×10^{-6}
OSB+staple	4.99×10^{-6}	2.04×10^{-6}	3.53×10^{-6}	3.18×10^{-6}
Plywood (no perforations)	0.89×10^{-6}	0.81×10^{-6}	0.52×10^{-6}	0.63×10^{-6}
Plywood+nail	2.16×10^{-6}	2.93×10^{-6}	2.96×10^{-6}	2.39×10^{-6}
Plywood+staple	0.85×10^{-6}	0.89×10^{-6}	3.87×10^{-6}	2.08×10^{-6}
MIC test	2.98×10^{-6}	2.89×10^{-6}	3.07×10^{-6}	4.06×10^{-6}

Onset of the Water Flow and Water Permeability Measured with Liquid Penetration Resistance (LPR) Test Method

Air entrapment in small pores of WRB prevents the liquid water from passing through the membrane. The force exerted by the water menisci created within the WRB layer stops the flow of liquid water. Water evaporates from the menisci and diffuses through the pore-air as a vapor. As long as the WRB pores are partially filled with air, water vapor transmission dominates (diffusion together with the flow in absorbed water). Water filtration takes place only when enough of the menisci are broken to form a continuous path for water transport across the WRB product.

If the WRB product is fresh and undisturbed, a very high water pressure is needed to break the menisci in the smallest pores of WRB. For instance, the test methods used for quality control for the class P materials apply pressures between 5.5 kPa and 28 kPa (2.8 m water head). However, air may be removed from the WRB pores by other means, not necessarily by a high water pressure. The entrapped air can be dissolved in the pore-water and removed by the water flow or may diffuse through the water to the surface of the WRB. This process depends on many factors such as the mean pore size, pore-size distribution, connectivity of the pores within the matrix, temperature variations, interaction with salts in the pore water, and even on electric or osmotic conditions on the surface. The hydrostatic pressure of 50 Pa that is used in the liquid penetration resistance (LPR) test is much lower than that required for creating the onset of liquid pressure in the unaged (fresh) Class P membranes.

In the LPR test, both faces of the WRB membrane are in contact with water and a given hydrostatic pressure but the difference across the specimen is only 50 Pa. The LPR test measures two factors:

(1) the time for onset of liquid flow; and
(2) the water conductivity coefficient under steady state conditions of capillary saturated water flow.

It is important to realize that the condition of water being present on both sides of the WRB membrane may not represent a typical field situation. Yet, this condition is necessary to accelerate the removal of air entrapped in the WRB pores

TABLE 10—Moisture transmission rate, kg/(m^2·s), measured with MIC test on fresh and outdoor weathered specimens (on the roof in period Aug–Dec).

Class	Initial (Undisturbed)	After Weathering Outdoor Aug-Dec
C	3.8×10^{-6}	2.3×10^{-6}
C	4.9×10^{-6}	4.0×10^{-6}
C	2.4×10^{-6}	1.6×10^{-6}
C	3.0×10^{-6}	1.8×10^{-6}
C	2.9×10^{-6}	2.5×10^{-6}
P	4.1×10^{-6}	3.7×10^{-6}
P	3.7×10^{-6}	4.0×10^{-6}
P	3.0×10^{-6}	3.2×10^{-6}

and thereby to accelerate the onset of liquid flow through a membrane. This condition is critical for reducing the test period and permit on discrimination between fresh and weathered membranes. This method is critical for evaluation of long-term performance of WRB, since it was the only method showing effects of weathering [19,36]. Table 10 shows results of moisture transmission measurements performed on fresh and aged WRB products. These products were exposed on the roof of a building with an angle adjusted for a maximum solar radiation in summer, driving rain in fall and rain/freezing in early winter. Yet neither air permeability [19] nor vapor transmission (MIC) measurements did not show any difference between test sperfored before and after 4 months field exposure.

Results for class C products shown in Table 10 show a slight improvement of performance of the class C products that can imply some migration of asphalt on cellulose fibers.

Figure 9 shows the results of LPR tests performed on fresh and aged WRB products class C indicating that time to the onset of liquid flow and water transmission were significantly reduced.

This comparison between results of air and vapor permeance with the LPR test method indicates that both MIC and LPR test methods are needed to evaluate performance of WRB in different service conditions.

Discussion on Proposed Test Methodology for WRB

Two aspects of WRB fibrous products jointly provide the capability of resisting water: the nature of porosity (pore size and pore size distribution) and the negative wetting angle of fibers or material modifiers (asphalt, wax, or other surface coating agents). While the first two tests relate to water vapor transfer only, one yielding the minimum (dry cup) and the other the maximum rate of vapor transmission (MIC) these tests deal with the first aspect only [19]. Aging, weathering and other changes in surface chemistry that may affect the affinity of the WRB to water do not affect air or vapor transmission to a significant degree. Yet, experience form the field and even preliminary laboratory work showed that under a combination of chemical and dust particles, the hydrophobic nature of WRB has been changed into hydrophilic allowing water passage in several spots of polymeric WRB products. Therefore, further development of LPR test is necessary to address the durability, i.e., effect of weathering on long-term performance of WRB.

These three tests, together with the measurements of transmission of water through WRB to an OSB board, improved our understanding of factors affecting moisture transfer through WRB (see Table 11).

Line 4 in Table 11 provides the water vapor permeance measured with a double-cup method. Water vapor transmis-

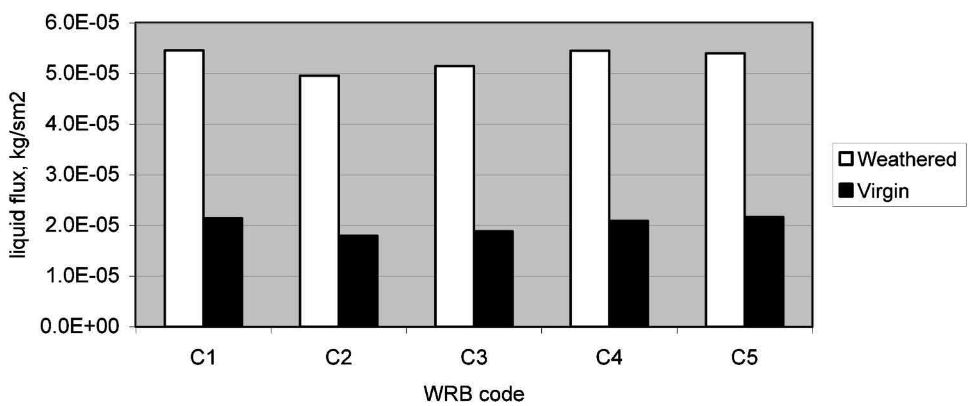


Fig. 9—Liquid flux measured with LPR method on (□) weathered, and (■) virgin type C products.

TABLE 11—Comparison of flow rates through a selected Type C—WRB product.

Line number	Description of transport conditions	Moisture flux, kg/m^2·s	Permeance, perms
1	Water flux measured in LPR	5.0×10^{-5}	
2	Modified Inverted Cup (MIC)	4.0×10^{-6}	22.1
3	Moisture flux OSB+staple (MF)	3.3×10^{-6}	—
4	Double Cup (0 to 100% RH)	2.1×10^{-6}	11.6
5	Moisture flux to OSB+staple	3.3×10^{-6}	—
6	Moisture flux to OSB alone	4.5×10^{-7}	—
7	Moisture flux to plywood alone	4.8×10^{-7}	—

TABLE 12—Change in the water absorption coefficient during water absorption of bricks.

Time	Clay brick 1	Clay brick 2
15 min	22.2	9.6
30 min	21.2	9.1
1 h	20.0	9.0
2 h	19.4	8.6
4 h	18.5	8.2
6 h	17.5	7.9

sion was measured between two environments, one near 100 % RH and the other near 0 % RH. It is noted that moisture flux determined with the MIC method (line 2) was about 100 % higher than that represented by the water vapor diffusion test. The difference can be attributed to the resistance offered by the still air layer under the material surface, and the effect of water on cellulose fibers (while the upper surface was exposed to the hydrostatic pressure of 50 Pa). In effect, the MIC test represented the worst conditions for water vapor dominant moisture transport. The water transfer obtained by the MIC test of 5.0×10^{-6} kg/(m$^2\cdot$s) represents the most permeable product among all tests performed on type C, P, and LA-WRB products [36]. This value is still one order of magnitude lower than the moisture flux resulting from water filtration that was measured with LPR test method.

Water Absorption Coefficient

Bomberg et al. [36] analyzed methods for determination of water absorption coefficient (*A*-coefficient). Traditional way of plotting cumulative water intake in a free water intake test against square root of elapsed time is shown in above. Yet, these measurements should be shown in a different manner to see the period of measurements for which the assumed function is well fitted.

The initial period of measurement cannot be used for calculations because the moisture profile develops in an initially dry material while the equation assumes infinitely high water inflow at time zero. Similarly, the long-term measurement, as currently postulated by different standards, e.g., 24 h absorption, may lead to physically incorrect values. In long measurement periods, there is a significant difference between the uniform flow assumed by equation and the finger-like flow of water accompanied by the redistribution of moisture, lateral dispersion in the material. In a long duration tests, the water vapor diffusion that precedes the liquid front has also a significant effect on moisture flow.

Table 12 shows measurements of water absorption coefficient performed on two different types of clay brick as a function of time.

If one wants to relate the measured *A*-coefficient to liquid dominated transport [52], one should restrict time of measurements to a few hours period (see Fig. 10). We shall call this type of measurement the initial water absorption coefficient and denote it as A_o. This coefficient is very useful to compare rate of water intake during rain or by capillary suction by different materials and should be reported for all porous cladding materials; e.g., stucco, lamina of EIFS, or masonry units.

Figure 10 shows A_o coefficient measured on two clay-brick specimens selected from a series of test in such a manner that they represent minimum and median values of capillary moisture content [53].

Capillary Moisture Content: The End of Free Water Intake Process

A free water intake process (often called uptake because water is sucked thought a bottom surface), as shown in Fig. 5, continues until the front of water field reaches the maximum capillary height or the upper end of the specimen. At this stage, the first period of water absorption is completed and water redistribution and air removal are the primary mechanisms in the second stage.

Actually, water flow in the specimen is non-uniform and often it is called a "finger-like" flow pattern. So water reaches the upper surface of material in some points, much before the whole volume of water is uniform. This is illustrated in Fig. 11.

TUD measurements for calcium silicate, gave times 48 s$^{1/2}$ and 60 s$^{1/2}$, respectively. The first point indicated the end of stage 1 and the second ($t_2 = 60$ s$^{1/2}$ in Fig. 10) indicates the second stage of the free water intake process and indicate achieving the capillary saturation.

While a proper test method for determination of capil-

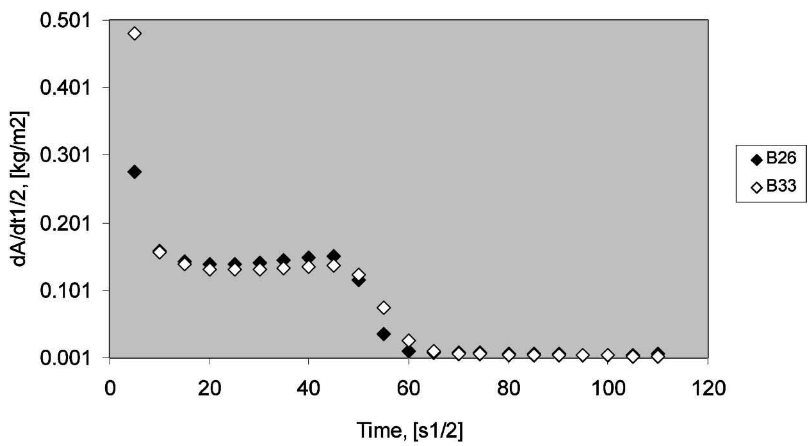


Fig. 10—A_o coefficients calculated for ceramic brick specimens: B-26 (minimum value of capillary moisture content), and B-33 (median value of capillary moisture content). Specimens B-26 and B-33 had densities of 1943 and 1957 kg/m^3, respectively.

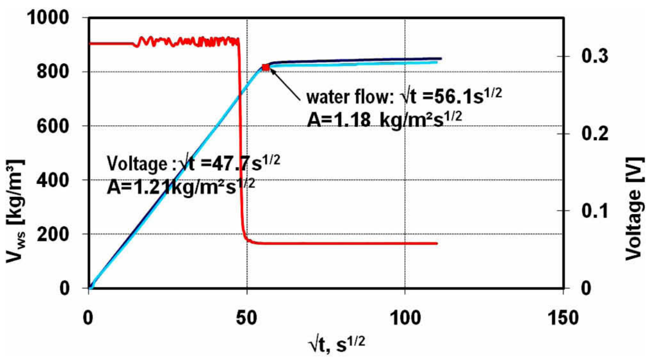


Fig. 11—Time when waterfront reaches the uppers surface measured as a change of the electric resistance on the surface (about 48 $s^{1/2}$), and end of the free water intake process measured as the mass increase (about 60 $s^{1/2}$). Measurements performed at Technical U, of Dresden and figure reprinted with permission of TUD.

lary moisture content remains to be developed, the significance of this concept in durability assessment cannot be overstated (see Chapter 27 of this manual).

Other Measurements of Hygric Properties

Sorption isotherm measurements involve moisture exchange between the specimen and the atmosphere with constant and known relative humidity. One measures the increase of moisture until the equilibrium condition is reached. The specimens are placed in desiccators containing a preselected saturated salt solution For most of inorganic materials the effect of temperature on the sorption isotherm is small, i.e., the same curve can be used in a range of temperatures. This is not he case for most organic materials where both RH and temperature affects the equilibrium moisture content. There are also materials that change dimensions during the water vapor sorption, typically the initial volume and mass are used for calculation of the sorption isotherm. The character of the sorption isotherm is closely related to the pore-size and pore-size distribution so that this technique is also used for material characterization.

The preselected saturated salt solutions have the corresponding relative humidity levels at a room temperature: 97.3 % by K_2SO_4; 96.0 % by KH_2PO_4; 84.7 % by KCl; 75.4 % by NaCl; 58.2 % by NaBr; 32.9 % by MgCl; 22.5 % by CH_3COOK, and 11.3 % by LiCl. A criterion for establishing the equilibrium moisture content requires that the difference in mass between two nonconsecutive weightings be less than 0.1 % over a minimum period of 10 days.

After completing the required series of measurement within the hygroscopic range of the water retention characteristics, the specimens are re-dried to a constant mass. A specimen is assumed to be oven dry, when the weight loss is less than 0.1 % between three nonconsecutive measurements performed within 24 h.

Generally speaking, the moisture storage is expressed as the relationship between the volumetric water content in the material and the used descriptor of the moisture potential. In the hygroscopic region (below 95 % RH), such a descriptor is the relative humidity of air. In above-hygroscopic region the descriptor is a capillary suction (the difference between pore-water pressure and air pressure acting on the water meniscus in the equilibrium state). The relation between moisture content and capillary suction is called the moisture retention curve (MRC).

To this end, one may use pressure plates. Each apparatus consist of a pressure chamber, a ceramic plate, and a gas pressure supply regulating system. Typically, the ceramic plates allow the MRC to be determined within the range of a few Pa up to 1500 kPa. The test starts with a saturated specimen whose moisture content is slightly above that of a capillary saturation. The chamber is closed and a desired air pressure is applied, causing the water to be drained from the specimen. The outflow continues until the equilibrium is reached between the capillary suction and the applied external air pressure.

Measurements of moisture transport characteristics are not discussed in this chapter because they are performed in the manner suitable for the used hygrothermal model [54].

Acknowledgments

The authors gratefully acknowledge input and invaluable insights of Mr. Ronald Tye, who wrote the previous chapter. Furthermore, many thoughts of Dr. Onysko and Dr. Lstiburek are incorporated here; where possible with the quoted sources, but as one of the authors worked with them together for so many years, it is often difficult to trace where the insights are coming from. The authors tried to write this chapter as the first step to the language of building physics (science) and science is always built on the knowledge of others.

REFERENCES

[1] M. T. Bomberg and W. C. Brown, "Building Envelope and Environmental Control-Part 1: Heat, Air and Moisture Interactions," *Construction Canada*, Vol. 35, No. 1, 1993 pp. 15–18; "Part 3: Issues of System Integration," *Construction Canada*, Vol. 35, No. 5, 1993, pp. 48, 50–52, 54.

[2] J. F. Straube and E. F. P. Burnett, *Overview of Hygrothermal Analysis Models*, ASTM Manual 40, ASTM International, West Conshohocken, PA, 2001.

[3] J. W. Lstiburek and J. K. Lischkoff, *A New Approach to Affordable, Low Energy House Construction*, Alberta Department of Housing, Alberta, 1984.

[4] NBCC, 1995

[5] M. Bomberg, D. Onysko, and J. Lstiburek, "Review of the Air Barrier Issues," IX Conf. on Building Envelopes, ASHRAE, December 5–8, 2004.

[6] G. Demarais, D. Derome, and P. Fazio, "Mapping of Air Leakage in Exterior Walls," *J. Therm. Envelope Build. Sci.*, Vol. 24, 2000, pp. 132–154.

[7] R. L. Quirouette, "The Difference Between a Vapor Barrier and an Air Barrier," Building Practice Note 54. IRC: NRC, 1985.

[8] Morrison Hershfield Ltd, "Testing of Air Barrier Construction Details," Canada Mortgage and Housing Corporation, Ottawa, ON, August 1991.

[9] K. D. Knight and J. B. Boyle, *Guidelines for Delivering Effective Air Barrier System*, CMHC, Ottowa, 2004. URL http://www.cmhc-schl.gc.ca/publications/en/rh-pr/tech

[10] T. Ojanen, R. Kohonen, and M. K. Kumaran, "Fundamentals of Transport and Storage of Moisture in Building Mat., and Components," *Moisture Control in Buildings, ASTM MNL 18*, ASTM International, West Conshohocken, PA, 1994, pp. 18–34.

[11] T. R. Ojanen and M. K. Kumaran, "Effect of Exfiltration on Hygrothermal Behavior of a Residential Wall Assembly," *J.*

Therm. Insul. Bould. Envenelopes, Vol. 19, 1996, pp. 215–228.
[12] CMHC, *Testing of Air Barrier Systems for Wood Frame Walls*, Technical Series 98–110, report by IRC-NRC Canada, 1988, see URL http://www.cmhc-schl.gc.ca/publications/en/rh-pr/tech
[13] NRCC, 1995.
[14] National Building Code of Canada, edition 1995.
[15] Morrison Hershfield Ltd, "Commissioning and Monitoring the Building Envelope for Air Leakage," Canadian Housing Information Center (CHIC), CMHC, Technical Series 96–235, 1996.
[16] N. Nisson and D. Best, *Exterior Insulation and Finish Systems*, Cutter Information Corporation, Arlington, MA, 1999.
[17] P. Burnett, "The Performance of Exterior Sheathing Membranes in Enclosure Wall System," 8th Conference on Building Science and Technology, February 22–23, 2001, Toronto, pp. 344–362.
[18] F. Baker and M. Bomberg, "The Functional Requirements for WRB Exposed to Incidental Water Leakage, Part1: Classification of Membranes," *J. Test. Eval.*, Vol. 33, 2005, p. 207.
[19] M. Bomberg, M. Pazera, J. Zhang, and F. Haghighat, "Weather Resistive Barriers: Assessment of Their Performance," 2nd Int. Conf. of Building Physics, Sept 14–16, 2003, KU Leuven, Belgium.
[20] M. Bomberg, M. Pazera, J. Zhang, T. Mungo, and F. Haghighat, "Weather Resistive Barriers: New Methodology for Their Evaluation," AIVC/BETEC Conference Oct 12–14, 2003, Washington, DC.
[21] D. Onysko, M. Bomberg, R. Desjardins, M. Pazera, and F. Nabhan, "Evaluation of Liquid-Applied Weather resistive barriers on Wood-Based Substrates for use with EIF systems," 2003 AIVC BETEC Conference "Ventilation, Humidity Control and Energy" Oct. 12–14, 2003, Washington, DC, AVIC.
[22] CMHC, 2004, Technical Series 04–124, "Summary of Research on Water Resistive Barriers," see also URL http://www.cmhc-schl.gc.ca/publications/en/rh-pr/tech
[23] X. Qiu, F. Haghighat, and K. Kumaran, "Moisture Transport Across Interfaces Between Autoclaved Aerated Concrete and Mortar," *J. Therm. Envelope Build. Sci.* Vol. 26, 2003, pp. 213–236.
[24] CMHC, "Best Practice Guide-Flashings," #61122, see also URL http://www.cmhc-chl.gc.ca/publications/en/rh-pr/tech
[25] M. Bomberg, "Moisture Flow Through Porous Building Materials," Technology D. Thesis at the Lund Institute of Technology, Report 52, LTH, Lund, 1974, p. 188.
[26] M. Cheple and P. H. Huelman, "Why We Need to Know More About Basement Moisture," Buildings VIII, ASHRAE/DOE Conference, 2001.
[27] CMHC, Investigating, "Diagnosing and Treating Your Damp Basement," Canada Mortgage and Housing Corporation, Ottawa, Ontario, 1992.
[28] P. Ellringer, "Minnesota Mold Busting," *Home Energy Magazine*, May/June 2002.
[29] T. Kesik, M. Swinton, M. Bomberg, K. Kumaran, W. Maref, and N. Normandin, "Cost Effective Residential Basement Wall Drainage Alternatives Employing Exterior Insulation Basement Systems," 8th Canadian Building Science Conference, Toronto, February 22–24, 2001.
[30] M. T. Bomberg, M. C. Swinton, and M. K. Kumaran, "Thermal Performance of Exterior Basement Insulation Systems (EIBS)," International Building Physics Conference, Holland, September 2000.
[31] M. C. Swinton, M. T. Bomberg, M. K. Kumaran, W. Maref, and N. Normandin, "In-situ Performance Evaluation of Spray Polyurethane Foam in the Exterior Insulation Basement System (EIBS)," IRC/NRCC Presented at the 8th Conf. on Building Science and Technology, Toronto, Ontario, Feb. 22–23, 2001.
[32] W. Maref, M. C. Swinton, M. K. Kumaran, and M. T. Bomberg, "3-D Analysis of thermal resistance of exterior basement insulation systems (EIBS)," *Build. Environ.*, Vol. 36, 2001, pp. 407–419.
[33] M. Bomberg, M. Pazera, and D. Onysko, "The Functional Requirements for WRB Exposed to Incidental Water Leakage, Part 2: Testing Materials," *J. Test. Eval.*, Vol. 33, 2005, 2583, see Ref [35].
[34] Kruger and Eriksson, 1925, see Ref. [35]
[35] M. Bomberg, 1974, "Moisture Flow Through Porous Building Materials," Tekn. D. Thesis at the Lund Institute of Technology, Report 52 LTH Lund, p. 188.
[36] M. Bomberg, M. Pazera, and P. Ellringer, "3E Wall for All Climates: Part 1: The Problem Part 2: A Proposed Solution," Proceedings of Int. Conference on lime in Buildings, Orlando March 9–11, 2005.
[37] A. K. Karagiozis and M. K. Kumaran, "Computer Model Calculation of the Performance of Vapor Barriers in Canadian Residential Buildings," *ASHRAE Trans.*, Vol. 99, No. 2, 1993, pp. 991–1003.
[38] M. Bomberg, and D. Onysko, "Heat, Air and Moisture Control in Walls of Canadian Houses: A Review of the Historic Basis for Current Practice," *J. Therm. Envelope Build. Sci.*, Vol. 26, pp. 2002, 3–31.
[39] J. Lstiburek, "Understanding Vapor Barriers," *ASHRAE J.*, August 2004, pp. 40–50.
[40] Joy and G. Wilson, "Standardization of the Dish Method for Measuring WVT," *Humidity and Moisture*, Vol. 4, National Building Institute, Oslo, 1965.
[41] K. Kiessl, H. M. Kuenzel, and H.-P. Leimer, "Performance of Innovative Vapor Retarders Under Summer Conditions," CIB W40, Meeting in NZ, 2001.
[42] P. Haeupl, Lecture at Syracuse University in the Course Moisture, Materials, and Durability, November 30, 2004.
[43] M. T. Bomberg and M. K. Kumaran, "A Test Method to Determine Air Flow Resistance of Exterior Membranes and Sheathings," *J. Therm. Insul.*, 9, 1986, pp. 224–235.
[44] ASTM Standard E2178, "Standard Test Method for Air Permeance of Building Materials," ASTM International, West Conshohocken, PA, 2001
[45] CMHC, *Field Investigation of Indoor Environment and Energy Usage in Mid-Rise Residential Buildings*, Housing Info Center, CMHC, Ottowa, 1997.
[46] M. T. Bomberg and D. M. Onysko, "Control of Air Leakage with Polyurethane Foams," 8th Canadian Building Science Conference, Toronto, February 22–24, 2001.
[47] G. Desmarais and M. Bomberg, "Design of the Wall-Window Interface: Performance Requirements and Water-Managed Stucco Examples," 8th Canadian Building Science Conference, Toronto, February 22–24, 2001.
[48] J. W. Lstiburek, "Toward an Understanding and Prediction of Air Flow in Buildings," Ph.D. Thesis, U. of Toronto, 2000.
[49] J. W. Lstiburek, K. Pressnail, and J. Timusk, "Transient Interaction of Buildings with HVAC Systems—Updating the State of the Art," *J. Therm. Envelops and Bould. Sci.*, Vol. 24, 2000, pp. 111–131.
[50] J. W. Lstiburek, K. Pressnail, and J. Timusk, "Evaluating the Air Pressure Response of Multizonal Buildings," *J. Therm. Envelope Bould. Sci.*, Vol. 25, 2002, pp. 299–320.
[51] G. Proskiw, "An Innovative Airtightness Test Procedure for Separating Envelope Air Leakage from Interior Partition Air Leakage in Multi-Zone Buildings," 2006, M A Sc thesis, Concordia U, 2006.
[52] M. Janz, "Methods of Measuring Moisture Diffusivity at High Moisture Levels, Licentiate Thesis Division of Building Mate-

rials," Lund U., LTH, Report TVBM-3076, 1997.

[53] M. Bomberg, M. Pazera, and R. Plagge, "Analysis of Selected Water Absorption Coefficient Measurements," *J. Therm. Envelope Build. Sci.*, Vol. 28, 2005, pp. 227–244.

[54] J. Grunewald, P. Haeupl, and M. Bomberg, "Towards an Engineering Model of Material Characteristics for Input to HAM Transport Simulations—Part 1: An Approach," *J. Therm. Envelope Build. Sci.*, Vol. 26, 2003, pp. 343–366.

3

Effects of Moisture on the Thermal Performance of Insulating Materials

Per Ingvar Sandberg[1]

Introduction

IN PREPARATION OF THIS CHAPTER, THE CON-tents of the first edition were drawn upon. The author acknowledges the coauthors of the first edition, Catherine Langlais and Anne Silberstein. The current edition will review and update the topics that were addressed by the previous authors, introduce new technology that has been developed, and include up to date references.

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 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. Solve the complete set of equations to evaluate the effects of moisture.
2. Apply some kind of correction to the dry thermal conductivity.

In this chapter, we discuss these two options. 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 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 chapter deals only with the effects of moisture on the thermal performance of insulating materials in general use.

After describing essential facts about heat transfer through dry insulating materials, the effects of moisture on overall thermal performance are described qualitatively. Then, after a short survey of existing simultaneous heat and mass transfer models and measurement techniques, the technical background necessary to understand in which conditions one can define the thermal conductivity of a wet insulating material is given. A laboratory test method to measure the "moist thermal conductivity" is described and guidelines to determine the thermal performance of a wet insulant in real conditions of use are given. Finally, this chapter reports and comments 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 materials* at temperatures greater than 0 Kelvin.
2. Heat transfer by natural convection occurs in *fluids* because of a temperature difference. It is the consequence of macroscopic particle displacements caused by a gradual change in density of a fluid depending on its temperature. The fluid in insulating materials is normally air.
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, in a vacuum, and in transparent materials*.

A confined insulating material without exchange of air with the surroundings is assumed in this discussion. The presumption of no airflows through the insulant is done partly because effects of airflows are typically very local and partly because reliable knowledge in this area is still sparse. Some references dealing with combined heat, air, and moisture transfer are given in Refs. [1–5] and also in prEN 15026, Hygrothermal Performance of Building Components and Building Elements—Assessment of Moisture Transfer by Numerical Simulation [6].

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, $\vec{q}$ (amount of heat going through the material per unit time and unit surface), and the temperature gradient, $\vec{\nabla}T$. The proportionality constant, called *thermal*

[1] *SP Technical Research Institute of Sweden, Borås, Sweden.*

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		
Antimony	24	Gases:	10^{-2}
Dielectrics:	10^0–10^1	Air	0.024
		CO_2	0.017
Ice	2.1	Freon	0.007
SiO_2	12.6		
Glass	0.8		

conductivity, is an intrinsic physical property of a homogeneous material.

$$\vec{q} = -k \cdot \vec{\nabla} T \tag{1}$$

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

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

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 reduce the heat losses across it to a given 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, semitransparent 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 many cases of application of porous insulation (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.

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 fiber diameters and arrangements.

Therefore, the data reported 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 (only the specific products used for subsequent measurement of wet thermal conductivity are cited). 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.

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 simulta-

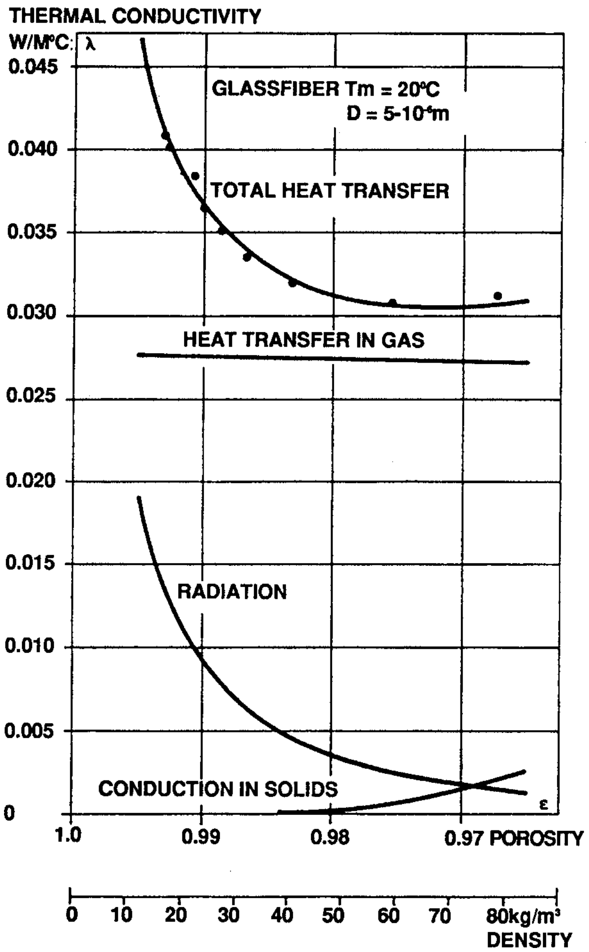


Fig. 1—Heat transfer mechanisms in a fibrous insulating material, from Ref. [80].

neous 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 [7], Krischer [8], Luikov [9], and Whitaker [10].

Combined heat and moisture transfer models found more recently in the literature [11–18] are mostly based on the De Vries or Luikov approach. They differ by the number of assumptions made to simplify the set of equations and the choice of driving forces.

The classical models take into account two driving forces to express mass transfer: temperature and moisture gradients. Then, it is generally assumed that the heat transfer due to mass flows is small compared to heat transfer due to phase changes; see also comments about Effect I, II, and III in the next clause.

The derivation of the equations within these assumptions is well beyond the scope of this chapter. It can be found in Ref. [13], with gravity effects neglected, as

$$\frac{\partial \theta_\ell}{\partial t} = \nabla \cdot (D_\theta \nabla\, \theta_\ell + D_T \nabla\, T) \qquad (7)$$

$$(\rho c)^* \cdot \frac{\partial T}{\partial t} = \nabla \cdot (\rho_\ell L D_{\theta v} \nabla\, \theta_\ell + (k^* + \rho_\ell L D_{Tv}) \nabla\, T) \qquad (8)$$

where

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

Different forms of this set of equations can be found in the literature. Two state variables are necessary to describe the moisture transport. Vapor pressure-suction, vapor pressure-moisture content, or humidity by volume-suction are frequent choices in addition to temperature-moisture content, which is shown here. Any two independent state variables may be used and they can readily be rewritten and expressed in other state variables.

At the other extreme, we can also mention a very common simplified method used to calculate moisture distributions and developed by Glaser [19]. This method accounts only for vapor diffusion as the transport process and assumes stationary conditions that almost never occur in reality. It has been standardized in EN ISO 13788 Hygrothermal Performance of Building Components and Building Elements—Internal Surface Temperature to Avoid Critical Surface Humidity and Interstitial Condensation—Calculation Methods [20].

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, and water in order to 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 in the water film 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

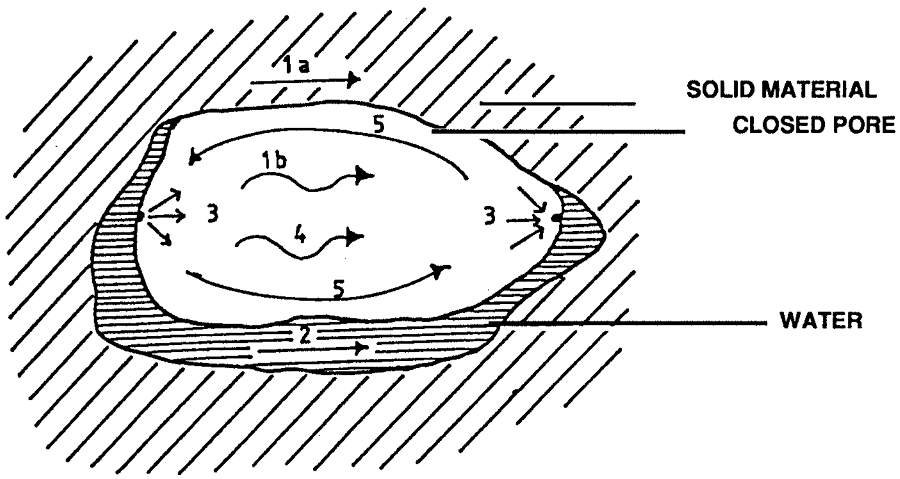


Fig. 2—Heat transfer mechanisms in the pore of a moist material.

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. 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

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

With a moisture content of, say 50 kg/m^3 (which is very high), 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

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

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

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

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

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

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

$$q_{II} = 0.03\ \text{W/m}^2$$

$$q_{III} = 1.7\ \text{W/m}^2$$

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. Such heat transfer may be of the same magnitude as the increase due to the presence of moisture in the material.

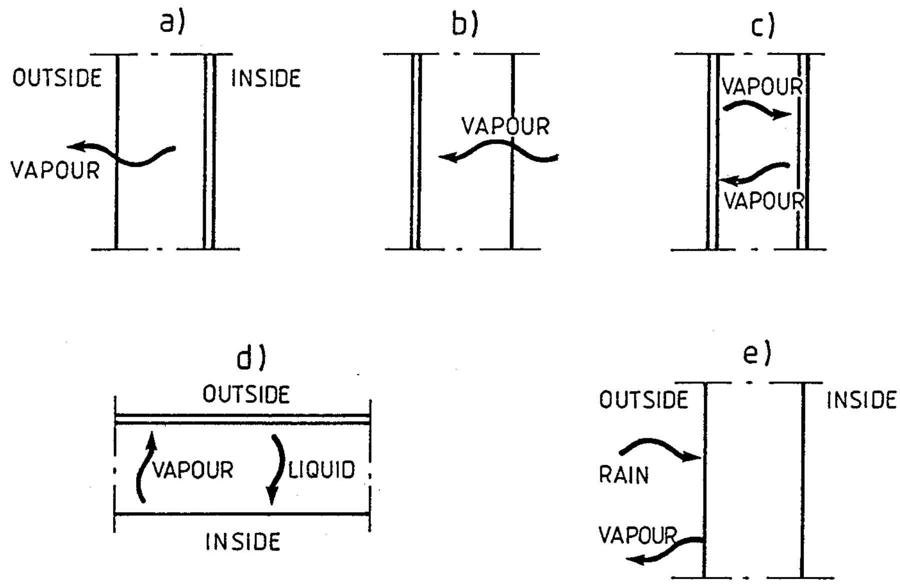


Fig. 3—Some examples in which moisture effects may have to be taken into consideration.

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 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.

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

$$k^* = f(T, \theta_\ell)$$

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

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

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

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

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

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

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

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

Steady State Measurements

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

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

Equation (9) then becomes

$$\vec{q} = -k^* \vec{\nabla} T + g_v (h_v - h_\ell) \tag{14}$$

or

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

with (see Ref. [13])

$$\vec{g}_\ell = -\rho_\ell (D_{\theta \ell} \vec{\nabla} \theta_\ell + D_{T\ell} \vec{\nabla} T) \tag{16}$$

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

combining Eqs (15)–(17) we get

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

which in most cases can be reduced to

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

Equations (15) and (19) finally give

$$\vec{q} \approx -(k^* + \rho_\ell D_{Tv} L) \vec{\nabla} T \tag{20}$$

which enables us to define again an equivalent thermal conductivity

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

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 nonsteady 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 ($\vec{g}_\ell = 0$)

$$\vec{q} = -k^* \vec{\nabla} T + \vec{g}_v h_v \tag{22}$$

or

$$\vec{q} \approx -k^* \vec{\nabla} T + \vec{g}_v L \tag{23}$$

Two cases are then of interest

- $\vec{g}_v L \langle\langle k^* \vec{\nabla} T$. 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 measured results found in literature show 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.

How to Measure 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 laboratory test 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.

A test method for the determination of k^* has been worked out within ISO and presented as ISO 10051 Thermal insulation—Moisture Effects on Heat Transfer—Determination of Thermal Transmissivity of a Moist Material [21]. The standard specifies a method to provide the apparent thermal conductivity of a moist material (k^*), a property of a moist material under steady state conditions, i.e., not af-

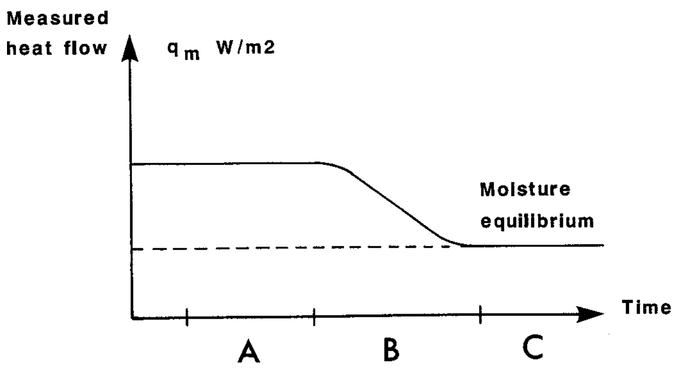


Fig. 4—Variation of heat flow during a test of a moist material.

fected 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.

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

$$q_m = (-k^* \cdot dT/dx)_{sur} + (g_v \cdot L)_{sur} \tag{24}$$

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 determining.

Data of 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 (C177) or ASTM Test Method for Steady-State Heat Flux Measurements and Thermal Transmission Properties by Means of the Heat Flow Meter Apparatus (C518) for dry materials [22,23].
- 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. [24]).

Table 2 recaps the main references we have found. Figure 5, mentioned earlier, 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 other materials and their interpretation in Refs. [45–73]. 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.

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 the 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).

For the dry materials, experimental results have been reported as $k^* = f$ (density) curves. For the wet materials, the ratio k^*_{wet}/k^*_{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.

Not enough data were available on cellulose fibers to be represented on a graph. The interested reader will find some information on this in Refs. [58,68].

Within ISO, measured data on k^*_{wet} have been compiled in ISO 10456 Building Materials and Products–Hygrothermal Properties–Tabulated Design Values and Procedures for Determining Declared and Design Values [74]. This standard specifies a procedure to convert dry values to moist values:

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

Authors	Reference	Type of Material
Cammerer	25	Extruded polystyrene
Zehendner	26	
Tobiasson et al.	27,28	
Knab et al.	29	
Dechow et al.	30	
Jespersen	31	
Kumaran	33	
Jespersen	31	Expanded polystyrene
Cammerer	25	
Fauconnier	32	
Tobiasson et al.	27,28	
Dechow et al.	30	
Zehendner	26	
Kumaran	33	
Cammerer	25	Polyvinylchloride foam
Fauconnier	32	
Zehendner	26	
Cammerer	25	Phenolic foam
Fauconnier	32	
Zehendner	26	
Sandberg	34	Aerated concrete
Fauconnier	32	
Cammerer	25	
Jespersen	35	
Hums	36	
Loudon	37	
Laurent et al.	38	
Boutin	39	
Kumaran	33	
Cammerer	25	Polyurethane foam
Zehendner	26	
Fauconnier	32	
Knab et al.	29	
Dechow et al.	30	
Tobiasson et al.	27,28	
Jespersen	31	
Chyu	40	
Cammerer	25	Cork
Fauconnier	32	
Jespersen	35	
Tobiasson	27	
Srinivasan	41	
Cammerer	25	Perlite
Knab et al.	29	
Tobiasson	27	
Jespersen	31	Urea formaldehyde foam
Cammerer	25	
Jespersen	31,35	Mineral wool
Cammerer	25	
Fauconnier	32	
Knab et al.	29	
Langlais et al.	42,43	
Tobiasson	27	
Kumaran	33	
Jespersen	31	Vermiculite
Anquez	44	

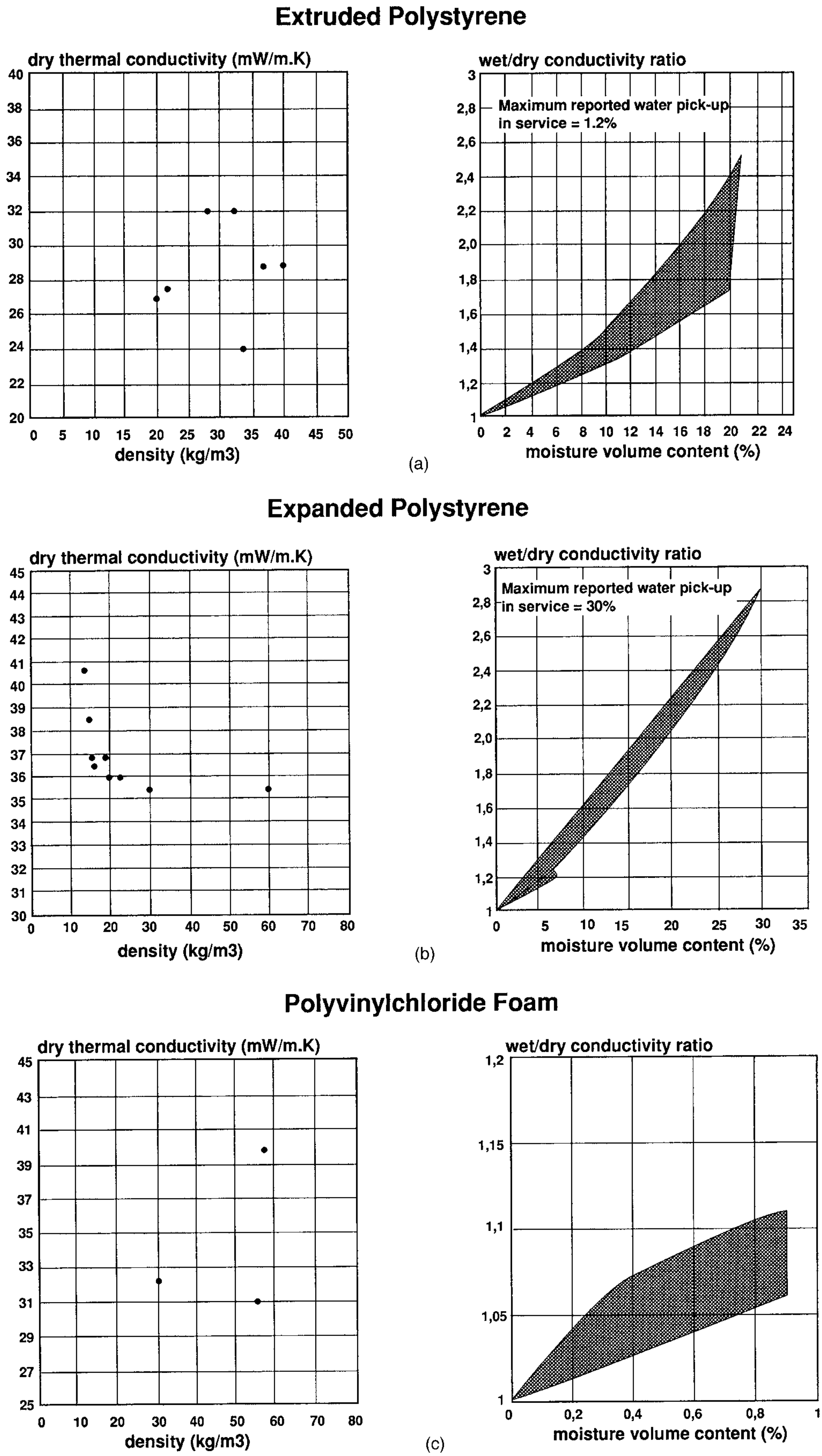
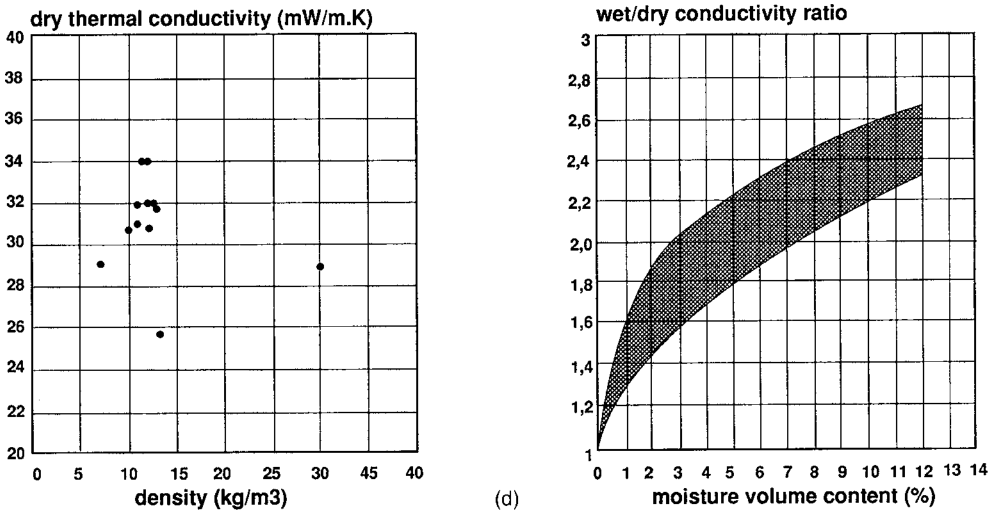


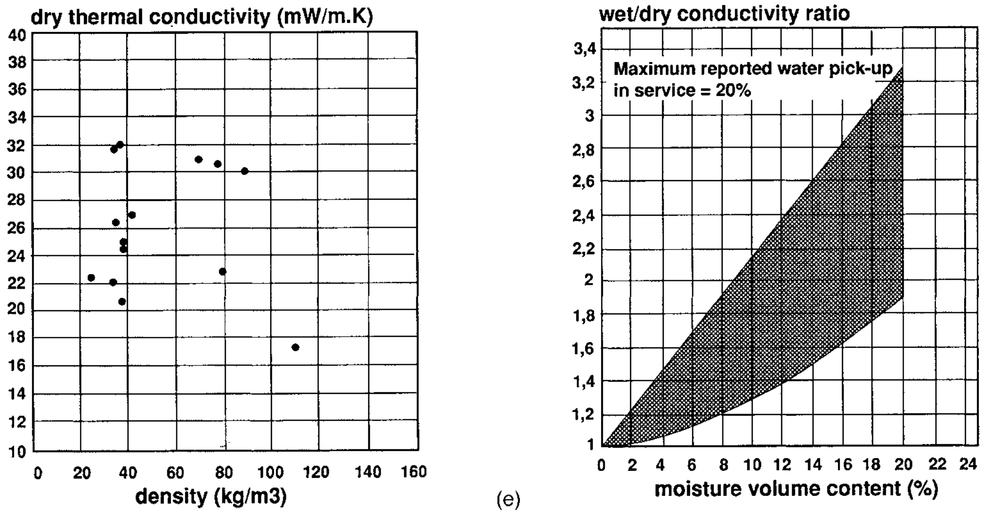
Fig. 5— The increase of thermal conductivity of various insulating materials with average moisture content (related to the dry product's thermal conductivity value) and corresponding product density and dry apparent thermal conductivity.

Urea Formaldehyde Foam



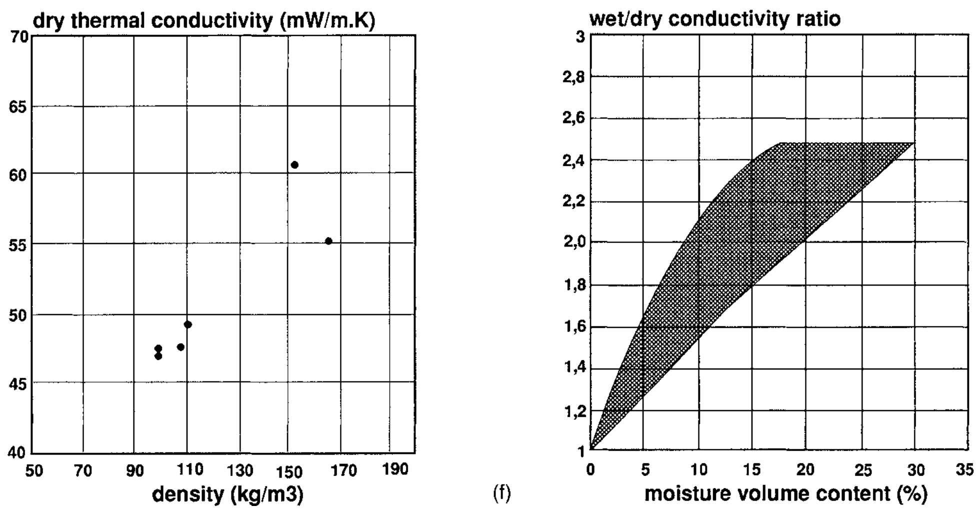
(d)

Polyurethane Foam



(e)

Perlite



(f)

Fig. 5— (*Continued*).

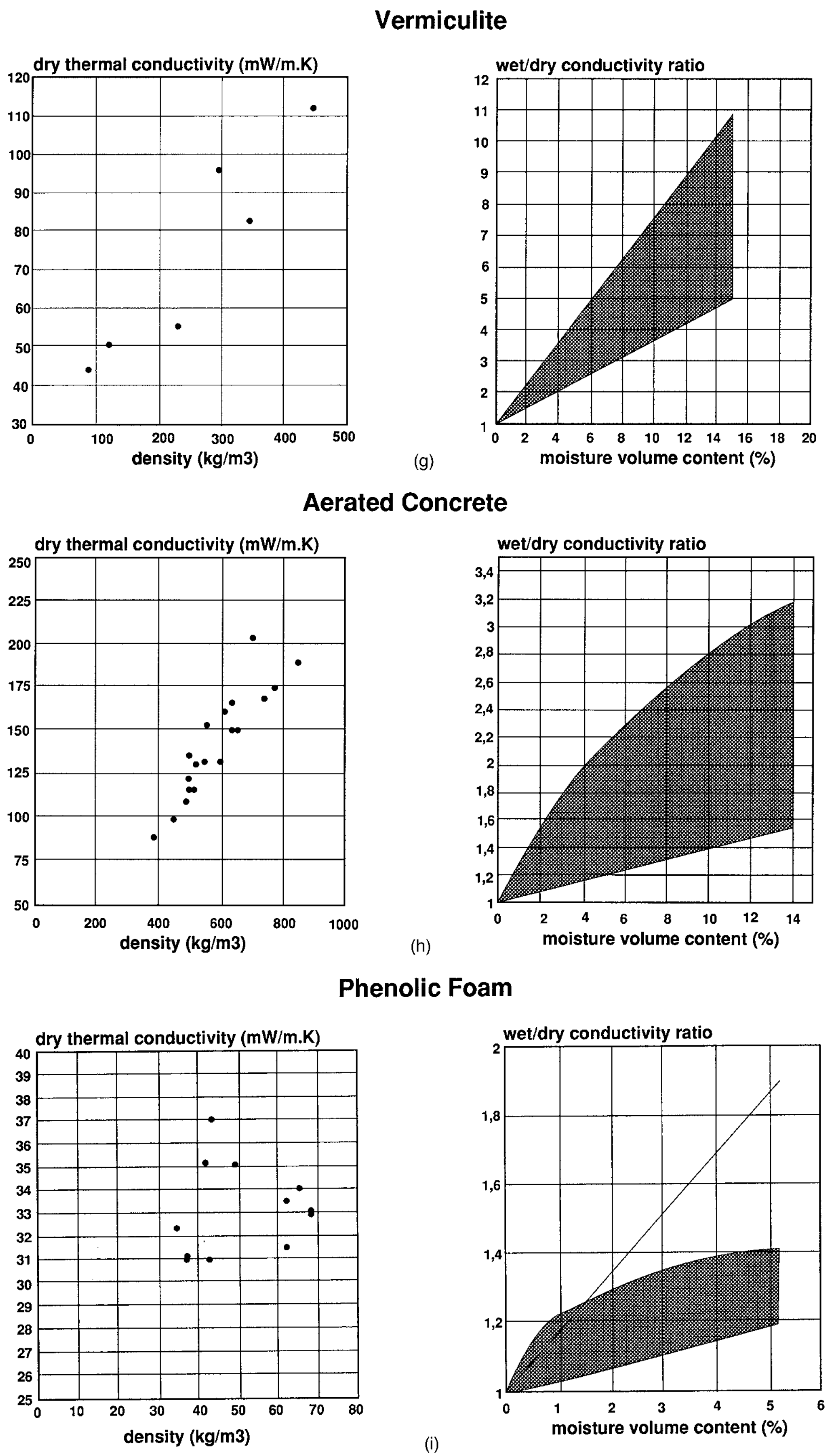
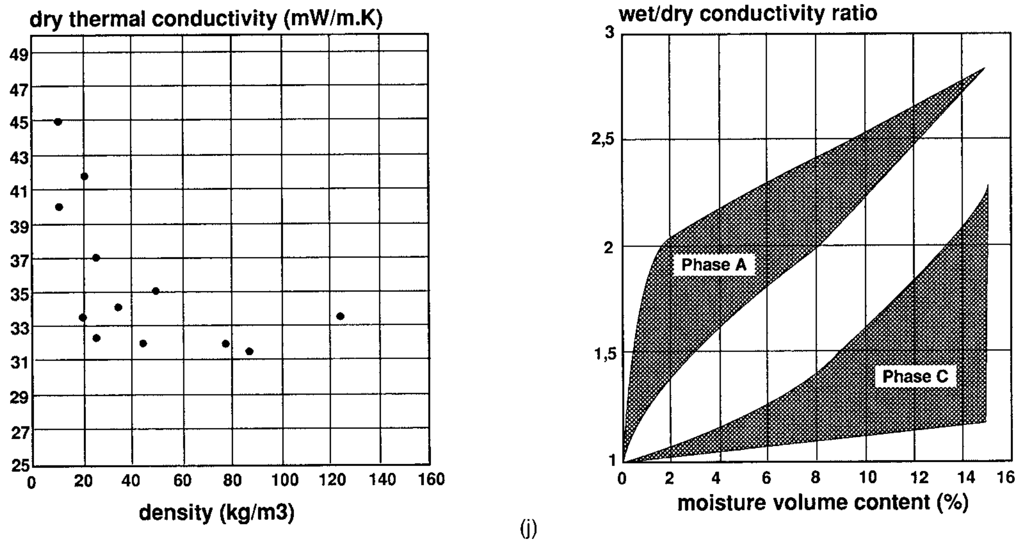


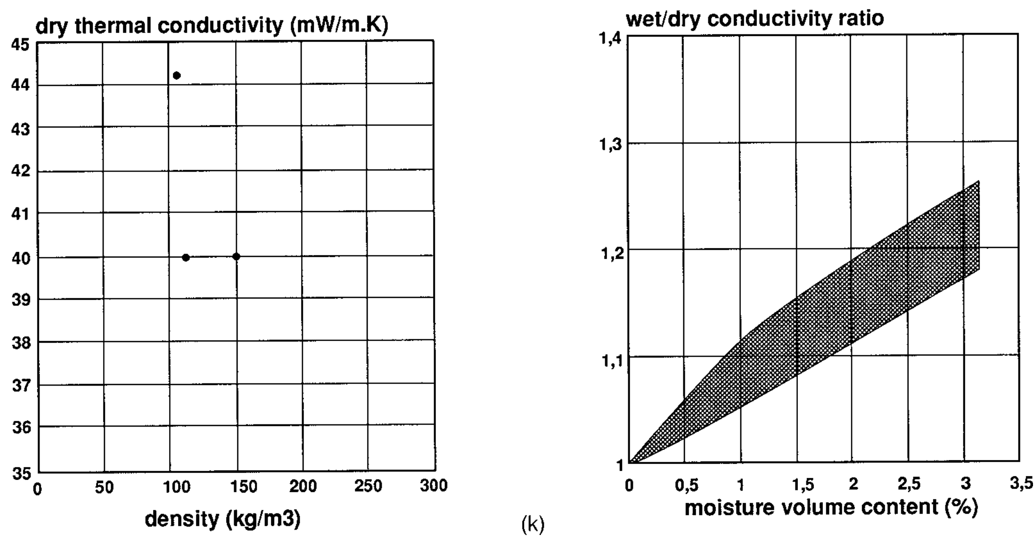
Fig. 5— (*Continued*).

Mineral Fibers



(j)

Cork



(k)

Fig. 5— (*Continued*).

$$k^*_{wet} = F_m \cdot k^*_{dry} \quad (25)$$

where F_m is the moisture conversion factor.

The factor F_m is determined as follows:

$$F_m = e^{f_u \cdot u} \quad (26)$$

or

$$F_m = e^{f_\psi \cdot \psi} \quad (27)$$

where f_u is the moisture content conversion coefficient mass by mass, u is the moisture content mass by mass (kg/kg), f_ψ is the moisture content conversion coefficient volume by volume, and ψ is the moisture content volume by volume (m^3/m^3). Values of f_u and f_ψ are given in Table 3.

For a loose fill cellulose fiber insulation with a service moisture content, $u = 0.15$ kg/kg, $F_m = e^{0.5 \cdot 0.15} = 1.08$ or 8 % deterioration of the dry thermal conductivity. For a mineral wool insulation with a service moisture content, $\psi = 0.0005$ m^3/m^3, $F_m = e^{4 \cdot 0.0005} = 1.002$ which is a negligible deterioration.

It should be noted that the dry values are converted to "true" thermal conductivity, k^*, and the standard states that "Effect of mass transfer by liquid water and water vapor, and effects of water phase changes are not covered by these data." See also Ref. [75].

Recommendations for the 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*

TABLE 3—Moisture conversion coefficients for insulation materials according to ISO 10456 [74].

Type of Material	f_u	f_ψ
Expanded polystyrene		4
Extruded polystyrene foam		2.5
Polyurethane foam, rigid		3
Mineral wool		4
Phenolic foam		5
Perlite board	0.8	
Expanded cork		6
Wood wool board		1.8
Wood fiberboard	1.5	
Urea-formaldehyde foam		2
Loose-fill cellulose fiber	0.5	
Loose-fill expanded perlite	3	
Loose-fill exfoliated vermiculite	2	
Loose-fill expanded clay	4	
Loose-fill expanded polystyrene beads		4

in the material using relevant thermal and moisture material characteristics and boundary conditions. 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 is 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 of k^* found in the literature, from which design values can be estimated, are given in Fig. 5 and in Table 3. 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.

Effect III (Phase Changes) May Be Neglected

The determining factor is the quotient: thermal conductivity/vapor permeability. As a rule of thumb, we may assume that for materials with a high value of this quotient such as

- plastic foam
- aerated or lightweight concrete
- wood fiber board
- brick

Effect III may be neglected.

For materials of this 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 find the corresponding value of k^*. Only for extremely nonuniform moisture distributions need the effects of moisture distribution be considered. k^* may then be used as k_{design} for this particular application.

Effect III (Phase Changes) May Not Be Neglected

For materials with a low value of the quotient: thermal conductivity/vapor permeability, such as fibrous insulation or highly porous materials, the effects of phase changes 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 this group. Hedlin [49,54], Sandberg [76], and Pedersen et al. [77] 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 [76] 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. More results of this kind can be found in Refs. [59,69,78,79].

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.

Conclusions and the Need for Future Work

In this chapter it is seen that, to consider the effects of moisture on the thermal performance of insulating materials, one 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 [21] 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.

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 other cases, however, *moisture movements* also have to be considered. All those cases sensitive to effects of moisture movements must 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 complex; and 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.

References

[1] Degiovanni, A. and Moyne, C., "Conductivité Thermique de Matériaux Poreux Humides: Évaluation Théorique et Possibilité de Mesure," *Int. J. Heat Mass Transfer*, Vol. 30, No. 11, pp. 2225–2245.

[2] Descamps, F., "Continuum and Discrete Modeling of Isothermal Water and Air Transfer in Porous Materials," Ph.D. Dissertation, Catholic University of Leuven, 1997.

[3] Rode, C. and Grau, K., "Whole-building Hygrothermal Simulation Model," *ASHRAE Symposium on Recent Simulation Advances—Building Loads*, Chicago, 2003.

[4] Adan, O. and Brocken, H., "Determination of Liquid Water Transfer Properties of Porous Building Material and Development of Numerical Assessment Methods," Final Technical Report, Project GRD1–1999–20007 (HAMSTAD), TNO Building and Construction Research, Delft, 2003.

[5] Adan, O. et al., "Determination of Liquid Water Transfer Properties of Porous Building Materials and Development of Numerical Assessment Methods: Introduction to the EC HAMSTAD Project," *J. Thermal Envelope Building Sci.*, Vol. 27, 2004, pp. 253–260.

[6] prEN 15026, "Hygrothermal Performance of Building Components and Building Elements—Assessment of Moisture Transfer by Numerical Simulation."

[7] Philip, J. R. and De Vries, D. A., "Moisture Movement in Porous Materials Under Temperature Gradient," *EOS Trans. Am. Geophys. Union*, Vol. 38, No. 2, 1957, pp. 222–232.

[8] Krisher, O. and Mahler, K., "Über die Bestimmung des Diffusionswiderstandes und der Kapillaren Flüssigkeits Leitzahl aus Stationären und Instationären Vorgangen," *V.D.I. Forschungsheft*, Düsseldorf, VDI-Verlag, 1959, p. 473.

[9] Luikov, A. V., *Heat and Mass Transfer in Capillary Porous Bodies*, Pergamon Press, Elmsford, NY, 1966.

[10] Whitaker, S., "Simultaneous Heat Mass and Momentum Transfer in Porous Media: A Theory of Drying," *Advances in Heat Transfer*, Academic Press, Vol. 13, 1977, pp. 119–203.

[11] Comini, G. and Lewis, R. W., "A Numerical Solution of Two Dimensional Problems Involving Heat and Mass Transfer," *Int. J. Heat Mass Transfer*, Vol. 19, 1976, pp. 1387–1392.

[12] Kohonen, R., "A Method to Analyze the Transient Hygrothermal Behaviour of Building Components and Materials," Publication 21, Technical Research Center of Finland, Espoo, 1984.

[13] Bories, S., "Transferts de Chaleur et de Masse Dans les Matériaux. Analyse Critique des Différents Modèles Utilisés," in *L'humidité Dans les Bâtiments*, Conseil International de la Langue Françcaise, Paris, 1984.

[14] Kerestecioglu, A. et al., "Modeling Heat, Moisture and Contaminant Transport in Buildings: Toward a New Generation Software," *Proceedings, CIB-W40 Meeting*, Victoria, Canada, 1989.

[15] Pedersen, C. R., "Combined Heat and Moisture Transfer in Building Constructions," Ph.D. Thesis, Technical University of Denmark, Lyngby, Report 214, 1990.

[16] Kerestecioglu, A. and Gu, L., "Theoretical and Computational Investigation of Simultaneous Heat and Moisture Transfer in Buildings: Evaporation and Condensation Theory," *ASHRAE Trans.*, Vol. 96, No. 1, 1990, pp. 455–464.

[17] Künzel, H. M., "Simultaneous Heat and Moisture Transport in Building Components—One- and Two-Dimensional Calculation Using Simple Parameters," IRB, Stuttgart, 1996.

[18] Bednar, T., "Beurteilung des Feuchte—und Wärmetechnischen Verhaltens von Bauteilen und Gebäuden—Weiterentwicklung der Mess—und Rechnensverfahren," Dissertation, TU Wien, 2000.

[19] Glaser, H., "Grafisches Verfahren zur Untersuchung von Diffusions-Vorgängen," *Kältetechnik*, No. 11, 1959, pp. 345–355.

[20] EN ISO 13788, "Hygrothermal Performance of Building Components and Building Elements—Internal Surface Temperature to Avoid Critical Surface Humidity and Interstitial Condensation—Calculation Methods."

[21] ISO 10051, "Thermal Insulation—Moisture Effects on Heat Transfer—Determination of Thermal Transmissivity of a Moist Material."

[22] ASTM Standard C177, "Standard Test Method for Steady-State Heat Flux Measurements and Thermal Transmission Properties by Means of the Guarded-Hot-Plate Apparatus," Annual Book of ASTM Standards, ASTM International, West Conshohocken, PA.

[23] ASTM Standard C518, "Standard Test Method for Steady-State Heat Flux Measurements and Thermal Transmission Properties by Means of the Heat Flow Meter Apparatus," Annual Book of ASTM Standards, ASTM International, West Conshohocken, PA.

[24] Joy, F. A., "Thermal Conductivity of Insulation Containing Moisture," *Symposium on Thermal Conductivity Measurements and Applications of Thermal Insulations, ASTM STP 217*, ASTM International, West Conshohocken, PA, 1957, pp. 157–174.

[25] Cammerer, J., "Einfluß des Feuchtegehaltes auf die Wärmeleitfähigkeit von Bau- und Dämmstoffen," Forschungsvorhaben no BI 5–80–01–83–4, Bundesminister für Raumordnung, *Bauwesen und Städtebau*, 1984.

[26] Zehendner, H., "Einfluß von Feuchtigkeit auf die Wärmeleitfähigkeit von Schaumstoffen im Bereich von −30°C bis +30°C," *Kunstoffe im Bau*, Heft 1/79, 1979.

[27] Tobiasson, W. and Ricard, J., "Moisture Gain and Its Thermal Consequence for Common Roof Insulation," Miscellaneous Paper 1361, U.S. Army Cold Regions Research and Engineering Laboratory, Hanover, NH, April 1979.

[28] Tobiasson, W., Greatorex, A., and van Pelt, D., "Wetting of Polystyrene and Urethane Roof Insulations in the Laboratory and on a Protected Membrane Roof," *Thermal Insulation: Materials and Systems, ASTM STP 922*, ASTM International, West Conshohocken, PA, 1987, pp. 421–430.

[29] Knab, L. I., Jenkins, D. R., and Mathey, R. G., "The Effect of Moisture on the Thermal Conductance of Roofing Systems," NBS Building Science Series 123, National Bureau of Standards, Washington, DC, 1980.

[30] Dechow, F. J. and Epstein, K. A., "Laboratory and Field Investigations of Moisture Absorption and Its Effect on Thermal Performance of Various Insulations," *Thermal Transmission Measurements of Insulation, ASTM STP 660*, ASTM International, West Conshohocken, PA, 1978, pp. 234–260.

[31] Jespersen, H. B., "The Effect of Moisture on Insulating Materials Made of Plastic Foam, Impregnated Mineral Wool, Vermiculite and Concrete Clinkers," IIF Commission 2, Belgrade, 9–10 June 1960, Annexe 1960-2 Supplément au

Bulletin de l'IIF, pp. 63–78.

[32] Fauconnier, R., "Influence de l'humidité sur la Consommation Énergétique d'un Bâtiment en Chauffage Discontinu (Modélisation et Couplage de Phénomènes)," in *L'humidité Dans les Bâtiments*, Conseil International de la Langue Française, Paris, 1984.

[33] Kumaran, M. K., "Task 3: Material Properties, Final Report," IEA Annex 24, Laboratorium Bouwfysica, K.U.-Leuven, Belgium, 1996.

[34] Sandberg, P. I., "The Effect of Moisture Content on Thermal Conductivity of Aerated Concrete," Swedish National Testing and Research Institute Internal Report, Borăs, 1982.

[35] Jespersen, H. B., "Thermal Conductivity of Moist Materials and Its Measurement," *J Inst. Heating and Ventilating Engineers*, Vol. 21, No. 216, 1953, pp. 157–174.

[36] Hums, D., "Relation Between Humidity and Heat Conductivity in Aerated Concrete," *Autoclaved Aerated Concrete, Moisture and Properties. Developments in Civil Engineering*, Elsevier, 1983, pp. 143–152.

[37] Loudon, A. G., "The Effect of Moisture Content on Thermal Conductivity," *Autoclaved Aerated Concrete, Moisture and Properties. Developments in Civil Engineering*, Elsevier, 1983, pp. 132–142.

[38] Laurent, J. P. and Guerre-Chaley, C., "Influence de la Teneur en eau et de la Temperature sur la Conductivité Thermique du Béton Cellulaire Autoclave (Influence of Water Content and Temperature on the Thermal Conductivity of Autoclaved Aerated Concrete)," *Mater. Struct.*, Vol. 28, 1995, pp. 464–472.

[39] Boutin, C., "Conductivité Thermique du Béton Cellulaire Autoclavé: Modélisation par Méthode Autocohérente (Thermal Conductivity of Autoclaved Aerated Concrete: Modeling by the Self-Consistent Method)," *Materials and Structures*, Vol. 29, 1996, pp. 609–615.

[40] Chyu, M.-C., Zeng, X., and Ye, L., "The Effect of Moisture Content on the Performance of Polyurethane Insultion Used on a District Heating and Cooling Pipe," *ASHRAE Trans.*, 4042(RP-721), 1997, pp. 309–317.

[41] Srinivasan, K. and Wijeysundera, N. E., "Heat and Moisture Transport in Wet Cork Slabs Under Temperature Gradients," *Build. Environ.*, Vol. 36, 2001, pp. 53–57.

[42] Langlais, C., Hyrien, M., and Klarsfeld, S., "Moisture Migration in Fibrous Insulating Materials Under the Influence of a Thermal Gradient and Its Effect on Thermal Resistance," *Moisture Migration in Buildings, ASTM STP 779*, ASTM International, West Conshohocken, PA, 1982, pp. 191–206.

[43] Langlais, C., Hyrien, M., and Klarsfeld, S., "Influence of Moisture on Heat Transfer through Fibrous Insulating Materials," *Thermal Insulations, Materials, and Systems for Energy Conservation in the '80s, ASTM STP 789*, ASTM International, West Conshohocken, PA, 1983, pp. 563–581.

[44] Anquez, J., "Mesure Instantanée de la Conductivité Thermique—Application aux Matériaux Humides," *Cahiers du CSTB*, No. 63, 1963 p. 519.

[45] Mincke, H., van Itterbeek, A., and Uyttenbroeck, J., "Some Considerations on a Non Steady State Method for the Measurement of the Heat Conductivity of Moist Materials," IIF, Commission 2, Turin, 1964.

[46] Palosaari, S. and Norden, H., *Heat Transfer in Fibrous Insulating Materials at Various Moisture Contents and Temperatures*, Kemian Teollisuus, Helsinki, No. 3, 1966.

[47] Bomberg, M. and Shirtliffe, C. J., "Influence of Moisture Gradients on Heat Transfer Through Porous Building Materials," *Thermal Transmission Measurements of Insulations, ASTM STP 660*, ASTM International, West Conshohocken, PA, 1978, pp. 211–233.

[48] Thomas, W. C., Bal, G. P., and Onego, R. J., "Heat and Moisture Transfer in a Glass Fiber Roof Insulating Material," *Thermal Insulations, Materials, and Systems for Energy Conservation in the '80s, ASTM STP 789*, ASTM International, West Conshohocken, PA, 1978, pp. 211–233.

[49] Hedlin, C. P., "Effect of Moisture on Thermal Resistance of Some Insulations in a Flat Roof Under Field-Type Conditions," *Thermal Insulations, Materials, and Systems for Energy Conservation in the '80s*, ASTM International, West Conshohocken, PA, 1983, pp. 604–625.

[50] Langlais, C. and Klarsfeld, S., "Etude de L'influence de L'humidité sur le Transfert de Chaleur Dans les Milieux Poreux. Application au cas des Isolants Fibreux," in *L'humidité Dans les Bâtiments*, Conseil International de la Langue Française, Paris, 1984.

[51] Kumaran, M. K., "Moisture Transport Through Glass-Fiber Insulation in the Presence of a Thermal Gradient," *J. Therm. Insul.*, Vol. 10, April 1987, pp. 243–255.

[52] Degiovanni, A. et al., "Conductivité Thermique Effective d'un Milieu Poreux en Présence D'évaporation-Condensation," *Compte Rendu de l'Académie des Sciences*, Paris, t. 307, serie II, 1988, pp. 1845–1850.

[53] Kumaran, M. K., "Comparison of Simultaneous Heat and Moisture Transport Through Glass-Fibre and Spray-on Cellulose Insulations," *J. Therm. Insul.*, Vol. 12, July 1988, pp. 6–16.

[54] Hedlin, C. P., "Heat Transfer in a Wet Porous Thermal Insulation in a Flat Roof," *J. Therm. Insul.*, Vol. 11, Jan. 1988, pp. 165–188.

[55] Kumaran, M. K., "Experimental Investigation on Simultaneous Heat and Moisture Transport Through Thermal Insulation," CIB, *Proceedings, 11th International Congress*, Theme 2, Vol. 2, 1989, pp. 275–284.

[56] Ashworth, T. and Ashworth, E., "Thermal Conductivity of Several Concretes as a Function of Moisture," *Insulation Materials: Testing and Applications, ASTM STP 1116*, ASTM International, West Conshohocken, PA, 1991.

[57] Zarr, R. R. and Nguyen, T., "Effects of Humidity and Elevated Temperature on the Density and Thermal Conductivity of a Rigid Polyisocyanurate Foam," *Proceedings of the SPI 34rd Annual Technical/Marketing Conference*, 1992.

[58] Sandberg, P. I., "Determination of the Effects of Moisture on the Thermal Transmissivity of Cellulose Fiber Loose-fill Insulation," *Thermal Performance of the Exterior Envelopes of Buildings V*, 1992, pp. 517–525.

[59] Hokoi, S. and Kumaran, M. K., "Experimental and Analytical Investigations of Simultaneous Heat and Moisture Transport Through Glass Fiber Insulation," *J. Thermal Insul. Building Envelopes*, Vol. 16, 1993, pp. 263–292.

[60] Zarr, R. R. and Nguyen, T., "Effects of Humidity and Elevated Temperature on the Density and Thermal Conductivity of a Rigid Polyisocyanurate Foam Co. Blown with CCl_3F and CO_2," *Journal of Thermal Insulation and Building Envelopes*, Vol. 17, 1994, pp. 330–350.

[61] Sandberg, P. I., "Thermal Conductivity of Moist Masonry Materials," *J. Therm. Insulation Building Envelopes*, Vol. 18, 1995, pp. 276–288.

[62] O'Rourke, A., "The Influence of Moisture Content on the Thermal Conductivity of Mortars," *International Symposium on Moisture Problems in Building Walls*, Porto, 1995.

[63] Sandberg, P. I. and Jonsson, B., "Analysis of the Hygrothermal Conditions During Determination of the Thermal Conductivity of Loose-Fill Expanded Clay," *International Symposium on Moisture Problems in Building Walls*, Porto, 1995.

[64] Cerny, R. and Toman, J., "Determination of Temperature and Moisture Dependent Thermal Conductivity by Solving the Inverse Problem of Heat Conduction," *International Symposium on Moisture Problems in Building Walls*, Porto, 1995.

[65] Rudtsch, S. and Rogass, H., "Dynamic Two Heat Flow Meter Method for the Measurement of Thermal Conductivity of

Moist Porous Materials," *Proceedings of the 4th Asian Thermophysical Properties Conference*, Tokyo, 1995, pp. 559–562.

[66] Rogass, H., Fischer, U., and Rudtsch, S., "Thermisch-hygrische Untersuchungen an frischem Porenbeton (Heat and Moisture Investigations on Aerated Concrete)," *Bauphysik 19*, Heft 5, 1997.

[67] Bouguerra, A., "Temperature and Moisture Dependence on the Thermal Conductivity of Wood-Cement-Based Composite: Experimental and Theoretical Analysis," *J. Appl. Phys., J. Phys. D*, Vol. 32, 1999, pp. 2797–2803.

[68] Rode, C., Kristiansen, F., and Rasmussen, N., "Investigation of the Hygrothermal Performance of Alternative Insulation Materials," *Building Physics in the Nordic Countries*, 1999, pp. 137–144.

[69] Baggio, P., Campanale, M., and Moro, L., "Analytical and Experimental Investigations on the Transient Heat Transfer Process in Moist Wood Wool Slabs," *J. Therm. Envelope Building Sci.*, Vol, 24, 2001, pp. 211–225.

[70] Salmon, D., Williams, R., and Tye, R., "Thermal Conductivity and Moisture Measurements on Masonry Materials," *Insulation Materials: Testing and Applications, ASTM STP 1426*, ASTM International, West Conshohocken, PA, 2002, pp. 58–75.

[71] Williams, R., "Overview of a Project to Determine the Thermal Resistance of Masonry Walls in Dry and Moist States and a Conversion Procedure to Determine the Appropriate Design Value," *Building Physics in the Nordic Countries*, Trondheim, 2002, pp. 539–546.

[72] "Thermal Performance of Building Materials and Components—Principles for the Determination of Thermal Properties of Moist Materials and Components," CEN/Technical Report 14613:2003.

[73] Koronthalyova, O. and Matiasovsky, P., "Thermal Conductivity of Fiber Reinforced Porous Calcium Silicate Hydrate-Based Composites," *J. Therm. Envelope Building Sci.*, Vol. 27, 2003, pp. 71–89.

[74] ISO 10456, "Building Materials and Products—Hygrothermal Properties—Tabulated Design Values and Procedures for Determining Declared and Design Values."

[75] Rode, C. and Rudbeck, C., "A Procedure to Determine the Design Value of Thermal Conductivity of Thermal Insulation Materials," *Research in Building Physics*, , Carmeliet, Hens & Vermeir, Eds., 2003.

[76] Sandberg, P. I., "Thermal Resistance of a Wet Mineral Fiber Insulation," *Thermal Insulation: Materials and Systems ASTM STP 922*, ASTM International, West Conshohocken, PA, 1987, pp. 394–404.

[77] Pedersen, C. and Courville, G., "A Computer Analysis of the Annual Thermal Performance of a Roof System With Slightly Wet Fibrous Glass Insulation Under Transient Conditions," *J.Therm. Insul.*, Vol. 15, 1991, pp. 110–136.

[78] Cammerer, J. and Achtziger, J., "Verminderung des Wärmeschutzes von Aussenwandkonstruktionen mit zusätzlicher Wärmedämmschicht Durch Wasserdampf-Diffusionsvorgänge (Reduction of Thermal Insulation of External Wall Constructions With Additional Heat Insulating Layer Due to Water Vapour Diffusion Processes)," *Bauphysik*, Vol. 14, 1992, pp. 129–133.

[79] Wijeysundera, N. E., "Effect of Initial Moisture Distribution on the Transient Heat Flow Through Wet Porous Insulations," *J. Therm. Insulation Building Envelopes*, Vol. 19, 1996, pp. 348–366.

[80] Bankvall, C. G., "Heat Transfer in Fibrous Materials," Document D4:1972, Swedish National Testing and Research Institute, Borås, 1972.

4

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

Charles Carll[1] and Alex C. Wiedenhoeft[1]

MOISTURE IS ARGUABLY THE MOST IMPORTANT factor affecting the performance and service life of wood and wood products. Moisture affects the dimensional movement of wood and wood products; under certain conditions, moisture change can result in major dimensional change. The integrity and strength of adhered (bonded) wood products can be compromised by swelling-induced stresses that accompany wetting. Progressive deflection over time of wood members under load is influenced by moisture conditions, particularly by large repetitive fluctuations in moisture content. Mechanical connections between wood members can be compromised by exposure to elevated moisture conditions or by significant moisture cycling. It is widely recognized that the structural integrity of wood can be irreversibly degraded by biological attack. In some cases biological infestation does not influence structural integrity but nevertheless influences serviceability. For many insect pests and all fungi, moisture conditions higher than the preferred in-service conditions are either required for infestation, or increase the likelihood of infestation.

Although wood, wood products, and wood construction can be degraded by elevated moisture levels or by greatly fluctuating moisture conditions, the vast majority of residential structures built in North America over the past three centuries were constructed primarily of wood, and most of these have performed reliably. Wood and wood products dried to an appropriate level, and maintained within a reasonable range of fluctuating moisture conditions will perform nearly indefinitely. In contrast, wooden buildings constructed without consideration of moisture control may rapidly suffer moisture-induced damage, leading to excessive repair and maintenance costs; in extreme cases the damage may even justify premature demolition.

The central topic of this chapter is how moisture affects the properties and behaviors of wood and wood-based products used in building construction. Physical properties and behaviors are discussed, as are structural behaviors, and what may be considered biological behaviors (specifically, the likelihood of biological infestation by microbes and insects). The order of discussion is that outlined in the previous sentence, namely physical first, then structural, then biological. Before the chapter delves into its central topic, it provides background information on wood and on adhered (bonded) wood products. The information presented on wood includes discussion of wood structure, composition and basic characteristics, with an emphasis on structure. The information presented on bonded wood products follows a similar discussion path, but inasmuch as these are manufactured products, the emphasis is on product classification, composition, fabrication, and characteristics. Information concerning contemporary wood products is presented, as is information on wood products produced in past decades. The intent is to provide information applicable to buildings of various ages, not just to recently-constructed buildings.

The chapter also presents recommendations and guidelines for in-service moisture content. The recommendations are reiterated values from the literature, and take the form of not-to-exceed values. The recommendations are applicable to prevention of biological infestation; there is evidence that these recommended values also roughly correspond with values that have structural performance implications, irrespective of biological infestation. The guidelines, in contrast to the recommendations, relate to limitation of fluctuation in moisture content. The guidelines provide a basis that allows the reader to develop their own project-specific limitations on moisture fluctuation.

Structure of Wood

Axial and Radial Systems

Wood, whether a hardwood (from a broad-leafed tree such as a maple or an oak) or a softwood (from a needle-leaved tree such as a pine or a spruce) is a complex composite. It is composed of a staggering number of cells arranged in a regular, organized fashion into two cell systems, the axial (or longitudinal) system, and the radial system [Fig. 1(*a*)]. The axial system runs parallel to the long axis (i.e., up and down the trunk) and is the collection of cells that people often refer to as "the grain" of the wood. The axial system is responsible for the bulk of the mechanical function of wood, holding aloft the branches and leaves, and the long-distance transport of water (sap) from the roots up to the leaves. It is made of cells that are generally 100 to 200 times longer than they are wide. The radial system runs in a horizontal direction in a standing tree, that is, at a right angle to the axial system. The radial system, formed of individual collections of cells called rays,

[1] *Forest Products Technologist and Botanist, respectively, USDA Forest Service, Forest Products Laboratory, Madison, WI.*

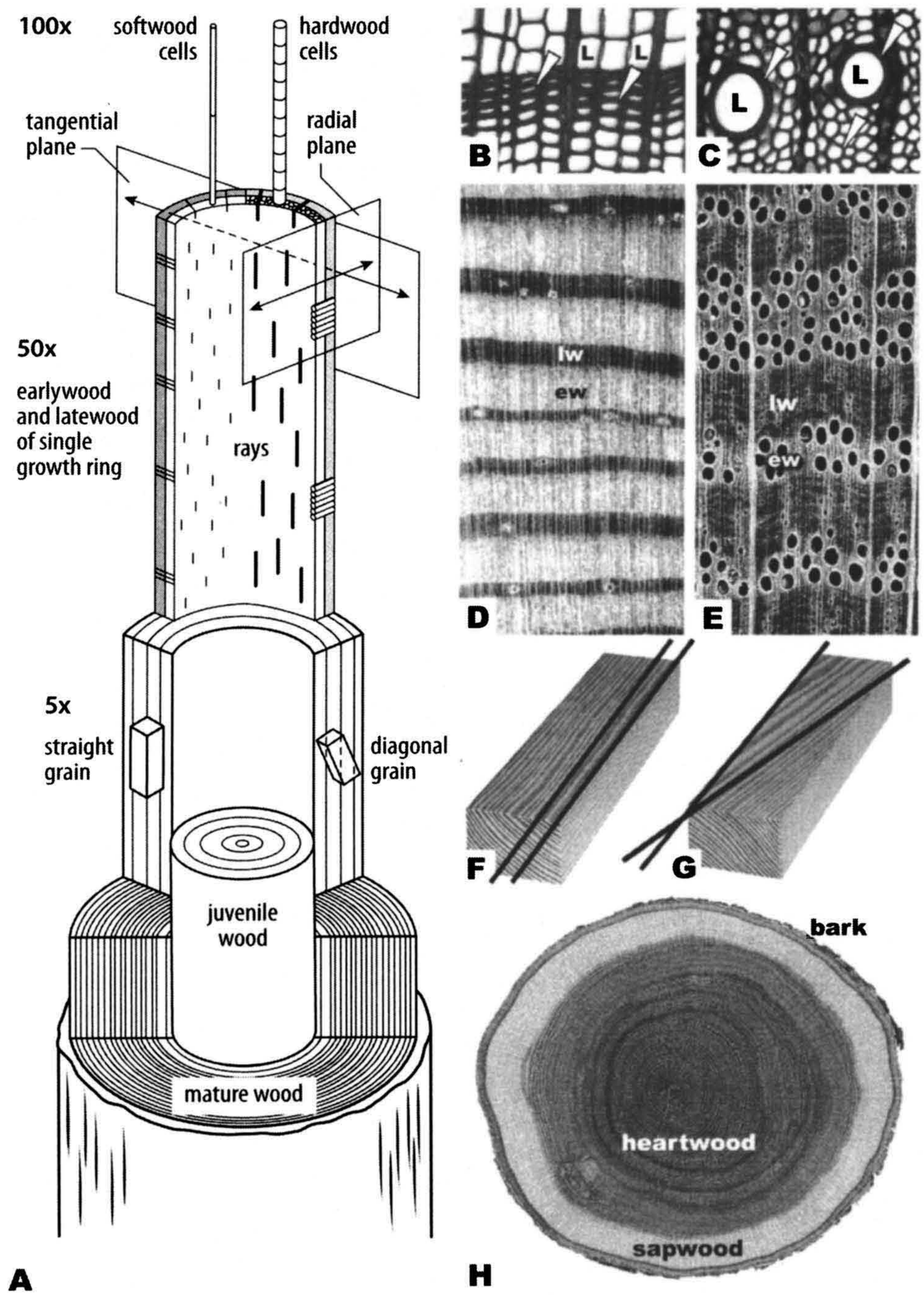


Fig. 1—(*a*) Illustration of a cut-away tree at various magnifications; it is intended to correspond roughly with the images to its right. At the top, at an approximate magnification of 100×, a softwood cell and several hardwood cells are illustrated, to give a sense of scale between the two. One tier lower is a single growth ring of a softwood (left) and a hardwood (right), as well as an indication of the radial and tangential planes. The magnification is approximately 50×. The next tier, at approximately 5× magnification, illustrates many growth rings together, and how one might produce a straight-grained rather than a diagonal-grained board. The lowest tier includes an illustration of the relative position of juvenile and mature wood in the tree, at a 1× magnification. (*b,c*) Light microscopic views of the lumina (L) and cell walls (arrowheads) of a softwood (B) and a hardwood (C). (*d,e*) Hand-lens views of growth rings, each composed of earlywood (ew) and latewood (lw) in a softwood (D) and a hardwood (E). (*f*) A straight-grained board; note that the line along the edge of the board is parallel to the line along the grain of the board. (*g*) A diagonal-grained board. Note that the two lines are markedly not parallel. This board has a slope of about 1 in 7. (*h*) The gross anatomy of a tree trunk, showing bark, sapwood, and heartwood.

runs in a pith-to-bark direction, although most rays do not extend continuously from the pith to the bark. The radial system is responsible largely for moving sugar and chemicals laterally within the trunk of the tree; its component cells are much shorter than those of the axial system.

To give some context to this discussion of cell systems and cell shapes, a one foot long 2 by 4 of Douglas-fir has on the order of 400 million cells; about 200 million of them are cells of the axial system, and the other 200 million are cells of the radial system. Despite the fact that the number of cells is nearly equal in the two systems, in Douglas-fir over 92 % of the total volume of the wood is made up of cells in the axial system [1]. This demonstrates numerically that cells of the radial system are much smaller than those of the axial system, particularly in softwoods.

Cell Wall, Lumen, and Moisture

Much as wood is made of cells occurring in two systems, any individual cell itself has two major domains; the cell wall and the lumen [Fig. 1(*b*) and 1(*c*)]. The cell wall comprises the physical matter of wood, and is formed primarily of layers of cellulose, hemicellulose, and lignin. Cellulose and hemicellulose are strongly hygroscopic (water-adsorbing), and water adsorption results in increases in the distances between the polymer chains and causes the swelling of the wall. Lignin is both an encrusting and matrix compound in the cell wall, providing rigidity to the wall, and constraining the cellulose and hemicellulose as they react to changes in moisture conditions. Lignin is also hygroscopic, but to a substantially lesser degree than cellulose or hemicellulose. It is the moisture relations within the cell walls that affect the movement (shrinkage and swelling) of wood and wood products. Shrinkage and swelling occur mostly in the thickness of the cell wall, resulting in a change in cell diameter. There are only tiny changes in the length of cells of normal wood with changes in moisture.

The moisture that is adsorbed to the hygroscopic portions of the cell wall is referred to as bound water. A given piece of wood has a finite number of sites in cell walls where water can bind; when all cell wall sites are occupied, the wood is said to have reached fiber saturation, beyond which further addition of water imparts no further change in the dimension of the cells. Thus, the range of moisture conditions across which wood responds with dimensional change is from completely dry up to the fiber saturation point (FSP). Although the concept of FSP is useful for explanatory purposes, transitory and spatial variations in moisture conditions make determination of a distinct FSP elusive. Tsoumis [2] uses the term "region of fiber saturation" to reflect such uncertainty.

The second domain of a cell in wood, the lumen (plural lumina), is the air space inside the cell where once the living contents of the cell resided [Fig. 1(*b*) and 1(*c*)]. In the living tree, the lumen was the domain of the cell through which the water flowed to travel from the roots to the leaves. In the case of wood and wood products, the lumen imparts void space in the bulk volume of wood. If it were not for the lumina, all woods would have a density of about 1.5 times that of water. In the context of moisture relations, the lumen is the space where liquid water accumulates when moisture is added after the FSP is reached. This liquid water, called free water, does not affect the dimensional movement of wood, but its presence greatly increases the susceptibility of wood to biological attack.

The relationship between bound water, free water, and wood is analogous to the various hydration states of a dish sponge. A perfectly dry dish sponge is relatively hard and inflexible. As the amount of water in the sponge increases, the sponge softens and swells. Swelling and softening occurs as water enters, occupies, and enlarges spaces within the sponge tissue. After a certain transition point (what is by analogy, FSP), all spaces within the sponge tissue are occupied. This is the familiar feeling a well-wrung sponge; it is quite moist, but no water can be squeezed from it. Adding water to the sponge after this point results in filling of internal spaces with water (by analogy, free water), displacing air. The sponge becomes heavier and wetter, but its size and flexibility undergo no further change.

Cell-to-Cell Connections

The cells of the axial system are connected to each other, and are also connected to the cells of the radial system via tiny thin areas in the walls, called pits. These pits come in a variety of shapes and sizes, and their relative resistances to the flow of water can play an important part in wood-moisture relations. Inasmuch as the axial system comprises most of wood's volume and the cells of the axial system are much longer than they are wide, it is not surprising that moisture moves into, out of, and within wood most readily in this direction. For this reason most manuals and instructors insist on protecting the end grain of wood from direct access to water. Axial cells are nonetheless tiny compared to the scale of structural lumber; an axial cell of a softwood will generally range from 2–6 mm in length. If water taken up at the end grain could get no farther than one cell-length into a board, it would make little difference whether end grain were exposed. Water taken up by the end grain, however, can pass from cell to cell through the pits. Conduction through pits allows water to propagate for centimetres into a board end, and thus greatly increases the amount of water taken up by the board.

Growth Rings and Grain Angle

In our progressive understanding of the organization of wood, the next important scale is that of the growth ring. Virtually everyone is familiar with the idea of growth rings in trees; in the temperate world, each year another layer of wood is added to the circumference of the tree, increasing its girth and providing a simple means to determine the age and relative growth rate of the tree. In tropical areas of the world, growth rings may be correlated with wet or dry seasons; however, many tropical species do not exhibit clearly demarcated growth rings. In the case of trees from temperate regions, a given growth ring is the amount of wood produced in one year, and thus is sometimes called an annual ring.

For most species with growth rings, each ring is divided into two distinct regions, known as earlywood and latewood [Fig. 1(*a*), 1(*d*), and 1(*e*)]. In such cases where the two portions of the ring are distinct, the earlywood is the first-formed wood of the ring, and typically bears thin-walled cells with wide lumina that are suited for the rapid conduction of sap under conditions of plentiful soil moisture. Because wood is formed just under the bark, the earlywood is found on the interior side of the growth ring. The latewood is then added later in the growing season to the outside of the ring, and is typically formed of stronger, thicker-walled cells with narrow lumina. Virtually all woods commonly used in construction in North America have some differentiation between earlywood and latewood.

Most of the cells that form the curving arc of a growth ring are cells of the axial system; the cells forming the lines perpendicular to the growth rings are the rays of the radial system. The orientation of growth rings and rays within a board define the grain angle of the board, and can be seen thanks to the differences in wood structure between earlywood and latewood within and between growth rings. In a flat-sawn board, the arc of the growth rings are parallel to the wide face (the tangential face) of the board, and thus the rays are perpendicular to it. In a quarter-sawn board the rings are perpendicular to the wide face of the board and thus the rays are parallel to the wide face (in this case, the radial face) of the board. The rays are responsible for the pronounced figure called ray-fleck that is characteristic on the wide faces of quarter-sawn hard maple, oak, or sycamore boards (or the narrow faces of flat-sawn boards of these species). The distinction between tangential and radial directions is important, as will be discussed later, in determining the ways in which wood changes dimension with changes in moisture.

Slope of Grain, Spiral Grain, and Interlocked Grain

Ideally, the axial cells of a growth ring in a piece of lumber would be oriented perfectly parallel to the long axis of the board. There are two main ways in which the cells of the axial system deviate from this idealized condition.

The first deviation from perfect straightness is due to the nature of the shape of the tree. Though we often think of the trunk of a tree as a cylinder, it is in fact a collection of conical layers of wood, with each cone widest at the base of the trunk tapering to a point at the top of the tree. Each growth ring is a continuous sheath of wood superimposed on the previous year's cone. As the diameter of a tree increases, each layer comes closer and closer to the idealized, vertical condition. The orientation of cells in the tree can make it difficult to cut a straight-grained piece of wood from a tapered log; if one saws parallel to the pith, growth rings will be at an angle to the face of the board that is cut, resulting in a condition called diagonal grain [Fig. 1(*a*), 1(*f*), and 1(*g*)]. Diagonal grain can be minimized or eliminated by cutting parallel to the bark of the tree, particularly in cases where the diameter of the tree is fairly small, and thus taper tends to be high. Boards with diagonal grain often behave differently from boards with straight grain with changes in moisture.

The second common deviation from a perfectly vertical orientation of axial cells in the growth ring is called spiral grain. Spiral grain occurs when the wood cells within a growth ring are formed at a slight angle from vertical, resulting in a helical orientation about the trunk of the tree. If the angle from vertical is small (for example, less than one degree), spiral grain is not likely to be noticed in lumber. As the angle from vertical increases, however, the deviation becomes more pronounced, and spiral grain may be noticeable in a board cut from such a log. A log containing spiral grain will not yield straight-grained lumber, regardless of how the lumber is sawn from the log. In some cases, spiral grain can occur in alternation within the same tree; for the first few years the wood may be laid down in a right-handed helix, then the next few years in a left-handed helix, and so on, switching every few years. In such a case, the wood is referred to as having interlocked grain. This condition can produce boards with an aesthetically striking figure, particularly in quarter-sawn material. Species such as African mahogany (*Khaya* spp.) often have interlocked grain, and produce interesting axial ribbonlike patterned boards. Wood with spiral or interlocked grain may show abnormal dimensional change with change in moisture.

Sapwood, Heartwood, and Natural Durability

Two regions of the trunk of the tree are germane to our discussion of wood; the heartwood and the sapwood [Fig. 1(*h*)]. Each of these regions is a collection of one to many growth rings. The heartwood, if present, always occurs in the center of the tree, and the sapwood is always the layer adjacent to the bark. Although there are many differences between heartwood and sapwood in the context of tree physiology, in the context of water relations of wood there are only two major differences; the closing of pits between cells and the accumulation of heartwood chemicals called extractives.

At the cell structural level, there is no appreciable difference between the anatomy or cell wall chemistry of cells in the heartwood compared to those in the sapwood. In a simple sense, the formation of heartwood is an ongoing process by which growth rings are decommissioned from transporting water to the leaves and are instead loaded to various degrees with extractives. As a given growth ring loses its transport function, it dries somewhat and in this process many of the pits in the cells close, thus making the wood less conductive of fluids. At the same time this drying is taking place, extractives are also being deposited, sometimes effectively sealing the pits closed. Such pit closure reduces the ability of the wood to allow fluid movement. If one is attempting to force preservatives into wood to increase the insect- and decay-resistance, a high proportion of sapwood is desirable, as the closed and often sealed pits of the heartwood greatly limit the penetration of the preservative into the board. In contrast, sapwood is much more prone to rapid wetting, and thus to more extreme fluctuation in moisture content in service.

Extractives are what impart the desirable colors to the heartwood of such species as cherry or walnut. Extractives give the cedars their pleasant odors, and extractives impart the great natural durability to the timber of black locust. Woods such as teak or lignum vitae, famous for their good performance in association with water, derive their utility from the quality, quantity, and type of extractives accumulated in their heartwood. In pines, spruces, larches, and Douglas-fir, accumulation of resinous extractives can affect appearance and performance of the wood.[2]

Within a species that has colored decay-resistant heartwood, coloration may provide a rough indication of the degree of decay resistance. Across species, however, heartwood

[2] Resinous extractives are found in both the sapwood and heartwood of these woods, but their compositions and amounts [3], and their distribution within the wood structure differ between sapwood and heartwood.

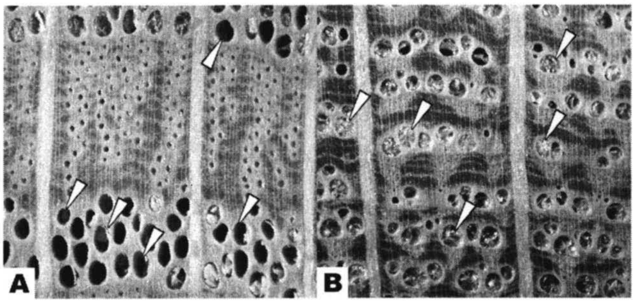


Fig. 2—Hand-lens views of two species of oak. (*a*) A species in the red oak group, with characteristic open vessels (arrowheads), making the wood highly permeable. (*b*) A species in the white oak group, showing vessels occluded with cellular ingrowths (arrowheads), rendering the wood highly impermeable. Note that the growth rate of the wood in A is much greater than that of B.

coloration should not be considered an indicator of resistance to biological attack. Some darkly colored heartwood has low resistance to biological attack, whereas nearly colorless heartwood (such as that of northern white cedar), or lightly colored heartwood (such as that of Alaska yellow-cedar) can be appreciably resistant to attack.

In some species, there are additional changes during heartwood formation that greatly affect the ultimate applications to which a wood might be suited. In species of oak, there is an important distinction between the heartwood formation process in the red oak group and that of the white oak group. In the former case, heartwood formation is much as described above; pits may close or become plugged or sealed during the deposition of extractives, and the wood dries out somewhat in the standing tree, but the overall permeability in these species is not greatly reduced [Fig. 2(*a*)]. In the white oak group, however, special cell wall ingrowths proliferate in the lumina of the largest conducting cells [Fig. 2(*b*)]. These ingrowths tightly plug the conducting cells and effectively seal the wood, and block the free flow of fluid. It is for this reason that the white oaks are used in shipbuilding and cooperage, and the red oaks are shunned. The red oaks do not form these plugs, and thus the permeability of red oak heartwood remains high. For this reason, the red oaks are commonly treated with creosote to produce railroad ties, and white oaks are not. By choosing the correct wood for the application, people have long been able to maximize the material benefits inherent in the diversity of wood structure.

Additional ways in which the relatively lower permeability of heartwood affects wood-moisture relations is in lumber drying and moisture cycling. Lower wood permeability often results in slower and more difficult drying of heartwood lumber by production mills. Conversely, the low permeability of heartwood can result in reduced fluctuation in moisture content under intermittent wetting or under fluctuating humidity conditions, and thus be a desirable trait.

Juvenile, Mature, and Reaction Wood

The bulk of our discussion of wood structure and chemistry to this point has implicitly assumed that we are speaking of mature wood cut from trees which had not been exposed to conditions that might have resulted in substantial trunk

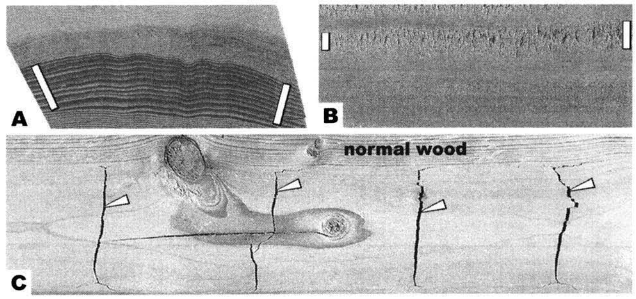


Fig. 3—(*a*) Wide band, spanning many rings, of compression wood (between the bars) as seen on the end-grain of a board. The wood outside the bars is mature, normal wood. (*b*) Fuzzy grain (between the bars) caused by incomplete cutting of tension wood fibers during planing. A partial band of fuzzy grain can be seen at the top edge of the image. (*c*) Dramatic longitudinal shrinkage of compression wood resulting in cross-grain checking (arrowheads). The normal wood at the top of the board does not exhibit this behavior.

lean. Such an assumption is not always valid; juvenile wood (formed early in the life of the trunk) and reaction wood (formed as a reaction to lean) are found to varying degrees in contemporary lumber.

Depending upon species, the first 5–25 years of growth can be considered juvenile wood. Juvenile wood was formed when the stem was of small diameter [Fig. 1(*a*)], and height-growth was rapid. The shape of juvenile wood cells often differs somewhat from that of mature wood cells, and the relative proportions and distribution of major chemical constituents in the cell wall (cellulose, hemicellulose, and lignin) can be significantly different [4]. It is thought that structural and chemical differences are responsible for the most significant undesirable property of juvenile wood; relatively large longitudinal shrinkage [5,6]. This aspect will be discussed in detail in the section on wood dimensional stability.

Reaction wood occurs in both hardwoods and softwoods, although the nature of the chemical and structural cell changes are different in each. Reaction wood in softwoods is known as compression wood due its position of formation, on the underside of the lean. Compression wood cells are generally shorter and misshapen compared to normal cells, have thick walls with a high percentage of lignin, and appear as dark bands on the end-grain of a board [Fig. 3(*a*)]. Though the density of compression wood is high, its relative strength is low. Compression wood tends to have high longitudinal shrinkage compared to normal wood, often resulting in cracks across the grain if only part of the board is compression wood [Fig. 3(*c*)].

In hardwoods, reaction wood is formed on the upper side of the lean, and is called tension wood. Tension wood is characterized by the formation of special cells with drastically altered cell wall characteristics. A common symptom of tension wood is fuzzy grain as seen on the longitudinal surface of a planed board [Fig. 3(*b*)]; the fuzzing effect is caused by the failure of the soft, specialized wall layers to be cut cleanly by planer knives.

Adhered (Bonded) Wood Products

Bonded Wood Products in Building Construction

Construction plywood panels have been widely used since the mid 1950s as sheathing and structural subflooring. Oriented strand board (OSB) panels have been used in these applications for about two decades. OSB currently commands a larger share of this market than plywood. Plywood and OSB panels used as sheathing or subflooring transfer loads to and between the building's framing members, and provide racking resistance to wall, roof, or floor systems. Plywood and OSB are also used in fabrication of structural frame components of buildings, for example, as web members of box beams or I-joists or as the facings of structural insulated panels. Glued laminated (glulam) timbers have been used for decades as structural frame elements in buildings. "Structural composite lumber" is a collective term that includes laminated veneer lumber (LVL), parallel strand lumber (PSL), laminated strand lumber (LSL), and, oriented strand lumber (OSL), fabricated to serve as framing material [7]. Structural composite lumber evolved from plywood and OSB manufacturing technologies. Plywood, OSB, glued laminated timbers and structural composite lumber are fabricated from pieces of wood, (collectively termed wood constituents), bonded into integral panels or members with adhesives. For the past two decades, waterproof (or nearly waterproof) synthetic polymeric adhesives have been used.[3] Plywood, OSB, and structural composite lumber are fabricated with waterproof adhesives and are hot-pressed. Glulam timbers are fabricated with either waterproof or nearly waterproof adhesives. They may be pressed with application of radio-frequency energy to heat the gluelines, but the wood laminations are not heated to as high temperatures as are attained by the wood constituents in structural panels or in structural composite lumber during hot pressing. The wood constituents in structural bonded wood products (plywood, OSB, glulam, and structural composite lumber) are, for the most part, indistinguishable chemically from the wood raw material from which they were derived Composition of structural bonded wood products is, by mass, roughly 90 % or more chemically-unmodified wood. Glued laminated timbers and plywood and OSB are usually sold as commodity products. Structural composite lumber is usually marketed on a proprietary basis.

Wood-based panels are also used in largely nonstructural roles in building construction. Wood fiberboard panels at densities of between 200 and 450 kg/m^3 are sometimes used as wall sheathing. Wood fiberboard sheathing panels usually incorporate resinous or asphaltic materials to inhibit water absorption. Wood fiberboards at densities of between 500 and 800 kg/m^3 (hardboards) are sometimes used as wall cladding material (siding) or as exterior trim; these typically incorporate thermosetting waterproof adhesive, the amount depending on the manufacturing method. In North America, particleboard and medium density fiberboard (MDF) (at densities of roughly 640 to 850 kg/m^3) are usually bonded with urea-formaldehyde (UF) adhesives. Urea-formaledhyde bonds are not waterproof, and UF-bonded particleboard and MDF are therefore used in interior locations. These products are commonly used in kitchen and bathroom countertops, where exposed faces and edges are overlaid with laminate to isolate the board from wetting. UF-bonded particleboard is sometimes used as mobile home floor decking; with this exception, UF-bonded particleboard is not used structurally in buildings in North America. The core material in laminated interior flooring, which may be subject to wetting in limited amounts, is usually specially-made particleboard or, more commonly, specially-made MDF fabricated with a comparatively water-resistant bonding system (often incorporating melamine resin). Laminated interior flooring is sold as a proprietary product, the specially-made MDF or particleboard core being an integral part of the finished product. Hardboard exterior trim is also sold on a proprietary basis. All other nonstructural wood-based panels are usually marketed as commodity products. Composition of nonstructural wood-based panels is, like structural bonded wood products, roughly 90 % or more wood material.

Fiber-cement board is finding widespread use as a exterior cladding (siding) material. Fiber-cement board is in some ways similar to the manufactured bonded wood products mentioned previously, but also differs in a number of important ways. In fiber-cement board, wood-derived fiber is, in mass proportion, a minor (although critically important) component. Silica and portland cement are, by mass, the major components of fiber-cement board. The fiber in fiber-cement board is unbleached pulp fiber; it is composed of individual wood cells. The separation of individual wood cells in pulp is facilitated by chemical removal of a portion of the wood's lignin; the fiber thus is not chemically identical to the wood from which it was produced. Portland cement, rather than an organic polymeric resin, is used as the binding agent. Fiber-cement sidings are sold as proprietary products. The moisture-related behaviors of fiber-cement siding are not addressed in this manuscript, in part because the authors could not locate such information in the research literature, and in part because the mass proportion of wood in the product is less than 50 %.

Composite materials composed of comminuted wood (commonly wood flour or fibers) and thermoplastic synthetic polymers (commonly polyolefins or polyvinyl chloride) have become widely used as exterior decking, and are also used to fabricate extruded parts for fenestration units. Wood/plastic composite materials are typically manufactured using extrusion technology developed in the plastics processing industry. The materials are sold as proprietary products. The moisture-related behaviors of wood/plastic composite materials are not addressed in this chapter; the reasons are similar to those outlined previously relating to fiber-cement siding.

Characteristics of Plywood and LVL

Plywood and LVL are fabricated from sheets of veneer, produced by lathe peeling of veneer bolts of roughly 2.5 m length. Lathe peeling yields veneer sheets with tangential-grain faces. In LVL, grain orientation in most, if not all, veneer sheets is parallel with the longest axis of the member. In

[3] Glulam timbers in buildings constructed before the mid 1960s may be adhered with casein glue. Plywood in buildings constructed before the early 1970s may be adhered with soy- or blood-protein glues. These older adhered wood products are more susceptible to water-induced delamination than are contemporary bonded wood products.

contrast, plywood is of cross-laminated construction; grain orientation in face veneers is parallel with panel long dimension, but orientation of grain in some or all interior plies is perpendicular to the panel length. In 3-ply and 4-ply plywood, grain direction of all interior plies is perpendicular panel length; in 5-ply plywood, grain direction in the center ply is parallel with panel length, and grain direction in the cross band plies between the core and face plies is perpendicular to panel length. The cross-laminated construction of plywood results in roughly equivalent along-panel and across-panel moisture-induced dimensional change.

Plywood panels may have edge veneer joints within plies, but the plies do not contain end joints. LVL members in contrast, will generally be longer than the veneer bolts from which their veneer sheets were peeled; the members will thus contain butt or overlap veneer end joints in all ply layers through the member thickness. For structural reasons, veneer end joints in LVL lumber are staggered. LVL members are most commonly installed with structural loads applied edgewise (joist configuration). Therefore, provided that the veneer end joints are staggered and adhesive bonds between plies are functional, the presence of veneer end joints in LVL members is not considered of structural consequence. In summary, the wood constituents (veneers) in plywood or LVL have an along-grain dimension of somewhere between the width of a plywood sheet (commonly 1.2 m) and the length of the veneer bolt from which the veneer was peeled (commonly about 2.5 m). Veneer sheets in plywood and LVL are, in general, neatly stacked. When manufacturing commercial softwood plywood, a compaction pressure of roughly 1.2 MPa (175 psi) will bring the veneer surfaces to be bonded into sufficiently close contact for adequate bonding [8].[4] These consolidation pressures do not exceed the compressive strength of wood perpendicular to the grain; compaction of the wood is largely restricted to projecting high spots on veneer surfaces. Plywood tends to be 5 to 10 % denser than the wood from which it was fabricated;[5] some of the densification comes from filling voids (including cell lumina on veneer surfaces) with adhesive. With LVL, consolidation pressures and glue spreads may be higher than in plywood,[6] and the veneers may be selected for their strength and stiffness (and thus have higher than average density). LVL may be in excess of 30 % denser than randomly-selected wood of the same species.

Construction plywood[7] has waterproof and boil-proof[8] bonds. This was not, however, always the case. Until its most recent revision [15], the U.S. Product Standard for construction plywood recognized plywood classes with Interior and Intermediate (or Exposure 2) bonds. Plywood panels classed Interior were commonplace prior to the 1970s.[9] Today, construction plywood panels are classed as either Exterior or Exposure 1. Exterior panels are intended for uses such as exterior wall cladding (siding). Exterior panels contain high grade veneers, and (with the protection afforded by exterior finishes) are expected to withstand indefinite weather exposure. Exposure 1 panels, in contrast, contain lower veneer grades. Although bonded with the same adhesives as Exterior panels, Exposure 1 panels are not intended for indefinite exterior exposure. Fabrication with waterproof and boil-proof adhesive allows Exposure 1 panels to withstand multiple cycles of wet-dry exposure as may occur during construction, allowing for jobsite delays. Exposure 1 panels may contain significant defects (e.g., knots) in their face plies. Face ply delamination at the defects can be expected if the panels are exposed indefinitely to the weather, particularly if a significant defect in a face ply happened to line up with a defect in a core or cross-band ply.

The bonds in LVL are also fully waterproof and boil-proof but, like Exposure 1 panel product,s are not intended for in-service exposure to the weather. The structural frame elements of wood frame buildings are expected to be protected from weather exposure,[10] insofar as they are relatively difficult to replace, and because their integrity is generally crucial to structural safety.

Characteristics of Wood Composition Materials

Maloney [16] suggested the term "wood composition material" as a collective category for a variety of materials (e.g.: fiber insulation board, hardboard, particleboard, MDF and OSB), which are fabricated of comminuted[11] wood, and bonded into panels or members, usually with adhesives. Fiber insulation board is the sole wood composition material in which bonding between constituents is not provided primarily by synthetic polymeric adhesive,[12] and with this exception, wood composition materials are usually denser (commonly about 30 %) than the wood from which they were fabricated [16]. Functional wood composition building materials can be economically fabricated from wood raw materials that would be unmerchantable as sawlogs or veneer logs, (for example, small-diameter trees from woodland

[4] Pressure required depends on adhesive consistency and is inversely related to smoothness and conformability of veneer surfaces [9]. Geimer et al. [10] successfully pressed smoothly cut (sliced) pine veneers into plywood using 1.03 MPa compaction pressure. Jokerst and Lutz [11] and Jokerst and Geimer [12] pressed plywood fabricated from lathe-cut veneers at 175 psi compaction pressure, (the same pressure cited by Baldwin [8] as adequate).

[5] A targeted compaction of from 3 to 5 % was promulgated by Rinne [13] as necessary for assuring adequate consolidation of plywood in industrial operations, where some variation in veneer thickness is expected.

[6] Fabrication parameters for LVL are not available [14].

[7] Construction plywood is termed "structural plywood" in the most recent version of the Department of Commerce Product Standard.

[8] Boil-proof adhesive bond lines will withstand immersion in boiling water for two hours without perceptible delamination. To withstand such exposure, the bond line must have sufficient elasticity to withstand strain induced by wood substrate movement, and must be chemically stable (neither dissolve nor undergo hydrolysis).

[9] This sentence comes, virtually verbatim, from Baker [17].

[10] Isolation of critical structural elements from the weather is a time-proven strategy in structures of many different types. The main steel suspension cables of the George Washington, Golden Gate, Mackinac, and Verrazano Narrows Bridges are enclosed in cable covers that isolate them from the weather.

[11] In the parlance of wood composition materials, "comminuted" means that the individual wood pieces have a dimension along the grain that is usually less than 0.2 m, with width and thickness dimensions not exceeding roughly 90 mm and roughly 1.5 mm, respectively; in other words the pieces are relatively small as compared to veneer sheets. The wood piece dimensions are frequently less than half these dimensions, but the pieces generally have length dimensions that are many times their thickness dimensions and could not be accurately characterized as minutely fine or pulverized (as some dictionary definitions of "comminuted" suggest).

[12] As indicated previously, asphalt or rosin "sizing" is commonly incorporated in fiberboard produced for use as sheathing. These materials apparently provide some bonding between fibers, but are added primarily to prevent water-induced disruption of the inter-fiber hydrogen bonds, which are responsible for the primary bonding [18].

TABLE 1—Moisture content of wood in equilibrium with stated temperature and relative humidity (source: Wood Handbook).

Temperature		Moisture Content (%) at Various Relative Humidity Values																		
°C	°F	5 %	10 %	15 %	20 %	25 %	30 %	35 %	40 %	45 %	50 %	55 %	60 %	65 %	70 %	75 %	80 %	85 %	90 %	95 %
−1.1	(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
4.4	(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
10.0	(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
15.6	(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
21.1	(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
26.7	(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
32.2	(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
37.8	(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
43.3	(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
48.9	(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
54.4	(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
60.0	(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
65.6	(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

thinning operations). Some wood composition materials are fabricated primarily from residues produced by other wood processing industries. Construction and urban wood waste is sometimes commercially utilized in the raw material mix used for fabrication of particleboard and MDF.

Comminuted wood constituents are, individually, substantially shorter, thinner, and narrower than any dimensions of the panel or member that they form. Integrity of a wood composition panel or member thus depends on a series of lap and bridge joints between the wood constituents. Inter-leaving of constituents in a wood composition material allows for formation of lap and bridge joints during pressing, but bond formation depends on constituent surfaces being brought into close contact during adhesive cure. The pressures required to bring constituents into close contact during hot-pressing result in noticeable densification of wood composition materials. Total surface area of the (comminuted) constituents in a wood composition panel is usually about an order of magnitude greater than the surface area of the constituents in a similar-sized panel or member fabricated with veneer sheets. Specific adhesive coverage (mass of adhesive per unit surface area of the wood constituents to be bonded) is not calculated for wood composition materials [9], but is recognized as being appreciably lower than in panels or members fabricated from veneer sheets. Adhesive application to the constituents in wood composition material is discontinuous, although adhesive flow during hot pressing can result in areas of more or less continuous bonding between constituents [19]. Where more or less continuous bonding has been observed, it was evident that particles had been brought into very close contact by application of substantial pressure in the direction of panel thickness. In pressing of wood composition materials, the pressure exerted changes during the pressing cycle, with peak pressure occurring as the mattress of particles or fibers first reaches its fully compacted thickness [20]. The literature suggests 2–8 MPa (300–1000 psi) as a reasonable estimated range of peak compaction pressure during production of commercial wood composition materials [21–23]. Some crushing of the cellular structure in individual wood constituents occurs during pressing of wood composition materials [24], attributable in large part to the compaction pressures involved.[13] Wang and Winistorfer [25] measured an average compaction of roughly 24 % in pine flakes pressed in mattresses using a press cycle believed to be representative of commercial flakeboard production.

Insofar as the individual constituents of wood composition materials are relatively short; they collectively have appreciable end-grain area through which liquid water might be rapidly absorbed. All commercial wood composition materials therefore contain a sizing agent (most commonly petroleum wax) to inhibit liquid water absorption. The adhesive system may also influence water absorptivity of a wood composition material, and may thus be a factor in the manufacturer's choice of adhesive system. Wood composition materials can be manufactured to have low levels of liquid water absorption, for use in applications where this is important [26]. PSL, LSL, and OSL, which are wood composition materials, are (as indicated previously), bonded with waterproof and boil-proof binder systems. Adhesive contents in PSL, LSL, and OSL (and thus production costs) are commensurate with the products' relatively critical end use (and higher unit market price). Nonetheless, and as also indicated previously, PSL, LSL, and OSL are not intended for exterior use.

Moisture Content

The moisture content of wood and wood products is defined as the mass (weight) of water in the member expressed as a fraction, usually a percentage, of the oven-dry mass of the member.

Wood placed in an environment of constant atmospheric conditions and isolated from liquid water, will eventually reach a moisture content in equilibrium with that environment, termed "equilibrium moisture content" (EMC). EMC is a function of the ambient relative humidity, and, to a lesser extent, the temperature. The EMC at any set of atmospheric conditions below 100 % RH, will be below the fiber saturation point. The relationship between EMC, temperature and relative humidity is shown in Table 1. At low and

[13] In a mattress of comminuted wood constituents undergoing compaction, the compaction pressure has an uneven spatial distribution within the panel plane; this is recognized as accentuating the crushing of cellular structure within some of the constituents.

TABLE 2—Moisture contents of wood panel products in equilibrium room temperature and stated relative humidity.

RH	Constr. ply-wood APA[a]	Constr. ply-wood NIST[b]	OSB APA	OSB NIST	Particle-board (interior) MSU[c]	Particle-board (interior) NIST	Fiber-board sheathing FPL[d]	Fiber-board sheathing NIST	Hardboard FPL[e]	Hardboard siding FPL[f]
10	1.2	2.3	0.8	1.7	3	1.9		2.1–2.3		
20	2.8	3.7	1.0	3.0	5–6	3.1		2.5–3.6		
30	4.6	4.8	2.0	4.1	6.2–7.5	4.1	3.4–6.1	2.9–4.7	2.4–5.3	
40	5.8	5.9	3.6	5.3	7–9.5	5.2		3.4–5.9		5–7
50	7.0	7.2	5.2	6.6	8–10	6.3	4.4–7.7	4.0–7.4	3.2–6.8	
60	8.4	8.7	6.3	8.1	8.5–11	7.7		4.9–9.3		7–10
70	11.1	10.8	8.9	10.1	9.5–12.2	9.8		6.2–12.0		
80	15.3	13.7	13.1	12.9	10.5–14	12.2		8.4–16.6	8.5–11.5	9–13.5
90	19.4	18.5	17.2	17.3	14–16	16.5	9.2–16.5		9.0–14.9	

[a]Zylkowski [37] (values correspond with Zylkowski [38] in which the data are for sorption direction, dry weight measured by oven drying).
[b]Richards et al. [34]: (average of adsorption and desorption for individual commercial products, dry weight measured by dessicant drying).
[c]Suchsland [33] (one commercial board, range indicates hysteretic effect, dry weight measured by oven drying).
[d]Nordenson [39]: (range in values indicates differences between different commercial products, adsorption direction only, dry weight by oven drying).
[e]Myers and McNatt [40].
[f]Carll and TenWolde [35] (range indicates hysteretic effect, dry weight by oven drying).

moderate levels of relative humidity, the values in Table 1 may be applied to wood of virtually any species. At high RH levels, values in the table should not be considered precise. Spalt [27], Hedlin [28], Choong and Manwiller [29], and Ahmet et al. [30] found essentially no between-species differences in EMC value at low and moderate levels of RH. In contrast, at RH levels of 71 % or higher Choong and Manwiller [29] and Ahmet et al. [30] observed between-species differences in EMC as high as 3–4 percentage points; Hedlin [28] observed larger between-species differences at very high RH (above 95 %). Spalt [27] proposed an explanation for the relatively larger between-species differences in EMC that occur at high relative humidity levels. This explanation, in which wood extractives play a mechanistic role, was evidently supported by the subsequent works of Wangaard and Granados [31] and by Choong [32].

Wood in service is exposed to both long-term (seasonal) and shorter-term (for example, daily) atmospheric changes in relative humidity and temperature. Wood is therefore always undergoing at least slight changes in moisture content. These changes are usually gradual, and short-term fluctuations tend to influence only the wood surface. Moisture content changes can be retarded, but not prevented, by surface coatings such as paint, exterior stain, or varnish.

The EMC that wood will attain when it adsorbs atmospheric moisture from an initially drier condition is always less than the EMC that the wood would reach if it were placed in the same environment, but instead reached moisture equilibrium from an initially wetter condition. This phenomenon is known as sorption hysteresis. The ratio of adsorption EMC to desorption EMC is commonly about 0.85. The EMC that wood will reach, however, in its first desorption from the green condition (that of freshly sawn wood) is greater than in any subsequent desorption. Data in Table 1 were derived primarily under conditions described as "oscillating desorption," which is thought to represent a condition midway between adsorption and desorption, and

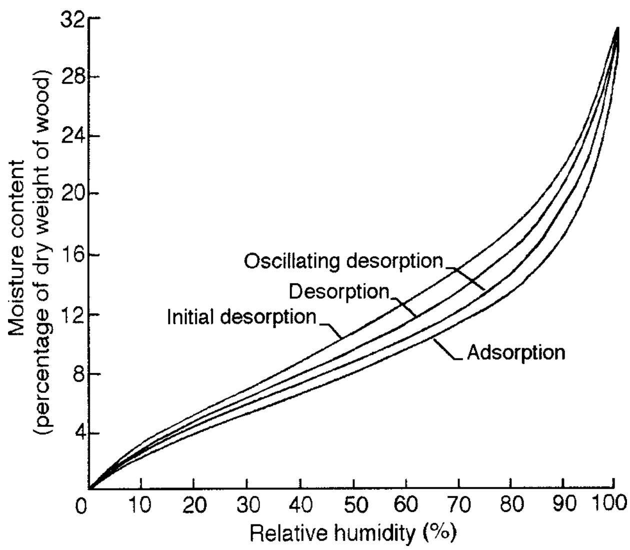


Fig. 4—Moisture content-relative humidity relationship at 20°C for wood under adsorption and various desorption conditions (source: *Wood Handbook*).

TABLE 3—Typical moisture contents of bonded wood products as shipped from production plants (courtesy APA—The Engineered Wood Association).

OSB, Particleboard and Hardboard	Plywood and Structural Composite Lumber	Glu-lam Timbers
3–5 %	6–8 %	11–12 %

TABLE 4—Equilibrium moisture content of wood, exposed to outdoor atmosphere, in several U.S. locations (source: Wood Handbook).

		Equilibrium Moisture Content[a]											
State	City	Jan.	Feb.	Mar.	Apr.	May	June	July	Aug.	Sept.	Oct.	Nov.	Dec.
AK	Juneau	16.5	16.0	15.1	13.9	13.6	13.9	15.1	16.5	18.1	18.0	17.7	18.1
AL	Mobile	13.8	13.1	13.3	13.3	13.4	13.3	14.2	14.4	13.9	13.0	13.7	14.0
AZ	Flagstaff	11.8	11.4	10.8	9.3	8.8	7.5	9.7	11.1	10.3	10.1	10.8	11.8
AZ	Phoenix	9.4	8.4	7.9	6.1	5.1	4.6	6.2	6.9	6.9	7.0	8.2	9.5
AR	Little Rock	13.8	13.2	12.8	13.1	13.7	13.1	13.3	13.5	13.9	13.1	13.5	13.9
CA	Fresno	16.4	14.1	12.6	10.6	9.1	8.2	7.8	8.4	9.2	10.3	13.4	16.6
CA	Los Angeles	12.2	13.0	13.8	13.8	14.4	14.8	15.0	15.1	14.5	13.8	12.4	12.1
CO	Denver	10.7	10.5	10.2	9.6	10.2	9.6	9.4	9.6	9.5	9.5	11.0	11.0
DC	Washington	11.8	11.5	11.3	11.1	11.6	11.7	11.7	12.3	12.6	12.5	12.2	12.2
FL	Miami	13.5	13.1	12.8	12.3	12.7	14.0	13.7	14.1	14.5	13.5	13.9	13.4
GA	Atlanta	13.3	12.3	12.0	11.8	12.5	13.0	13.8	14.2	13.9	13.0	12.9	13.2
HI	Honolulu	13.3	12.8	11.9	11.3	10.8	10.6	10.6	10.7	10.8	11.3	12.1	12.9
ID	Boise	15.2	13.5	11.1	10.0	9.7	9.0	7.3	7.3	8.4	10.0	13.3	15.2
IL	Chicago	14.2	13.7	13.4	12.5	12.2	12.4	12.8	13.3	13.3	12.9	14.0	14.9
IN	Indianapolis	15.1	14.6	13.8	12.8	13.0	12.8	13.9	14.5	14.2	13.7	14.8	15.7
IA	Des Moines	14.0	13.9	13.3	12.6	12.4	12.6	13.1	13.4	13.7	12.7	13.9	14.9
KS	Wichita	13.8	13.4	12.4	12.4	13.2	12.5	11.5	11.8	12.6	12.4	13.2	13.9
KY	Louisville	13.7	13.3	12.6	12.0	12.8	13.0	13.3	13.7	14.1	13.3	13.5	13.9
LA	New Orleans	14.9	14.3	14.0	14.2	14.1	14.6	15.2	15.3	14.8	14.0	14.2	15.0
ME	Portland	13.1	12.7	12.7	12.1	12.6	13.0	13.0	13.4	13.9	13.8	14.0	13.5
MA	Boston	11.8	11.6	11.9	11.7	12.2	12.1	11.9	12.5	13.1	12.8	12.6	12.2
MI	Detroit	14.7	14.1	13.5	12.6	12.3	12.3	12.6	13.3	13.7	13.5	14.4	15.1
MN	Minneapolis-St. Paul	13.7	13.6	13.3	12.0	11.9	12.3	12.5	13.2	13.8	13.3	14.3	14.6
MS	Jackson	15.1	14.4	13.7	13.8	14.1	13.9	14.6	14.6	14.6	14.1	14.3	14.9
MO	St. Louis	14.5	14.1	13.2	12.4	12.8	12.6	12.9	13.3	13.7	13.1	14.0	14.9
MT	Missoula	16.7	15.1	12.8	11.4	11.6	11.7	10.1	9.8	11.3	12.9	16.2	17.6
NE	Omaha	14.0	13.8	13.0	12.1	12.6	12.9	13.3	13.8	14.0	13.0	13.9	14.8
NV	Las Vegas	8.5	7.7	7.0	5.5	5.0	4.0	4.5	5.2	5.3	5.9	7.2	8.4
NV	Reno	12.3	10.7	9.7	8.8	8.8	8.2	7.7	7.9	8.4	9.4	10.9	12.3
NM	Albuquerque	10.4	9.3	8.0	6.9	6.8	6.4	8.0	8.9	8.7	8.6	9.6	10.7
NY	New York	12.2	11.9	11.5	11.0	11.5	11.8	11.8	12.4	12.6	12.3	12.5	12.3
NC	Raleigh	12.8	12.1	12.2	11.7	13.1	13.4	13.8	14.5	14.5	13.7	12.9	12.8
ND	Fargo	14.2	14.6	15.2	12.9	11.9	12.9	13.2	13.2	13.7	13.5	15.2	15.2
OH	Cleveland	14.6	14.2	13.7	12.6	12.7	12.7	12.8	13.7	13.8	13.3	13.8	14.6
OK	Oklahoma City	13.2	12.9	12.2	12.1	13.4	13.1	11.7	11.8	12.9	12.3	12.8	13.2
OR	Pendleton	15.8	14.0	11.6	10.6	9.9	9.1	7.4	7.7	8.8	11.0	14.6	16.5
OR	Portland	16.5	15.3	14.2	13.5	13.1	12.4	11.7	11.9	12.6	15.0	16.8	17.4
PA	Philadelphia	12.6	11.9	11.7	11.2	11.8	11.9	12.1	12.4	13.0	13.0	12.7	12.7
SC	Charleston	13.3	12.6	12.5	12.4	12.8	13.5	14.1	14.6	14.5	13.7	13.2	13.2
SD	Sioux Falls	14.2	14.6	14.2	12.9	12.6	12.8	12.6	13.3	13.6	13.0	14.6	15.3
TN	Memphis	13.8	13.1	12.4	12.2	12.7	12.8	13.0	13.1	13.2	12.5	12.9	13.6
TX	Dallas-Ft. Worth	13.6	13.1	12.9	13.2	13.9	13.0	11.6	11.7	12.9	12.8	13.1	13.5
TX	El Paso	9.6	8.2	7.0	5.8	6.1	6.3	8.3	9.1	9.3	8.8	9.0	9.8
UT	Salt Lake City	14.6	13.2	11.1	10.0	9.4	8.2	7.1	7.4	8.5	10.3	12.8	14.9
VA	Richmond	13.2	12.5	12.0	11.3	12.1	12.4	13.0	13.7	13.8	13.5	12.8	13.0
WA	Seattle-Tacoma	15.6	14.6	15.4	13.7	13.0	12.7	12.2	12.5	13.5	15.3	16.3	16.5
WI	Madison	14.5	14.3	14.1	12.8	12.5	12.8	13.4	14.4	14.9	14.1	15.2	15.7
WV	Charleston	13.7	13.0	12.1	11.4	12.5	13.3	14.1	14.3	14.0	13.6	13.0	13.5
WY	Cheyenne	10.2	10.4	10.7	10.4	10.8	10.5	9.9	9.9	9.7	9.7	10.6	10.6

[a]Equilibrium moisture content values were determined from the average of 30 or more years of relative humidity and temperature data available from the National Climatic Data Center of the National Oceanic and Atmospheric Administration [44].

is thus considered a practical compromise, suitable for situations where the direction of sorption/desorption may not be known. Hysteresis is shown in Fig. 4, as is the influence of relative humidity on EMC at constant temperature. This "sorption isotherm" also indicates that the change in EMC with changing relative humidity is comparatively modest within the range of 30 to 70 % RH, whereas change in EMC with change in relative humidity is relatively great at humidity levels in excess of 80 % RH.

Bonded wood products are by mass mostly wood and thus show EMC response to atmospheric conditions similar to that of wood. Sorption isotherms of bonded wood products have a similar shape as the sorption isotherm for wood. Like wood, bonded wood products show sorption hysteresis [33–35]. Because of the adhesives (and other additives, for example, wax) incorporated in bonded wood products, and because of the high temperatures they typically experience during pressing, these products characteristically show

TABLE 5—Recommended moisture content values for various wood items at time of installation (source: Wood Handbook).

	Recommended Moisture Content (%) in Various Climatological Regions					
	Most Areas of the United States		Dry Southwestern Area[a]		Damp, Warm Coastal Area[a]	
Use of Wood	Average[b]	Individual Pieces	Average[b]	Individual Pieces	Average[b]	Individual Pieces
Interior: woodwork, flooring, furniture, wood trim	8	6–10	6	4–9	11	8–13
Exterior: siding, wood trim, sheathing, laminated timbers	12	9–14	9	7–12	12	9–14

[a]Major areas are indicated in Fig. 5.
[b]To obtain a realistic average, test at least 10 % of each item. If the quantity of a given item is small, make several tests [44].

lower EMC values than solid wood.[14] EMC values for construction plywood, OSB, wood fiberboard sheathing, hardboard, and particleboard with interior binder are presented in Table 2. This table suggests that, as with wood, variation in EMC is more pronounced at higher levels of humidity.

Initial Moisture Content of Commercial Building Materials

In freshly sawn ("green") wood, the cell walls are completely saturated with water, and some free water is also present in cell lumina. Green construction lumber is usually dried at the producing mill before dressing (surfacing or planing) to size and subsequent grading, packaging, and shipment. Construction lumber may be air-dried at the production mill. More commonly, commercial drying operations utilize dry kilns, which accelerate the drying process. The American Softwood Lumber Standard [41] specifies that lumber grade-stamped as "S-dry" must have a moisture content at dressing of no more than 19 % (or some lower moisture content as may be specified in a grading agency rule or purchase agreement). Grading agency rules generally allow for 5 % of lumber pieces to exceed 19 % (or a specified lower) moisture content at time of dressing. The expectation is thus that most pieces of construction lumber grade-stamped as dry will be at 19 % moisture content or less as shipped from the producing mill. In some locales, most notably California, buildings are commonly framed with lumber that was not commercially dried before dressing, and are grade-stamped with the designation "Green" or "S-Green."

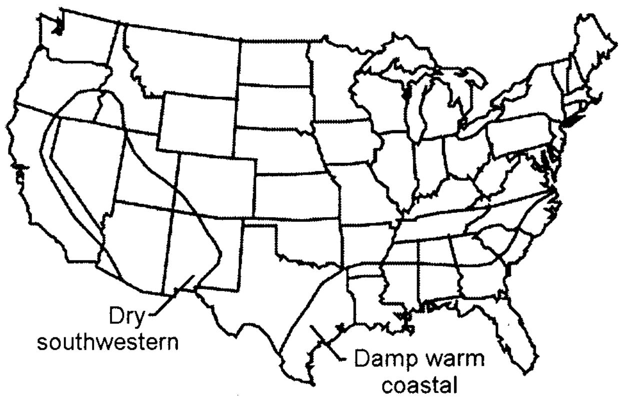


Fig. 5—Regional areas referred to in Table 5.

The processes inherent in manufacture of bonded wood products result in low material moisture contents. Control of constituent moisture content is essential during manufacture for adequate bond formation by adhesives.[15] Furthermore, hot-pressed materials undergo drying during pressing and as hot material emerges from the press. Finally, heat exposure during manufacture, (and interaction of wood with adhesive), may also result in subtle chemical changes in the wood constituents that reduces hygroscopicity and liquid water absorptivity. Moisture contents of bonded wood products as shipped from production plants are given in Table 3.

Moisture content at time of construction is influenced by the conditions to which the materials were exposed during shipment and storage. Lumber moisture content on construction jobsites varies; in lumber grade-stamped as dry it may appreciably exceed 19 % [42]. Jobsite check of moisture content by use of a commercial moisture meter is therefore prudent. Commercial handheld moisture meters provide reliable readings provided that manufacturer's use instructions are followed, (these generally concur with ASTM D4444 [43]), and compensation made where necessary for wood species or wood-based material, and temperature.

Anticipated Moisture Content in Service

Wood and wood products should be installed at moisture content levels as close as possible to the average moisture content they will experience in service in order to minimize dimensional change after installation. Dimensional change is usually most critical in finish carpentry (e.g., interior floors, exterior siding and soffits, and interior and exterior millwork and trim), although significant dimensional changes in framing lumber or sheathing can result in problems such as cracking of exterior cement plaster (stucco), or interior plasterboard. The in-service moisture content of exterior wood (siding and exterior trim) depends on outdoor relative humidity and exposure to rain and sun, or both. The in-service moisture content of interior wood primarily depends on indoor relative humidity. Anticipated outdoor EMC values for various locations in the United States are given in Table 4. It should be noted that the values in this

[14] This sentence is paraphrased from Koch [36].

[15] Control of moisture level into hot presses is also necessary to prevent excessive within-press steam generation that would cause explosive delamination upon press opening.

table are based on ambient atmospheric conditions and thus assume neither absorption of rainwater nor exposure to solar radiation.

Recommended moisture content values for wood items at time of installation are given in Table 5. The recommended values for exterior wood are in general accord with those in Table 4 and thus account for neither solar exposure nor appreciable absorption of rainwater. The values were developed for exterior siding, soffits, and trim. In these applications, rainwater exposure may not occur (e.g., soffits), and where it occurs (siding and trim) will primarily be from windblown rain (or roof splash), and will largely be from one (the exterior) side. In addition, exterior siding or trim is generally painted or stained; the applied finish will retard absorption of rainwater. The authors recommend that siding and trim installed on walls exposed to direct solar radiation be a couple percentage points drier than the values listed in Table 5 at installation.[16] The values in Table 5 for interior wood assume that the building is well-ventilated, has no unusual moisture sources, and is not air-conditioned. Average EMC values for interior wood in air-conditioned buildings will likely be toward the low end of the range listed for individual pieces in Table 5, provided that the air-conditioning equipment has been selected and sized to provide humidity control. Wood installed in basements or crawl spaces may experience higher moisture contents than the maximum value (14 %) listed in Table 5. Seasonal peak framing lumber moisture contents approaching 20 % have been recorded in crawl spaces [47].[17] With appropriate moisture control practices, wood in insulated walls and in attics should not reach moisture contents much outside the range of values listed in Table 5.

Tables 4 and 5 are not intended for application to bonded wood products. As discussed previously, these products usually have lower EMC values than the wood from which they were fabricated, and EMC values can vary from product to product. A reasonable approximation is to acclimate bonded wood products to equilibrium with 30 to 40 % RH for interior applications, and to 55 to 65 % RH for exterior applications. In applications where dimensional movement can be accommodated, wider acclimation bounds than specified above may be acceptable.

The *APA Engineered Wood Handbook* assumes that structural wood-based panels or structural composite lumber (which as discussed above have lower EMC values than wood) will not exceed 16 % MC in service. This value roughly corresponds with a 19 % MC value for wood (compare EMC values in Tables 1 and 2). As will be discussed later, a wood moisture content of 20 % (roughly the EMC at room temperature and 90 % RH) is commonly considered the "not to exceed" value for confidence in preventing propagation of wood-destroying fungi.

[16] This recommendation is based on: (a) measured in-service siding moisture contents on southeast- and southwest-facing walls on buildings in Florida than were roughly 1.5 percentage points lower than on northeast-facing walls on the same buildings [45], (b) measured in-service wood-siding moisture contents on south-facing walls in southern California below 5 % [46], and (c) the lead author's unpublished measurement of 6–9 % EMC at 22°C and 50 % RH in wood siding removed from sun-exposed exterior walls of buildings in Wisconsin and New York (these EMC values ranged from 0–3 % lower than the value at this set of conditions shown in Table 1).

[17] Crawl spaces monitored by Stiles and Custer [47] included ones that would likely have been judged "musty," but did not include any craw spaces which showed evidence of standing water nor any in which decay was observed.

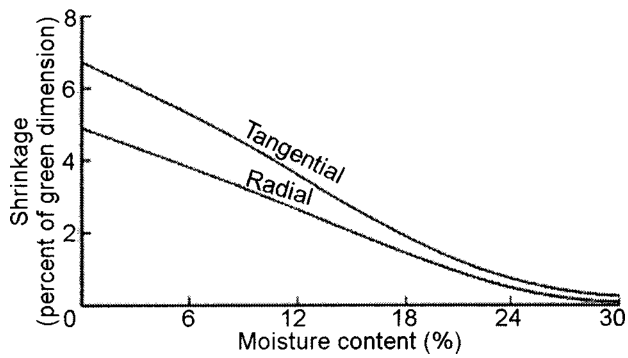


Fig. 6—Typical moisture content-shrinkage curves (source: *Wood Handbook*).

Dimensional Changes

Dimensional Stability of Wood

Below the fiber saturation point, wood changes dimension with changes in moisture content. It shrinks when losing moisture from the cell walls and swells when gaining moisture in the cell walls. Wood is orthotropic: it shrinks or swells most in the tangential direction, about half as much in the radial direction, and only slightly in the longitudinal direction. Dimensional movement of lumber has traditionally been measured as shrinkage from green (the condition at which lumber is sawn) to oven-dry. Dimensional movement is usually correlated with density, and is roughly proportional to change in moisture content. Figure 6 shows typical relationships between shrinkage and moisture content in tangential and radial directions. It indicates that the relationship between dimensional movement and moisture content is not linear over the entire moisture content range from fiber saturation to oven dry, but that it is linear from roughly 20 % moisture content to oven dry. Dimensional change of a given piece of wood depends on its density and growth characteristics. Figure 7 indicates that dimensional change can vary appreciably between pieces of wood thought to be similar. Changes in dimension in tangential or radial directions can be estimated using the following formula.

$$\Delta D = D_i[C_R(M_f - M_i)] \quad (1)$$

where ΔD is change in dimension, D_i length at initial MC, C_R dimensional change coefficient in radial anatomic direction, (alternatively, C_T, dimensional change coefficient in tangential anatomic direction), M_f moisture content (%) at end of change, and M_i moisture content (%) at start of change. Values for C_R and C_T are given in Table 6.

The coefficient values are based on dimension at 10 % MC and the assumption of a linear relationship between dimension and moisture content change over the entire hygroscopic range. The coefficients may therefore slightly under estimate dimensional movement across the range of 0–20 % moisture content, and over estimate it across the range of 20 % moisture content to fiber saturation. Variation in dimensional change between pieces of wood, (Fig. 7), suggest that Eq (1) should not be counted on to precisely predict dimensional movement of individual pieces of wood.

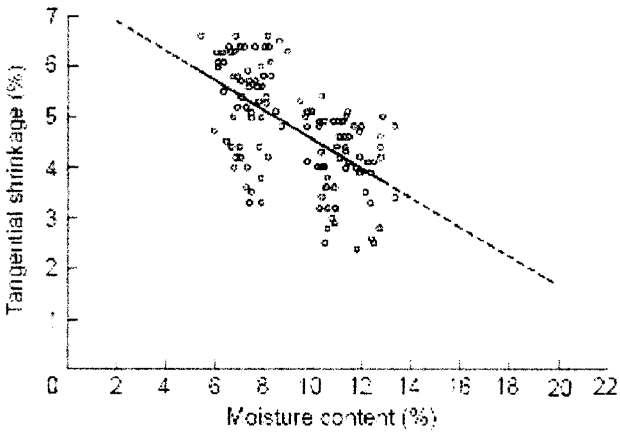


Fig. 7—Variation in individual tangential shrinkage values of several Douglas-fir boards from one locality, dried from green condition (source: *Wood Handbook*).

Movement of wood in either transverse direction (radial or tangential) can be of substantial consequence when wet framing lumber is used for floor joists in platform construction. The balloon framing technique, which was widely used in the 1920s and earlier (and which has been largely replaced by the platform framing technique), was designed to accommodate relatively large amounts of across-grain shrinkage of floor and rim joists. In construction of log buildings, attention must be paid to dimensional change in wall heights (which are across the grain direction). In log buildings with gable roofs there is the potential for significant differential movement between roof eave lines and roof peaks. In log buildings there is also potential for significant differential change between the height of openings and of fenestration units installed in them; competent design of log buildings will anticipate and allow for such differential movement.

TABLE 6—Dimensional change coefficients. C_R and C_T, in radial and tangential directions respectively, for various species of wood (per percent change in moisture content) (source: Wood Handbook).

Species	C_R	C_T
Aspen, quaking	1.2×10^{-3}	2.3×10^{-3}
Birch, yellow	2.6×10^{-3}	3.4×10^{-3}
Cottonwood, black	1.2×10^{-3}	3.0×10^{-3}
Locust, black	1.6×10^{-3}	2.5×10^{-3}
Maple sugar	1.6×10^{-3}	3.5×10^{-3}
Red oak, commercial	1.6×10^{-3}	3.7×10^{-3}
White oak, commercial	1.8×10^{-3}	3.7×10^{-3}
Walnut, black	1.9×10^{-3}	2.7×10^{-3}
Yellow-poplar	1.6×10^{-3}	2.9×10^{-3}
Cedar, northern white	1.0×10^{-3}	2.3×10^{-3}
Cedar, western red	1.1×10^{-3}	2.3×10^{-3}
Douglas-fir, interior	1.5×10^{-3}	2.5×10^{-3}
Fir, grand	1.1×10^{-3}	2.4×10^{-3}
Hemlock, western	1.4×10^{-3}	2.7×10^{-3}
Larch, western	1.6×10^{-3}	3.2×10^{-3}
Pine, eastern white	7.1×10^{-4}	2.1×10^{-3}
Pine, jack	1.3×10^{-3}	2.3×10^{-3}
Pine, loblolly	1.7×10^{-3}	2.6×10^{-3}
Pine, ponderosa	1.3×10^{-3}	2.2×10^{-3}
Pine, slash	1.9×10^{-3}	2.7×10^{-3}
Redwood, second growth	1.0×10^{-3}	2.3×10^{-3}
Spruce, black	1.4×10^{-3}	2.4×10^{-3}
Spruce, white	1.3×10^{-3}	2.7×10^{-3}
Spruce, Sitka	1.5×10^{-3}	2.6×10^{-3}

Source: Forest-Products Laboratory [44].

Dimensional movement in the longitudinal direction has traditionally been considered as negligible. The *Wood Handbook* [44] states that the average values of longitudinal shrinkage from green to oven-dry normally ranges between roughly 0.1 and 0.2 %. This range of values assumes that the wood contains neither juvenile nor reaction wood. Juvenile and reaction wood are, however, present to some degree in commercial lumber; softwood lumber grading rules require exclusion of neither juvenile nor compression wood. Softwood lumber grading rules also commonly allow slope of grain (observed as diagonal grain) of from 1-in-8 to 1-in-14, depending on grade. It therefore is not particularly surprising that green to OD lengthwise shrinkage values exceeding 0.3 % occur with some regularity in commercial lumber. Longitudinal shrinkage of 0.6 % has been observed in second-growth redwood [48,49], and longitudinal shrinkage as high as 2 % has been observed in rapidly-grown, second growth, southern pine [48]. The degree of longitudinal shrinkage that Ying et al. [6] observed in fast-growth loblolly pine usually exceeded 0.5 % in the first ten growth rings. Hann [5] observed longitudinal shrinkage values in baldcypress that were similar to those observed by Ying et al. [6] in loblolly pine or by Chern [49] in redwood. All researchers found that within-species longitudinal movement in second-growth material commonly varied by a factor of four or more. Predictions of longitudinal movement of any given piece of lumber are therefore likely to be imprecise. Moisture control appears to be the most reliable way to avert problems related to longitudinal movement of lumber. Hann [5] found that longitudinal movement between EMC at 80 % RH and EMC at 30 % RH was always less than half of that between the green and ovendry conditions. Gorman [50] found that longitudinal movement of juvenile wood was a factor in seasonal arching of roof trusses, but that truss arching could often be controlled by management of moisture conditions. Percival [51] indicated that problems associated with truss arching could largely be controlled by a combination of construction practice and moisture control.

Dimensional Stability of Bonded Wood Products

Dimensional movement of glulam timbers and that of LVL members are essentially indistinguishable from that of wood under similar environmental conditions. As indicated previously, these products are manufactured under well-controlled moisture conditions, and thus usually undergo less dimensional change than construction lumber during the period from construction through the first year of building occupancy.

The dimensional movement characteristics of wood-based panels generally differ from those of wood. The three principal dimensional axes for wood-based panels are: along the panel, across the panel, and through the thickness of the panel. Proportional changes are consistently greatest through the thickness of panels. Because nominal panel thicknesses are generally 20 mm or less, high proportional

TABLE 7—Published values for within-plane dimensional movements of wood-based panel products.

Material	Source	RH Range (unless otherwise specified)	Linear Expansion Along Panel (%)	Linear Expansion Across Panel (%)
Construction plywood	Zylkowski [38]	Ovendry–soak	0.15–0.29	0.20–0.40
Construction plywood	Talbott et al. [52]	30 %–92 %	0.04–0.06	0.08
OSB	Zylkowski [38]	Ovendry–soak	0.19–0.28	0.36–0.63
OSB	Wu and Suchsland [53]	35 %–85 %	0.13–0.17	0.19–0.32
Waferboard	Alexopolous and Szabo [54]	Ovendry–soak	0.25–0.27	0.31–0.38
Waferboard	Talbott et al. [52]	30 %–92 %	0.15	0.19
Sheathing fiberboard	Lehmann [55]	30 %–90 %	0.37–0.53 (average of along and across)	
Sheathing fiberboard	Luxford [56]	50 %–97 %	0.20–0.47 (direction not specified–likely the average of along and across)	
Sheathing fiberboard	ASTM C 208-95 [57]	50 %–90 %	0.5–0.6 maximum allowable (average of along and across), (dependent on structural grade)	
Particleboard (interior)	Lehmann [55]	30 %–90 %	0.45–0.46 (average of along and across)	
Particleboard (medium-density interior)	ANSI A208.1–1999 [58]	50 %–80 %	0.35 maximum allowable (average of along and across)	
Hardboard siding	Biblis [59]	30 %–90 %		0.19–0.29 (panel siding)
Hardboard siding	Biblis [60]	35 %–90 %	0.19–0.26 (lap siding)	
Hardboard siding	ANSI/AHA A135.6-1998 [61]	30 %–80 %	0.31–0.35 max (lap siding) (dependent on panel thickness)	0.31–0.35 max (panel siding) (dependent on panel thickness)
Hardboard siding	ANSI/AHA A135.6-1998 [61]	30 %–90 %	0.36–0.40 max (lap siding) (dependent on panel thickness)	0.36–0.40 max (panel siding) (dependent on panel thickness)

change usually does not result in large measured dimensional change. Proportional dimensional changes along and across wood-based panels generally exceed that of normal wood in the longitudinal direction, and are significantly less than that of wood in radial or tangential directions. Dimensional movement characteristics of commodity panel products can generally be found in the research literature. Dimensional movement characteristics of proprietary products, if available, must generally be obtained from the respective manufacturers.

Values in the research literature for dimensional change along the length or across the width of wood-based panels are most commonly reported as percentage increase in dimension (linear expansion) between a low humidity and a high humidity condition (in accord with ASTM D1037 [52]) or between a dry and a soaked condition. Published values are given in the Table 7.

Dimensional movement in the plane of wood-based panels, reported as a function of moisture content, is not commonly found in the research literature, but is available. Suchsland [33] and Lang and Loferski [62] have presented dimensional change coefficients per percent change in moisture content. Their measurements were taken between two moisture conditions. Using such coefficients, an equation of the same form as Eq (1) can be used to predict dimensional change.

$$\Delta D = D_i[C_{along}(M_f - M_i)] \qquad (2)$$

where ΔD, D_i, M_f, and M_i are as in Eq (1) and C_{along} is dimensional change coefficient for the panel long dimension (alternatively, C_{across} for dimensional change coefficient across the panel width). Values of C_{along} and C_{across} are given in Table 8. A comparison with the dimensional change coefficient values for wood in radial and tangential directions (Table 6) indicates that proportional change across the widths of wood-based panel products is significantly less than that of wood in either radial or tangential directions.

Talbott et al. [52], Zylkowski [38], and Wu and Suchsland [63] made dimensional change measurements over multiple (more than two) different moisture conditions. Zylkowski [38] and Wu and Suchsland [63] found the relationship between dimensional movement in the plane of the panel and moisture content to be nonlinear. Within limited moisture ranges, however, linear approximations can be useful for estimating panel dimensional change. Values of C_{along} and C_{across}, derived from values reported by Zylkowski [38] are shown in Table 9.

TABLE 8—Within-plane dimensional change coefficients for panel products obtained from two-point measurement protocols.

Material	Source	Moisture Range	C_{along}	C_{across}
Construction plywood	Lang, Loferski [62]	45 % RH–95 % RH	1.8×10^{-4}	2.3×10^{-4}
OSB	Lang, Loferski [62]	45 % RH–95 % RH	2.2×10^{-4}	2.3×10^{-4}
Particleboard (interior)	Suchsland [33]	40 % RH–90 % RH	1×10^{-4}–5.6×10^{-4} (avg. of both directions)	

The major concern with within-plane dimensional movement of wood-based panels is the potential for out-of-plane distortion (buckling), particularly between framing members. Because construction panels are relatively thin (and thus of limited stiffness) as compared with framing members, panel dimensional change along the framing members can be restrained to a significant degree by stiffness of the framing members, provided that panels are adequately fastened to them. Buckling between framing members may occur if panels are installed at appreciably lower moisture content than the framing members. Buckling at panel edges can occur (in either direction) if insufficient gaps are provided between panels at installation. Shingle ridging is associated with within-plane dimensional movement of wood-based panels in roof sheathing applications. It occurs when edge gaps between panels decrease in width and roof shingles (most commonly low-cost thin shingles) that bridge the gaps noticeably buckle as the distance between shingle nailing points decreases with panel linear expansion. Structural panels used in Exposure 1 environments have historically shown little tendency to buckle unless installed without adequate edge gaps, if inadequately fastened to framing, and if subjected to significant wetting between installation and building "dry-in," or unless installed over wet framing lumber on walls that were enclosed while the lumber remained wet. Buckling of wall sheathing may be wholly undetectable if the wall cladding material is brick veneer or vinyl siding, whereas slight buckling or change in between-panel gaps may result in noticeable cracking of cement-plaster stucco. Visually objectionable out-of-plane distortion of wood-based panel materials used as siding or as combination sheathing/siding has occurred with some frequency. Attention to moisture content at time of installation and to building moisture control can significantly reduce the incidence of problems associated with dimensional changes in length or width of wood-based panels.

TABLE 9—Within-plane dimensional change coefficients for panel products over different moisture ranges (obtained from a multi-point measurement protocol).

Material	Moisture Range	C_{along}	C_{across}
Construction plywood	4.5 %–9 % mc (EMC over 30 % to 65 % RH range)	1.3×10^{-4}	1.6×10^{-4}
Construction plywood	9 %–19 % mc	2.0×10^{-5}	3.6×10^{-5}
OSB	2 %–7 % mc (EMC over 30 % to 65 % RH range)	2.1×10^{-4}	4.2×10^{-4}
OSB	7 %–17 % mc	5.7×10^{-5}	6.1×10^{-5}

As mentioned previously, proportional dimensional changes through the thickness of wood-based panels are significantly higher than those across panel length or panel width directions. For panels fabricated of lathe-cut veneer, dimensional change through the panel thickness is roughly 40 to 50 % greater than dimensional change in the radial direction of the wood from which it was fabricated (or roughly equivalent to the dimensional change in the tangential direction). For panels fabricated of comminuted wood, but not significantly densified by pressing, (fiberboard sheathing) dimensional change in the thickness direction is not recognized as being of consequence. The ASTM/ANSI standard for fiberboard sheathing (ASTM C208 [57]) does not promulgate dimensional stability requirements in the thickness direction, and thickness swelling potential of fiberboard sheathing is apparently modest [64]. For densified wood composition materials, however, proportional dimensional movement in the thickness direction can be of appreciable magnitude, substantially exceeding that of wood in either of its transverse directions. Up to EMCs corresponding with 70 % relative humidity, thickness swelling of densified wood composition materials is roughly similar to swelling of the denser wood species in the tangential direction, and the swelling is mostly recoverable. Beyond EMCs corresponding with 80 % RH, however, swelling increases significantly and a significant portion of the swelling becomes nonrecoverable [63,65]. The proportion of swelling that is nonrecoverable continues to increase as conditions get progressively wetter. Upon exposure to soaking, thickness swelling of 35–40 % may occur in densified wood composition materials (relative to the dimension at an EMC corresponding with 50 % RH) [38]. The literature [63,65] suggests that when thickness swelling exceeds 20 %, more than half of it (around 70 %) is nonrecoverable.

Nonrecoverable (or irreversible) thickness swelling almost always occurs unevenly, being greatest at panel edges. The uneven swelling can be visually objectionable, for example, when irreversibly swollen edges of subflooring panels telegraph through floor coverings. Uneven irreversible swelling, along with surface roughening near swollen edges, results in edge welting of laminate flooring and edge welting of hardboard siding. Irreversible thickness swelling is generally recognized as occurring to the greatest extent when material is immersed in water for the first time, with marginal increases in irreversible swelling becoming progressively less in subsequent soaking cycles. Internal swelling stresses

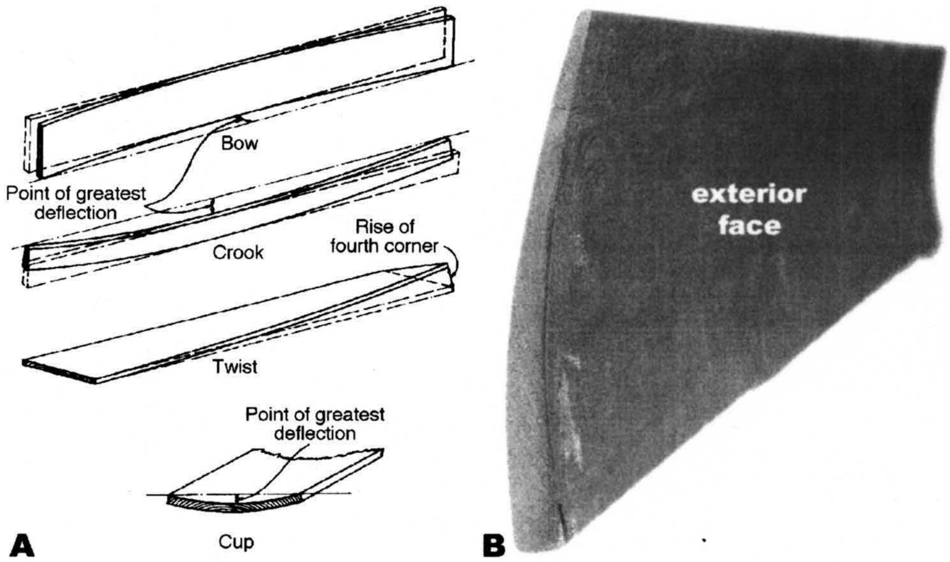


Fig. 8—(*a*) Types of warp. (*b*) Permanent cup in a piece of thin, 140-mm wide bevel wood siding that had been stained a dark color and installed on a wall with direct solar exposure.

associated with irreversible thickness swelling have, however, been shown to result in internal mechanical damage to panels [66]. Internal changes influence panel properties, with progressive property degradation occurring with repeated wetting. Progressive increase in liquid water absorptivity has been observed in OSB with repetitive wetting cycles [67]. Progressive degradation of mechanical properties with repetitive wet cycling is generally recognized as occurring at a decreasing marginal rate. Not all properties necessarily degrade at a decreasing marginal rate. In exterior exposure, edge welting in hardboard siding has been observed to accelerate with repetitive wetting cycles, even while in-service edge thickness remained relatively steady [35]. The degree to which densified wood composition panels undergo irreversible thickness swelling can vary appreciably, even between panels bonded with similar adhesive systems [68]. Densified wood composition panels fabricated from wood fibers tend to show less irreversible thickness swelling than those fabricated from particles or flakes [68]. Appreciable differences in irreversible swelling between commercial products in the same product class have been observed [26,35,59,60].

OSB panels are Exposure 1 panels, intended to withstand weather exposure during construction, but not intended for use in exterior exposure. The amount of property degradation OSB will undergo during construction as a result of thickness swelling is not generally recognized as being of practical consequence. Owing to its incorporated sizing, the initial water-absorptivity of OSB is fairly low [69]. As indicated in Table 3, OSB is very dry as shipped from the manufacturing plant. OSB sheets are furthermore edge-sealed by manufacturers, sometimes with sealer formulated specifically for the application. For these reasons OSB edge swelling that occurs over a few months exterior exposure during building construction, is generally recognized as being less than the swelling that would be observed on an unsealed edge of the same panel if it were immersed in water for 24 hours. Edge swelling of wood composition materials exposed to chronic water exposure (for example, indefinite weather exposure or ongoing water intrusion) is, however, likely to result in objectionable irreversible damage. Wood composition materials intended for use in exterior applications (hardboard siding or exterior trim, or resin-paper-overlaid OSB siding[18]) are universally recognized as being subject to objectionable water-induced damage associated with irreversible thickness swelling, unless the materials are adequately coated with a high quality exterior paint system. Edge swelling of web members in OSB-webbed I-joists has the potential to significantly compromise joist structural integrity. OSB used for I-joist web material evidently has less than half the swelling potential of sheathing-grade OSB [63].[19] The importance of maintaining structural integrity, however, suggests that OSB-webbed I-joists should be protected from wetting, (during construction as well as in service).

Warp

Warp occurs when there is spatial variation in dimensional change within a wooden member. Differential dimensional change can occur across the member width, resulting in cup. It can occur along the member length on opposite wide faces, resulting in bow, or along the member length on opposite narrow faces, resulting in crook. It can also occur in a compound manner, resulting in member twist [Fig. 8(*a*)].

Warp that occurs during lumber manufacture and processing can be traced to two causes: (a) differences between

[18] OSB siding with resin paper overlay is a proprietary product explicitly marketed as siding. It has a higher adhesive content than sheathing-grade OSB, an incorporated preservative to inhibit decay and insect infestation, and sealed back surfaces and edges

[19] I-joist manufacturers have property requirements for web material and can demand that OSB manufacturers provide material that meets their requirements. These requirements are not in the realm of public information.

radial, tangential, and longitudinal shrinkage as the lumber dries, or (b) growth stresses within the tree. Warp is aggravated by irregular or distorted grain and by the presence of juvenile and reaction wood. Juvenile and reaction wood are often unevenly distributed within wood members. As mentioned in the discussion of wood anatomy, the helical angle of wood cells of the tree's axial system may change as the tree grows. This can result in differing degrees of spiral grain at different locations within a wood member, and this can be a factor in warp. Warp that has its genesis in growth stresses or in differential shrinkage upon drying from the green condition can be mitigated by drying under restraint. Commercial lumber drying operations can stack lumber and weight the stacks so that the pieces dry under restraint; the elevated temperatures involved in kiln drying aid in mitigation of warp during drying under restraint. To some degree, wet framing lumber nailed into frames and sheathed with rigid sheathing will also be held under restraint while drying in place. This approach to mitigating warp of framing lumber was used successfully before the widespread use of kiln-dried lumber, most notably in 2 by 4 construction (hip roofs of modest span and walls) sheathed with 19 mm lumber boards installed at a moisture content similar to that of the framing material. The current viability of this approach can be questioned, considering that contemporary framing lumber is more likely to contain larger proportions of juvenile wood and thus be more prone to warp, and that panel sheathing materials have largely replaced the thicker and relatively stiffer lumber board sheathing. As mentioned previously, a mismatch of relatively dry sheathing panels and relatively wet framing lumber can result in problems associated with linear expansion of the sheathing. Furthermore, drying of wet framing lumber in walls is likely to be relatively slow in contemporary construction, where enclosure often occurs rapidly, and where air leakage rates through enclosed walls are lower than commonly occurred through walls sheathed with lumber boards.

Warp sometimes occurs in service in members that were flat and straight as installed, even in members installed at moisture contents reasonably close to average long-term end-use conditions. If transient in-service moisture conditions on opposite sides of a member differ appreciably, warp may occur. Where appreciable warp occurs as a result of transient differential wetting, some of the warp is likely to be irreversible; the member may retain significant warp when the differential moisture conditions across the member are dissipated. Wood flooring installed over a wet concrete slab will warp, and much of the warp may be permanent. Wood siding that is wetted by rain and then exposed to sun is likely to undergo some degree of permanent warp [Fig. 8(*b*)]. The likelihood that the permanent warp will be objectionable is increased if the siding is thin, and if it is unfinished or if it is finished with a dark finish, (which will result in higher peak siding temperatures during solar exposure). Significant warp is usually more common in thinner members; the cross-sectional rigidity of thicker members is greater, and the rigidity will restrain warp. Thicker and larger members are, however, not necessarily immune to problems associated with rapid changes in surface moisture content.

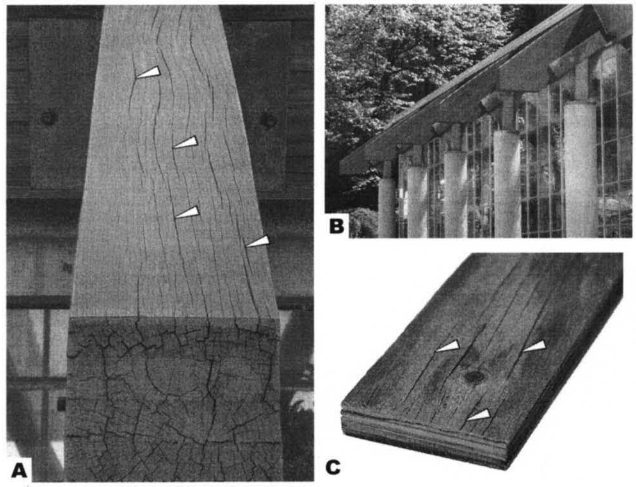


Fig. 9—(*a*) Top-surface checking (arrowheads) and end-checking in glued laminated beam, the end of which has been exposed to the weather. (*b*) Glulam beam ends exposed to the weather (the beam end shown in A is one of the five shown in this picture). (*c*) Surface checking in the face veneer of sheathing-grade plywood resulting from moderate weather exposure. Face veneer checking is noticeable (arrowheads) although surface defect (knot) remains tightly adhered, and virtually no surface erosion has occurred.

Surface Checking

Noticeable surface checking can occur in wood and in bonded wood products fabricated from lumber or veneers if they are exposed to rapid wetting and drying. Surface checking is related to restrained shrinkage of surface layers by inner layers during drying, and is exacerbated by intense drying conditions. The more extreme examples of in-service surface checking occur in insufficiently protected members in exterior exposure (Fig. 9), where the progressive influences of rain wetting and direct solar exposure result in rapid changes in surface moisture content. Surface checking tends to be more severe in members with relatively large cross sections [Fig. 9(*a*) and 9(*b*)]; pronounced surface checking can also occur in plywood [Fig. 9(*c*)]. Surface checking in members of appreciable cross section is related to significant differences in core and surface layer moisture contents under transient conditions. In plywood, checking is related to the relatively great unrestrained dimensional change potential of wood in the tangential direction (across the width of lathe-cut veneer sheets) and to restraint of that movement by core or cross-band plies.

Compression Set Shrinkage

If wood is subjected to restrained swelling it is subjected to mechanical compression. As indicated previously, moisture-induced dimensional change is proportionally least in the longitudinal direction and greatest in the tangential direction. Exertion of compressive force by restrained swelling is thus usually greatest in the tangential direction, and next greatest in the radial direction. If the compressive force results in strain beyond that at the proportional elastic limit (PEL), permanent deformation will result, and upon drying the wood will return to a smaller dimension than its dimension at the same moisture content before subjection to restrained swelling. The reduction in dimension from subjection to restrained swelling is termed compression set shrinkage, or sometimes simply as compression set. The effect of compression set is most commonly observed in loosened handles of hammers or axes, or in progressive widening of gaps between pieces of tongue and groove porch flooring (particular if flat-grained) that has been subjected to wetting. It can also occur in interior wood strip flooring[20] or in mortise and tenon joints of windows, doors, and furniture [70].

In wood subjected to compression perpendicular to the grain, the PEL is most commonly recognized as occurring at roughly 1 % strain [71,72].[21] This value for strain at PEL was evidently the basis for the 1 % allowable compressive strain rule, used by woodcrafters for evaluating the design of mortise and tenon joints [70]. This woodcrafters' rule is that calculated restrained moisture-induced swelling should not exceed 1 %.[22] The limit to change in moisture content that results in no more than 1 % strain can be calculated by dividing 1 % (0.01) by the appropriate coefficient (for species and grain direction) in Table 6. For example, the allowable MC changes that limit dimensional change of loblolly pine to 1 % are 5.9 MC percentage points, and 3.8 MC percentage points in the radial and tangential directions, respectively.

Strength

The strength of wood increases as its moisture content decreases from the green condition until it reaches roughly 6 to 4 % moisture content. Wood mechanical property values are typically greatest at about 4 to 6 % moisture content; they are slightly less at the oven-dry condition. The National Design Specification (NDS) for Wood Construction [73] contains a default assumption that structural members are in a dry environment, where member moisture content does not exceed 19 % (for sawn lumber) or 16 % (for interior glulam, structural composite lumber, prefabricated wood I-joists, or wood structural panels). Within the range of moisture contents in the dry region, the influence of moisture content on design values for wood members is not considered by the NDS as being of practical concern; it acknowledges no increase in design values for in-service moisture contents below 19 % MC. The NDS does acknowledge, and provide for, de-rating of design mechanical property values in wet use environments. The wet use adjustment factors are applicable to the treated lumber used in wood foundations, and to wood used in intermittently wet environments, such as exterior decks. Designers may also apply wet use factors to untreated members used in humid interior environments, such as in buildings with indoor swimming pools, (where in-service wood moisture contents may exceed 15 % and may not be precisely known), and to damp crawl spaces, (where in-service moisture contents may seasonally exceed 19 %).

As will be discussed later, if in-service moisture conditions exceed 20 % MC in wood (the EMC for wood products corresponding to roughly 90 % RH), there may be problems with biological infestation, and concerns relating to dimensional movement, to serviceability issues associated with progressive deflection of members under load, or of integrity of mechanically fastened connections. These other concerns generally overshadow concerns over the influence of moisture condition on immediate load-carrying capability.

Provided that attack by biological agents is avoided, and that significant warp or checking does not occur, wood is generally recognized as being capable of undergoing significant moisture cycling without perceptible damage. In contrast, significant moisture cycling of bonded wood products will stress the adhesive bonds, and this may result in some degradation of mechanical properties. Adhesive type and quantity, as well as fabrication variables influence the degree of degradation. It is generally recognized that products fabricated with boil-proof adhesives and either sawn lumber or wood veneers will, if carefully manufactured, withstand moisture cycling from ovendry to moisture contents in excess of fiber saturation without perceptible loss in mechanical properties, provided that the changes in moisture content are gradual and thus do not induce large internal stresses via spatial differences in moisture content. Delamination of bonded wood products will (obviously) result in a degradation of their mechanical properties. Internal stresses associated with irreversible thickness swelling of densified wood composition materials are, as indicated previously, a causal factor in degradation of mechanical properties [66]. Over a limited number of wet-dry cycles, the flatwise load carrying capacity in bending of irreversibly swollen wood composition panels may be unaffected due to increase in cross-sectional moment of inertia in bending, but the load carrying capacity will eventually be degraded with repetitive cycling [54,68,74,75].

Creep

Wood members placed under constant structural load undergo progressive deformation (creep). The rate of creep increases with increasing imposed load, that is, as imposed load becomes a greater portion of the member's load carrying capacity. Moisture conditions influence creep deformation; creep in constant damp conditions exceeds that in constant dry conditions, and creep under fluctuating moisture conditions exceeds that under constant damp conditions. The term "mechano-sorption" reflects the recognized influence that moisture content changes have on mechanical behavior of members under load.[23] The direction of change (wet to dry or dry to wet) has been observed to be inconsequential [76,77]; it is the magnitude, rather than the direction of change, that matters. When creep deformation is significant, and the imposed load that caused the creep deformation remains applied, failure will eventually occur [78]. This time-dependent failure, occurring after significant deflection, is termed duration of load or creep-rupture. Elevated temperatures can interact with high moisture levels or with mechano-sorption to exacerbate creep deformation and creep-rupture.

[20] Compression set in strip flooring is exacerbated if dirt is allowed to collect in the spaces between strips (which are open widest during the dry periods of seasonal moisture cycles).

[21] Compression testing of wood perpendicular to the grain has traditionally been in the tangential direction (load applied to a radial face).

[22] The widest range of allowable moisture content change is obtained by selecting mating pieces with regard to grain direction (the largest dimension of both the mortise and the tenon should be in the radial direction) and with regard to species and density.

[23] Mechano-sorption is recognized as occurring in members that are either subjected to deformation or are restrained while undergoing sorption or desorption. It plays a role in mitigation of warp of lumber by drying under restraint, in compression set shrinkage, and in loosening of fasteners in members subjected to moisture cycling.

Fig. 10—(*a*) Sag in the wood roof framing of a stone-wall house built in the 1850s (photo taken in 2005). Line above roof accentuates ridgeline sag. Roof framing was under-sized by modern standards. (*b*) Sag along the span of rafters in a house built in 1940 (photo taken in 2005). Reference stick touches the roof near peak and at eave. Arrowheads point to deflection of approximately 65 mm at mid span.

Despite the potential for creep and creep-rupture in wood structures, wood design codes in North America do not show much concern over these phenomena. Although noticeable sag is common in older structures (Fig. 10; [78]), in-service failure by creep-rupture is uncommon. The National Design Specification [73] does not address creep-rupture. The (unstated) assumption is that if the guidance of the NDS is followed (relating to adequate structural performance without consideration of of creep-rupture) that imposed stresses will be sufficiently low that creep-rupture will not occur. The NDS does, in certain circumstances, however, recognize creep deflection as an issue, with the issue relating to serviceability (as opposed to structural integrity). Consideration of creep by the NDS is confined to a deflection allowance for members in bending; it specifies that a higher amount of anticipated creep deflection be calculated for wood beam members installed in the green condition and maintained in a dry environment. Failure to adequately account for the larger deflection of window or door headers installed green sometimes results in excessive header deflection and accompanying problems with fenestration units installed in such openings. The NDS does not address the effect of seasonal fluctuation in moisture conditions on creep. If substantial seasonal moisture cycling occurs, creep deformation as great as would occur in green material drying under load (the situation addressed by the NDS) may occur.

The creep and creep-rupture behaviors of wood composition materials are conceptually similar to those of wood or of glued wood products fabricated from veneer [79,80]. Wood composition materials are however somewhat more prone to creep and creep rupture [79,81] than wood or than bonded wood products fabricated from lumber or veneers. The creep behavior of OSB has been reasonably well researched [82–84]; the *APA Engineered Wood Handbook* [17] specifies a substantially larger creep adjustment factor for OSB exposed to elevated moisture conditions in service than for OSB that remains in a continually dry environment.

Fastener Performance

The structural integrity of wood buildings depends on the integrity of connections between members. Where catastrophic structural failures of wood buildings occur (most commonly as the result of extreme wind or earthquake), failure of mechanical connections usually plays a critical role. Fasteners used in building structures are usually made of carbon steel. Carbon steel fasteners may be treated to resist corrosion (galvanized, or coated with phosphate, organic or ceramic coatings), or may be untreated (commonly sold as "bright"). In exposures where wet conditions can be anticipated (e.g.: treated wood foundations, exterior exposure), corrosion resistance is particularly important. In wet exposures where maintenance of connection integrity is crucial, use of fasteners with dual treatment (galvanized with organic coating) or of fasteners made from nonmagnetic stainless steel may be specified by trade association construction guides. Wood used in wet environments is usually pressure-treated with preservative chemicals, some of which accelerate fastener corrosion. A literature review [85] indicates that the issue of corrosion of fasteners in pressure-treated wood has been widely investigated, but is not fully understood. In situ corrosion resistance is important in selection of fasteners for treated wood, [81,86], especially where in-service MC may exceed 20 %.

In-service moisture content level and moisture cycling are recognized as influencing the strength of mechanical connections in untreated wood. The NDS [73] specifies load adjustment factors for mechanical connections based on wood moisture content at time of joint fabrication and on in-service moisture content. Where fasteners are installed in dry wood (defined as moisture content of 19 % or lower) and the wood remains dry, no adjustment in connection load carrying capacity is deemed necessary (adjustment factors are 1.0). This applies to any type of connector, in either lateral load transfer[24] or in withdrawal resistance.[25] Adjustment factors ranging from 0.9 to 0.25 are specified for load-carrying capacity of mechanical connections when in-service conditions either exceed 19 % moisture content, or where there is change from wet to dry conditions or dry to wet conditions. The greatest adjustment (factor of 0.25) applies to withdrawal resistance of nails where there is a wet to dry or dry to wet change between moisture content at time of driving and moisture content in service. All other adjustment factors are relatively modest, ranging from 0.9 to 0.7, depending on fastener type, loading mode, and moisture history. The adjustment factors for load-carrying capacity of mechanical connections in the NDS do not appear to address significant repetitive moisture cycling, nor do they account for significant corrosion of fasteners.

Complete failure of wood joints, associated with corrosion of steel fasteners, has been observed within six years in damp wood under moderately acidic conditions at elevated temperature [87]. Baker [88] reported that nearly complete weakening of nailed connections, resulting from steel fastener corrosion, frequently occurs in weathered house or barn siding. In weakened joints with significantly corroded fasteners, joint weakening results from degradation of the

[24] Load transfer perpendicular to the fastener axis.

[25] Force needed to remove (pull) the fastener axially from the wood member.

fastener itself, and also from chemically-induced deterioration of the wood in contact with the corroding fastener [85,88–91]. Quantification of fastener corrosion rate of nails in wood at moisture contents below fiber saturation has been investigated fairly recently by Cole et al. [92] and by Imamura and Kiguchi [93].

Cole et al. [92] found corrosion rate to depend on wood moisture content, in a rather complex manner, and that the relationship between corrosion rate and wood moisture content varied with wood type and to generally be different for bright than for galvanized steel nails. They proposed the following generalized description for the relationship between corrosion rate and wood moisture content.

- Minimal or no corrosion occurs at moisture contents below a threshold MC value, with threshold values ranging from roughly 10 to 14 % MC depending on wood and fastener type.
- A plateau in corrosion rate (usually) occurs at some wood moisture content below fiber saturation, with no marginal increase in corrosion as wood MC increases beyond the maximum rate value. Untreated woods show a plateau in corrosion rate of embedded fasteners, with "maximum rate" MC value varying from roughly 16 to 24 % MC. The behavior of wood pressure-treated with waterborne preservatives can differ from that of untreated wood; in such wood, a plateau in corrosion rate may not occur.
- Between the threshold value and maximum rate value, fastener corrosion rate correlates with wood moisture content.

Cole et al. [92] apparently did not observe iron-induced wood degradation around fasteners; the duration of their tests was 120 days, a time period that evidently was insufficient to result in noticeable degradation.

Imamura and Kiguchi [93] performed longer-term tests than Cole et al. [92]. They found that corrosion of bright steel nails embedded in hemlock at room temperature for four years was significantly influenced by relative humidity (and in turn equilibrium moisture content). In a parallel investigation, they observed that lateral resistance of nailed joints was significantly influenced by the degree of nail deterioration. Joints with nails that had lost around 11 % of their mass (5 % of shank diameter) to corrosion had roughly 40 % of the strength of joints with nails that were scarcely rusted. Finally, in a forensic investigation, they observed nail condition and surrounding wood condition in sheathing boards behind cement plaster stucco-cladding on houses that were roughly three decades old. In the vicinity of cracks in the stucco cladding, they observed very significant nail corrosion (25 % or greater loss in shank diameter), and noticeable iron-induced deterioration of wood surrounding deteriorated nails. Time/temperature/moisture histories at these locations were unknown, but moisture contents in these locations at time of cladding removal ranged from 18 to 24 %. They concluded that moisture conditions in excess of 20 % would cause 5 % loss in nail shank diameter in four years, and could plausibly lead to 25 % or greater loss in shank diameter over three decades, and finally that joint deterioration associated with such a loss of shank diameter (and accompanying wood deterioration) might significantly compromise the shear resistance of exterior building walls.

Moisture and Biological Attack

Although moisture conditions (including fluctuations) affect the physical and mechanical properties of wood, wood products, and constructions, it is the role of moisture in the biological attack of wood and wood products that is regularly viewed as being most significant. There are two main groups of organisms that attack or alter wood in buildings: microbes and insects. In the case of microbes, moisture relations within the wood are critical to the prevention of attack, the type of microbes that may grow, and the damage that may be done. For insects, the question of moisture is of varying importance depending on the type of insect infesting the wood.

Moisture and Microbes

The susceptibility of wood to microbial attack is a function of the moisture content and duration of the wetting. For bacteria, stains, and wood decay, the FSP of the wood must be exceeded for a significant duration (generally weeks or months), and to reach this point, liquid water must be regularly available to the wood. For molds, the FSP need not be reached, and moisture contents sufficiently high to permit the growth of mold can be reached by high relative humidity, over shorter time periods.

Molds

Molds are fungi that grow on moist surfaces, scavenging their nutrition from either their substrate (the wood) or the dust and other particles that accumulate on the substrate. They typically produce dark brown, purplish, or black growths that spread over a surface. Because mold growth is essentially a surface phenomenon, it is influenced by surface moisture conditions, which may differ from substrate bulk moisture content. Mold propagation does not require surface moisture conditions in excesss of fiber saturation. Mold growth can occur when humidity level in the air immediately adjacent to the wood surface (termed "surface equilibrium RH") exceeds roughly 80 %, and growth occurs rapidly when surface RH values exceed roughly 90 % [94,95]. A surface equilibrium RH value of 80 % corresponds with a wood surface moisture content of approximately 16 % at room temperature (Table 1). To prevent mold growth, a 75 % surface RH value at room temperature appears to be a reasonable daily-average not-to-exceed value. It appears however that this target surface RH value should not be considered a never-to-exceed value. Viitanen and Salonvaara [95] indicate that unfinished softwood surfaces that are otherwise maintained at 75 % surface RH can withstand as much as two hours per day of exposure to a 95 % surface RH without developing mold growth. If the dry-period RH value is increased above 75 % or the duration of the wet period is lengthened beyond two hours per day, noticeable mold growth can occur over a roughly half-year period.

Molds are primarily an aesthetic problem, and often can be wiped away or removed with gentle abrasion. They generally do not penetrate deeply into the wood, and do not cause appreciable damage to the cell walls, instead living on free sugars, starches, and other metabolites (generally found in cell lumina, particularly in sapwood). Although molds do not cause structural failure of wood, they can give off unpleasant odors or produce large numbers of spores which may become an indoor air quality concern.

Bacteria

Bacterial contamination of wood can occur where the moisture content of the wood remains substantially in excess of the FSP for extended periods. Wood-dwelling bacteria generally have the ability to live anaerobically. The oxygen-deficient environment of very wet wood is most conducive for bacterial growth as it inhibits growth of other microbes with which the bacteria would otherwise have to compete. Very wet conditions rarely occur in wood or wood products in buildings; therefore risk of bacterial infestation in service is hardly, if ever, recognized. Concern over bacterial colonization of wood is instead related to wood harvested from infested trees and to colonization that may occur during pond storage of logs, or both. Wood-dwelling bacteria generally do not cause a reduction in the mechanical properties of wood. Utilization concerns are related to strongly malodorous compounds produced during anaerobic respiration, or to challenges faced by commercial drying operations in drying wood of exceptionally high moisture content.

Stains

Microbial staining of wood is caused by fungi that penetrate the wood, often colonizing the sapwood of trees within a short time after felling as the sapwood begins to dry out, but the wood is still above FSP. They live on the free sugars, starches, and other cellular contents of the sapwood, but do not harm the structural integrity of the cell walls. For this reason, stain fungi are not considered wood decay fungi. Their growth can, however, be problematic to the wood industry, because they produce aesthetically objectionable blue, green, black, or purple stains inside the wood that cannot be removed by sanding or surfacing. Stained wood is also considered unsuitable for use as siding or exterior millwork as stain infestation often results in greatly increased permeability, which in turn results in increased water absorbtivity.

Wood Decay

Wood decay, or rot, is caused by a group of fungi that derive nutrition primarily from the components of wood cell walls. Consumption of cell wall material results in structural degradation. It is estimated that 10 % of the wood harvested each year goes to replace decayed wood in existing structures [96]. Cell wall material, in particular the lignin component, is fairly resistant to biochemical breakdown. Wood decay fungi have thus developed relatively specialized biochemical processes to digest cell wall material. These processes require free water, in other words, a moisture content in excess of fiber saturation. In addition, the MC must remain in excess of fiber saturation for a substantial period of time; rapid cycling of MC is not conducive to fungal decay propagation. Increasing the drying rate of wetted wood can be helpful in preventing decay establishment [97]. There can, however, be limitations on the utility of this strategy; as indicated in previous discussions, rapid and significant fluctuation, or both, in moisture content may engender nonbiological problems with wood products.

There are three main types of wood decay; soft rot, white rot, and brown rot. Soft rot fungi grow in wood that remains substantially wetter than fiber saturation for long periods of time, such as inside pilings just above the water line, in posts set in damp earth, and in other more or less constantly wet locations. Soft rot fungi are most closely related to the mold fungi, though their effect on the structural properties of wood, unlike the molds, can be severe. Soft rot is rarely seen inside buildings in North America; further discussion of wood decay in this chapter is thus limited to that caused by white rot and brown rot fungi.

For decay to propagate, five major factors must be present: there must be a wood decay fungus, there must be wood, there must be a regular source of water, the temperature must be appropriate, and there must be oxygen. If any of these are missing, wood will not decay. For the most part, only the moisture content of the wood can be regulated by people; oxygen is always present in buildings, decay fungi are ubiquitous as spores in the air, and, of course, wood is present. In the exterior envelopes of buildings, the temperature during winter may be too low for decay propagation, and in parts of unshaded roof structures during summer, the temperature may even reach a level that is lethal to decay fungi. For significant periods of the time, however, in most locations within buildings, the temperature is within a range that decay fungi will not only tolerate, but also find reasonably conducive for propagation.

White rot and brown rot fungi degrade the cell walls of wood in ways that differ significantly from a biochemical standpoint, and the appearance of wood decayed by the two types of fungi also differs. Both, however, can cause significant structural damage to wood. In nature, white rot fungi grow on hardwood logs on the forest floor, and brown rot fungi tend to grow on softwoods. In the laboratory and in buildings, either type of decay can progress in either type of wood, but as buildings in North America are made predominantly from softwood species, brown rot decay is the most common type of decay found in buildings.

The current guideline for confidence in prevention of decay establishment in wood and wood products (specifically those that have no marked decay resistance) is to keep them at a moisture content equivalent to that of wood at 20 % MC. The value has been prescribed in textbooks for decades [98]. Experimental work to support the guideline has been presented by Zabel and Morrell [96]. There is some mechanistic evidence [99] that wood decay may propagate, albeit relatively slowly, under conditions where capillary condensation occurs in the smallest of cell-wall pores (at conditions slightly drier than fiber saturation). More recently, Viitanen [100] reported that decay propagation can occur at 90–92 % RH at a constant ideal temperature; this is the apparent lower RH limit for decay propagation, and propagation at this limit progresses very slow (60 months for detectable weight loss to occur). The 20 % MC guideline, which has been used for decades, obviously could not at its promulgation, reflect the findings of Viitanen [100], but it did reflect acknowledged imprecision in estimate of where fiber saturation occurs, it allowed for spatial variation in moisture content within members, and it provided some margin of safety. Carll and Highley [101] concluded that no published experimental data exist that would contradict the long standing 20 % MC guideline. Where in-service moisture content can be anticipated to exceed 20 % MC, material with marked decay resistance (either adequately treated with preservative chemical, or heartwood from a durable species) should be selected. Exceptions can be made where moisture conditions in excess of 20 % MC are known to occur only under temperature conditions unfavorable for decay propagation.

Moisture and Insects

Insect pests of wood are generally able to infest wood at much lower moisture contents than can most microbes. This means that wood destroying insects can be a problem even in structures that are maintained at the correct moisture conditions. Despite the ability of wood destroying insects to colonize dry wood, insect infestation is nevertheless more common and generally more severe in wood maintained at moisture levels that correspond with high RH levels (for example, above 18 % MC). In some cases, insects also prefer to infest wood in which decay is taking place, presumably because the wood is easier to chew. There are three main types of insects that infest wood structures in the United States; carpenter ants, boring beetles, and termites.

Carpenter Ants

Carpenter ants are typically large black or brown ants that delve tunnels and galleries in wood in order to produce secure dwellings. They do not ingest wood and they remove any wood debris from their tunnels, resulting in piles of wood dust near their entrances. Despite the fact that they do not eat wood for sustenance, they nonetheless can do significant structural damage, particularly to solid wood products such as dimensional lumber. They prefer to inhabit damp wood, often attacking decaying wood, presumably due to the greater ease of mastication. Due to their preference for moist or decaying wood, elimination of excess moisture is often an effective way to prevent infestation.

Wood-Boring Beetles

There are a variety of wood-boring beetles that can infest wood. Most such beetles are pests to living trees in the natural world, and do not cause problems for wood or wood products once the products are dried. A few of the woodborers will emerge from dried wood, but do not reinfest dry wood; they instead seek living trees. Of the remaining woodboring beetles, most will be killed by the kiln-drying process, and some even by air-drying. There are only a few types of borers, specifically the anobiid and lyctid powder-post beetles, that will grow in woods with a moisture content lower than about 20 %. The former do damage very slowly and will not thrive at moisture contents less than 15 %; they typically are not a major economic problem. Lyctid powderpost beetles only infest large-pored hardwoods like ash and oak, and thus are unlikely to infest structural members of buildings, which are typically softwood species.

Termites

The most destructive of the wood-damaging insects in the United States are the termites. There are three general classes of termites in the United States, and they are, in rising order of economic importance, the dry-wood termites, the subterranean termites, and the Formosan termite. In each case, termites dwell in large colonies of thousands to millions of individual insects, and consume wood as their food.[26] They use their excrement as an adhesive to bind soil particles to form tunnel passageways. Dry-wood termites are only found in the southern-most reaches of the United States, but as their name implies, they require little water and thus cannot be controlled by keeping wood at low moisture content. Fumigation and exclusion are the only practical controls.

Subterranean termites are a significant problem across much of the United States, although the rate of infestation is currently believed to be lower than it was in the past. Much of the reduction in termite infestation of buildings appears to be due to improved building practices and site preparation. This includes better foundation backfill practices (keeping wood scrap out of backfill material), use of pressure-treated mudsills, better understanding of the role of soil moisture, and better understanding of the propensity of termites to access wood structures through hidden passageways. Subterranean termites almost exclusively infest structures by building tunnels up from their underground colonies. In nature they eat the woody detritus on the forest floor, and do not attack living trees. Subterranean termite colonies require a regular source of water, which need not come from the wood itself, and so improving drainage around homes to keep the soil near the foundation relatively dry can limit infestation risk. Maintaining a moderately large distance between the soil line and the lowest wood of a structure (300–450 mm) can help prevent termites from easily reaching wood via their tunnels, and increases the likelihood that tunnels, if constructed, will be noticed by concerned parties. Apart from the tunnels that they build, subterranean termites do not leave conspicuous evidence that they are at work in a building, preferring to eat away the interior of a piece of wood and leave a thin veneer of uneaten wood between their tunnels and the air. Subterranean termites prefer moist or decaying wood, but are capable of eating dry wood that is free of decay if the colony has a source of regular moisture. For this reason, moisture exclusion can limit infestation risk, although it does not preclude the possibility of attack.

The Formosan termite is an introduced species (not native to North America) with substantial destructive potential. Formosan termites can infest and destroy living trees as well as wood and wood products. It has been estimated that the annual cost of wood and tree destruction by the Formosan termite exceeds one billion dollars annually in the United States. Whereas subterranean termites only form colonies in the ground, Formosan termites can form colonies isolated from ground contact as well as underground colonies. Exclusion of the termites from the structure is an important tool in preventing infestation, as is moisture control. Although the Formosan termite colonies can form colonies isolated from the ground, they must have regular access to water to thrive. Therefore control of moisture in the building can be particularly helpful in limiting the risk of colony formation within a building. As is the case with subterranean termites, moisture control also limits the risk of Formosan termite infestation via the soil, although it does not preclude the possibility of attack.

[26] Termites depend on a complicated interaction of micro-organisms (protozoa and bacteria) within their gut to utilize wood for sustenance.

Summary

The effect of moisture on wood and wood product properties and behaviors has its origin in the chemical composition and biological structure of wood. Wood products can react differently than solid wood to moisture and to changes in moisture; the extent to which wood products respond differently than solid wood is related to the degree of physical or chemical alteration of the product relative to the parent wood material.

Bonded wood products came into use in building construction, for the most part, after the Second World War, and their widespread adoption generally coincided with development and industrial availability of synthetic polymeric adhesives. Bonded wood products have evolved over time with regard to the adhesives and wood constituents used, and with regard to processing techniques and intended end uses. Some bonded wood products are suitable for use on building exterior walls; some have shown decades of acceptable performance in this end use when protected with a suitable exterior finish system. A few bonded wood products (for example, pressure-treated plywood) can even be used in wet environments. Most bonded wood products, however, including sheathing panels, I-joists, and structural composite lumber adhered with waterproof adhesives, are neither intended nor suitable for exterior exposure or for wet service, and are thus expected to be protected from wetting in service.

Moisture content (MC) in excess of 20 % is a major predictor of performance problems with wood and wood products, influencing their susceptibility to fungal and insect infestation and the susceptibility of fasteners embedded in them to corrosion. High MC and repetitive, large fluctuations in MC are also implicated in creep deflection. To prevent these deleterious effects and to provide for the long service life of solid wood in use, an MC of 20 % or less has therefore long been recommended. This level is approximately the equilibrium MC value of wood at 90 % relative humidity and room temperature. It corresponds with approximately 19 % MC in construction plywood and 17 % MC in oriented strand board. Maintaining wood and wood products below these target MCs will prevent the establishment and growth of decay fungi and will preclude the possibility of objectionable creep deflection in adequately sized members. It will also greatly reduce the likelihood or extent of fastener corrosion and of insect infestation. Maintaining wood and wood products below these target levels, although useful for limiting risk of biological infestation, for limiting long-term deflection of load-bearing members, and for helping assure long-term integrity of fastened connections, cannot be expected to prevent all moisture-related moisture problems in all end uses.

Normal seasonal fluctuations in ambient temperature and relative humidity (RH) give rise to changes in MC of wood in service. Serviceability issues associated with dimensional movement of wood or wood-based components may be better served by limits on in-service moisture content more restrictive than the 20 % MC rule, both in terms of the maximum average MC and range across which MC is allowed to vary. Judgment of what constitutes unacceptable dimensional movement varies with the application. Dimensional change equations are provided in this chapter [Eqs (1) and (2)], along with applicable coefficients (Tables 6, 8, and 9). These equations should allow the reader to set their own restrictions for acceptable in-service MC fluctuation based on application-specific criteria for acceptable dimensional movement. Alternatively, a rough rule for acceptable in-service MC fluctuation in finish carpentry can be extracted from Table 5 of this chapter; the rule is for fluctuations to be restricted to no more than 2–3 % above or below the average annual MC for the location of service. This rule will in many cases roughly correspond with allowable moisture fluctuation as calculated by the 1 % allowable dimensional change rule, used by wood craftsmen for prevention of compressive set shrinkage in joinery. This is clearly a much more restrictive criterion than the 20, 19, and 17 % maximum values for wood, construction plywood, and OSB, respectively, outlined in the preceding paragraph. It is almost certainly an excessively restrictive criterion for application to framing or sheathing of light frame buildings.

Wood has been used for millennia in construction; there are structurally sound buildings constructed largely of wood in Scandinavia, China, and Japan that exceed 500 years of age. Invariably, these buildings were designed and constructed such that the wood members were effectively isolated from wetting. The vast majority of residential structures built in North America over the past three centuries were constructed primarily of wood, and most of these have performed reliably. Wood and wood products dried to an appropriate level and maintained within a reasonable range of fluctuating moisture conditions appear capable of performing nearly indefinitely.

Acknowledgments

The authors recognize the varied assistance of individuals of the professional and support staffs of the U.S. Forest Laboratory. These individuals include: JoAnn Benisch, Karen Nelson, Mary Funmaker, David Green, John Hermanson, David Kretschmann, Douglas Rammer, Stephen Schmieding, and Ronald Wolfe.

References

[1] Panshin, A. and deZeeuw, C., *Textbook of Wood Technology: Fourth Edition*, McGraw-Hill (ISBN 07-048440-6), 1980.

[2] Tsoumis, G., *Science and Technology of Wood: Structure, Properties, Utilization*, Van Nostrand Reinhold (ISBN 0-442-23985-8), 1991.

[3] Anderson, A., "The Influence of Extractives on Tree Properties: II Ponderosa Pine," *Jour. Institute of Wood Science*, Vol. 10, 1962, pp. 29–47.

[4] Kretschmann, D. E., Moody, R. C., Pellerin, R. F., Bendtsen, B. A., Cahill, J. M., McAlister, R. H., and Sharp, D. W., "Effect of Various Proportions of Juvenile Wood on Laminated Veneer Lumber," Research Paper FPL 521, U.S. Department of Agriculture, Forest Service, Forest Products Laboratory, 1993.

[5] Hann, R., "Longitudinal Shrinkage in Seven Species of Wood," Research Note FPL-0203, USDA Forest Service, Forest Prod. Laboratory, 1969; Harris, J. and Meylan, B., "The Influence of Microfibril Angle on Longitudinal and Tangential Shrinkage of Pinus Radiate," *Holzforschung*, Vol. 19, No. 5, 1965, pp. 144–153.

[6] Ying, L., Kretschmann, D., and Bendtsen, B., "Longitudinal

Shrinkage in Fast-grown Lollolly Pine Plantation Wood," *For. Prod. J.*, Vol. 44, No. 1, 1994, pp. 58–62.

[7] Bao, Z., "Chapter 6: Structural Composite Lumber," *APA Engineered Wood Handbook*, T. Williamson, Ed., McGraw-Hill (ISBN 0-07-136029-8), 2002.

[8] Baldwin, R., *Plywood Manufacturing Practices. Miller Freeman Publications Inc.* (ISBN 0-87930-030-2), 1975.

[9] Marra, A., *Technology of Wood Bonding: Principles in Practice*, Van Nostrand Reinhold (ISBN 0-442-00797-3), 1992.

[10] Geimer, R., Herian, V., and Xu, D., "Influence of Juvenile Wood on Dimensional Stability and Tensile Properties of Flakeboard," *Wood Fiber Sci.*, Vol. 29, No. 2, 1997, pp. 103–120.

[11] Jokerst, R. and Lutz, J., "Oak-Cottonwood Plywood—Minimum Cure Time," Research Paper FPL 231, U.S. Dept. Agriculture, Forest Service, Forest Products Laboratory, 1974.

[12] Jokerst, R. and Geimer, R., "Steam-Assisted Hot-Pressing of Construction Plywood," *For. Prod. J.*, Vol. 44, No. 11/12, 1994, pp. 34–36.

[13] Rinne, V., *The Manufacture of Veneer and Plywood* [textbook in English], Kuopio, Finland1952.

[14] Williamson, T., 2002, *APA Engineered Wood Handbook*, T. Williamson, Ed., McGraw-Hill (ISBN 0-07-136029-8), 1967.

[15] U.S. Department of Commerce, "Voluntary Product Standard PS1-07: Structural Plywood ," 2007.

[16] Maloney, T., *Modern Particleboard and Dry-Process Fiberboard Manufacturing*, Miller Freeman Publications (ISBN 0-87930-063-9), 1977.

[17] Baker, W., "Chapter 2: Wood Structural Panels," *APA Engineered Wood Handbook*, T. Williamson, Ed, MCGraw-Hill (ISBN 0-07-136029-8), 2002.

[18] Suchsland, O. and Woodson, G., *Fiberboard Manufacturing Practices in the United States*, United States Agriculture Handbook 640, U.S. Dept. of Agriculture, Forest Service, Washington, DC, 1986.

[19] Lehmann, W., "Improved Particleboard Through Better Resin Efficiency," *For. Prod. J.*, Vol. 15, No. 4, 1965, pp. 155–161.

[20] Liiri, O., "Pressdruck bei der spanplattenherstellung (Pressure in Particleboard Manufacture)," *Holkz als Roh-und Werkstoff*, Vol. 27, No. 10, 1969, pp. 371–378. (Translated in part in 1971 by the New Zealand Forest Service, and presented in the 1974 textbook, *Particleboard:Volume 2*, by A. Moslemi, Southern Illinois Univ. Press (ISBN 0-8093-0656-5).

[21] Carll, C., "Basic Mechanical Properties of Flakeboards from Ring-Cut Flakes of Eastern Hardwoods," *For. Prod. J.*, Vol. 44, No. 9, 1994, pp. 26–32.

[22] Kamke, F. and Casey, L., "Fundamentals of Flakeboard Manufacture: Internal-Mat Conditions," *For. Prod. J.*, Vol. 38, No. 6, 1988, pp. 38–44.

[23] Dai, C. and Wang, S., "Press Control for Optimized Wood Composite Processing and Properties, Part 1: Pressing Variables and Sensors," *Proceedings of a Workshop: Fundamentals of Composite Processing* J. Winandy and F. Kamke, Eds., General Technical Report FPL-GTR-149, U.S. Dept. Agriculture, Forest Service, Forest Products Laboratory, 2004.

[24] Geimer, R., Mahoney, R., Loehnertz, S., and Meyer, R., "Influence of Processing-Induced Damage on Strength of Flakes and Flakeboards," Research Paper FPL 463, U.S. Dept. Agriculture, Forest Service, Forest Products Laboratory, 1985.

[25] Wang, S. and Winistorfer, P., "Flake Compression Behavior in a Resinless mat as Related to Dimensional Stability," *Wood Sci. Technol.*, Vol. 35, No. 5, 2001, pp. 379–393.

[26] Groom, S., "Plywood vs. OSB," *Fine Homebuilding* #169, March 2005.

[27] Spalt, H., "The Sorption of Water Vapor by Domestic and Tropical Woods," *For. Prod. J.* Vol. 7, No. 10, 1957, pp. 331–335.

[28] Hedlin, C., "Sorption Isotherms of Twelve Woods at Subfreezing Temperatures," *For. Prod. J.*, Vol. 17, No. 12, 1967, pp. 43–48.

[29] Choong, E. and Manwiller, F., "Dimensional and Hygroscopic Properties of Hardwoods from Southern Pine Sites," *Wood Sci.*, Vol. 9, No. 1, 1976, pp. 39–43.

[30] Ahmet, K., Dai, G., Tomlin, R., Kacsmar, P., and Riddiough, S., "The Equilibrium Moisture Content of Common U.K. Species at Three Conditions of Temperature and Relative Humidity," *For. Prod. J.*, Vol. 50, No. 6, 2000, pp. 64–68.

[31] Wangaard, F. and Granados, L., "The Effect of Extractives on Water-Vapor Sorption by Wood," *Wood Sci. Technol.*, Vol. 1, 1967, pp. 253–277.

[32] Choong, E., "Effect of Extractives on Shrinkage and Other Hygroscopic Properties of Southern Pine Woods," *Wood Fiber*, Vol. 1, 1969, pp. 124–133.

[33] Suchsland, O., "Linear Hygroscopic Expansion of Selected Commercial Particleboards," *For. Prod. J.*, Vol. 22, No. 11, 1972, pp. 28–32.

[34] Richards, R., Burch, D., and Thomas, W., "Water Vapor Sorption Measurements of Common Building Materials," *ASHRAE Transactions*, VoL. 98, No. 2, 1992.

[35] Carll, C., and TenWolde, A., "Durability of Hardboard Lap Siding: Determination of Performance Criteria," Research Paper FPL-RP-622. U.S. Dept. Agriculture, Forest Service, Forest Products Laboratory, 2004,.

[36] Koch, P., "Utilization of the Southern Pines, Volume I, The Raw Material," *Agriculture Handbook No. 420*, USDA, Forest Service, Southern Forest Exp't. Sta. Libr. of Congress Card # 79-188-856, 1972.

[37] Zylkowski, S., "Chapter 1: Introduction to Wood as an Engineering Material," *APA Engineered Wood Handbook*, T. Williamson, Ed., McGraw-Hill (ISBN 0-07-136029-8), 2002.

[38] Zylkowski, S., "Dimensional Stability of Structural-Use Panels," Report No. R&D86L-43, American Plywood Association, Tacoma, WA, 1986.

[39] Nordenson, D., "Equilibrium Moisture Content and Effects of Moisture on Flexural Properties of Typical Building Fiberboards and Particleboards," Office report (unpublished), U.S. Dept. of Agriculture, Forest Service, Forest Prod. Laboratory, 1965.

[40] Myers, G. and McNatt, J., "Fiberboard and Hardboard Research at the Forest Products Laboratory: A 50-Year Summary," General Technical Report FPL-GTR-47, U.S. Dept. Agriculture, Forest Service, Forest Products Laboratory, 1985.

[41] U.S. Department of Commerce, "PS-20: American Softwood Lumber Standard," 1999.

[42] Garrahan, P., Meil, J., and Onysko, D., "Moisture in Framing Lumber: Field Measurement, Acceptability and Use Surveys," Submitted to Canada Mortgage and Housing Corporation, Forintek Canada Corp, 1991.

[43] ASTM Standard D4444, "Standard Test Methods for Use and Calibration of Hand-Held Moisture Meters," *Annual Book of ASTM Standards*, ASTM International, West Conshohocken, PA, 1992.

[44] Forest Products Laboratory, "Wood Handbook: Wood as an Engineering Material," General Technical Report FPL-GTR-113, U.S. Dept. Agriculture, Forest Service, Forest Products Laboratory, 1999.

[45] Carll, C., Knaebe, M., Malinauskas, V., Sotos, P., and TenWolde, A., "Performance of Back-Primed and Factory-Finished Hardboard Lap Siding in Southern Florida," Research Paper FPL-RP-581, U.S. Dept. Agriculture, Forest Service, Forest Products Laboratory, 2000.

[46] Dost, W., "Shrinking Siding: Estimating Prior Moisture Con-

tent," *Wood Design Focus*, Vol. 9, No. 4, 1998, pp. 20–23.
[47] Stiles, L. and Custer, M., "Reduction of Moisture in Wood Joists in Crawl Spaces—A Study of Seventeen Houses in Southern New Jersey," Recommended Practices for Controlling Moisture in Crawl Spaces, *ASHRAE Technical Data Bulletin*, Vol. 10, No. 3, 1994 pp. 30–40.
[48] Forest Products Laboratory, "Longitudinal Shrinkage of Wood," FPL Report #1093 U.S. Dept. Agriculture, Forest Service, Forest Products Laboratory, 1960.
[49] Chern, J., "Shrinkage of Redwood Siding," Office report (unpublished), U.S. Dept. of Agriculture, Forest Service, Forest Products Laboratory, 1980.
[50] Gorman, T., "Juvenile Wood as a Source of Seasonal Arching in Trusses," *For. Prod. J.*, Vol. 35, No. 11/12, 1985, pp. 35–40.
[51] Percival, D., "Separation Between Ceiling/Floor and Partition Walls," *Wood Design Focus*, Summer, 1991.
[52] ASTM Standard D1037, "Standard Test Methods for Evaluating Properties of Wood-Base Fiber and Particle Panel Materials," *Annual Book of ASTM Standards*, ASTM International, West Conshohocken, PA, 1996; Talbott, J., Maloney, T., Hufaker, E., Hoyle, R., and Meyer, R., "Linear Expansion Design Theory for Com-Ply Panels," Research Paper SE-224, USDA Forest Service, Southeast Forest Experiment. Sta., 1981.
[53] Wu, Q. and Suchsland, O., "Linear Expansion and Its Relationship to Moisture Content Change for Commercial Oriented Strandboards," *For. Prod. J.*, Vol. 46, No. 11/12, 1996, pp. 79–83.
[54] Alexopoulos, J. and Szabo, T., "Performance of Waferboard: Load Duration, Dimensional Stability and Biodeterioration," *Proceedings of a Workshop on the Durability of Structural Panels*, General Technical Report SO-53. U.S. Dept. of Agriculture, Forest Service, Forest, Southern Forest Experiment Sta, 1984.
[55] Lehmann, W., "Moisture-Stability Relationships in Wood-Base Composition Boards," *For. Prod. J.*, Vol. 22, No. 7, 1972, pp. 53–59.
[56] Luxford, R., "Properties of Insulating Fiberboard Sheathing," FPL Report #2032, U.S. Dept. Agriculture, Forest Service, Forest Prod. Laboratory, 1955.
[57] ASTM Standard C208, "Standard Specification for Cellulosic Fiber Insulating Board," *Annual Book of ASTM Standards*, ASTM International, West Conshohocken, PA, 1995.
[58] American National Standard Institute (ANSI), American National Standard for Particleboard: ANSI A208.1–1999. Published by Composite Panel Assn. Gaithersburg, MD (www.pbmdf.com), 1999.
[59] Biblis, E., "Engineering Properties of Commercial Hardboard Siding. Part 1. Embossed Panels," *For. Prod. J.*, Vol. 39, No. 9, 1989, pp. 9–13.
[60] Biblis, E., "Engineering Properties of Commercial Hardboard Lap Siding. Part 2. Smooth Boards," *For. Prod. J.*, Vol. 41, No. 3, 1991, pp. 45–49.
[61] American Hardboard Assn. (AHA), American National Standard for Hardboard Siding: ANSI/AHA A135.6-1998, Palatine, IL, 1998.
[62] Lang, E. and Loferski, J., "In-Plane Hygroscopic Expansion of Plywood and Oriented Strandboard," *For. Prod. J.*, Vol. 45, No. 4, 1995, pp. 67–71.
[63] Wu, Q. and Suchsland, O., "Effect of Moisture on the Flexural Properties of Commercial Oriented Strandboards," *Wood Fiber Sci.*, Vol. 29, No. 1,1997, pp. 47–57.
[64] McNatt, J., "How Cyclic Humidity Affects Static Bending and Dimensional Properties of Some Wood-Base Panel Products," *Proceedings of a Workshop on the Durability of Structural Panels*, General Technical Report SO-53, U.S. Dept. of Agriculture, Forest Service, Forest, Southern Forest Experiment Sta., 1984.
[65] Wu, Q. and Piao, C., "Thickness Swelling and Its Relationship to Internal Bond Strength Loss of Commercial Oriented Strandboard," *For. Prod. J.*, Vol. 49, No. 7/8, 1999, pp. 50–55.
[66] Linville, J. and Wolcott, M., "Controlling Thickness Swell in Oriented Strand Composites," *Proceedings, 35th International Particleboard/Coposite Materials Symposium*, Washington State Univ., Pullman, WA, 2001.
[67] Nofal, M. and Kumaran, K., "Moisture's Effects on OSB," *Professional Roofing*, April 2000, pp. 28–30.
[68] River, B., "Outdoor Aging of Wood-Based Panels and Correlation with Laboratory Aging," *For. Prod. J.*, Vol. 44, No. 11/12, 1994, pp. 55–65.
[69] Quarles, "How Durable is Structural Sheathing?" *Proceedings: 35th International Particleboard/Composite Materials Symposium*, Washington State Univ., Pullman, WA, 2001.
[70] Hoadley, R. B., *Understanding Wood: A Craftsman's Guide to Wood Technology*, Taunton Press (ISBN 0-918804-05-1), 1980.
[71] Kollman, F. and Côte, W., *Principles of Wood Science and Technology: Vol. I Solid Wood*, Springer-Verlag. Libr. or Congress Card # 67-29614, 1968.
[72] Markwardt, L. and Wilson, T., "Strength and Related Properties of Woods Grown in the United States," Technical bulletin 479, U.S. Dept. Agriculture, Washington, DC, 1935.
[73] American Forest and Paper Association, National Design Specification for Wood Construction: ANSI/AF&PA NDS-2001, 2001.
[74] Lehmann, W., "Durability of Composition Board Products," *Proceedings, 11th International Particleboard/Composite Materials Symposium*, Washington State Univ., Pullman, WA, 1977.
[75] Sekino, N. and Suzuki, S., "Durability of Wood-Based Panels Subjected to Ten-Year Outdoor Exposure in Japan," *Proceedings: The 6th Pacific Rim Bio-Based Composites Symposium*, Oregon State Univ., Corvallis, OR, 2002.
[76] Grossman, P., "Requirements for a Model that Exhibits Mechano-Sorptive Behavior," *Wood Sci. Technol.*, Vol. 10, 1976, pp. 163–168.
[77] Bengtsson, C., "Short-Term Mechano-Sorptive Creep of Well Defined Spruce Timber," *Holz als Roh-und Werkstoff*, Vol. 59, 2001 pp. 117–128.
[78] Gehards, C., "Bending Creep and Load Duration of Douglas-fir 2 by 4s Under Constant Load for up to 12-Plus Years," *Wood Fiber Sci.*, Vol. 32, No. 4, 2000, pp. 489–501.
[79] Dinwoodie, J., Robson, D., Paxton, B., and Higgins, J., "Creep in Chipboard Part 8: The Effect of Steady-State Moisture Content, Temperature and Level of Stressing on the Relative Creep Behavior and Creep Modulus of a Rang of Boards,"*Wood Sci. Technol.*, Vol. 25, No. 3, 1991a, pp. 225–238.
[80] Dinwoodie, J., Paxton, B., Higgins, J., and Robson, D., "Creep in Chipboard Part 10: The Effect of Variable Climate on the Creep Behavior of a Range of Chipboards and One Waferboard," *Wood Sci. Technol.*, Vol. 26, No. 1, 1991b, pp. 39–51.
[81] Baker, A., "Corrosion of Nails in CCA- and ACA-Treated Wood in Two Environments," *For. Prod. J.*, Vol. 42. No. 9, 1992, pp. 39–41; McNatt, J. and Laufenberg, T., "Creep and Creep-Rupture of Plywood and Oriented Strandboard," *Proceedings The 1991 International Timber Engineering Conference*, Vol. 3, 1991, pp. 3.457–3.464.
[82] Pu, J., Tang, R., and Cos Davis, W., "Creep Behavior of Commercial Oriented Strandboard Under High Relative Humidity," *For. Prod. J.*, Vol. 42, No. 4, 1992a, pp. 49–54.
[83] Pu, J., Tang, R., and Price, E., "The Effect of Hot and Humid Environmental Conditions on the Creep Behavior of Commercial Structural Oriented Strandboards," *For. Prod. J.*, Vol. 42, No. 11/12, 1992b, pp. 9–14.
[84] Pu, J., Tang, R., and Hse, C., "Creep Behavior of Sweetgum OSB: The Effect of Load Level and Relative Humidity," *For.*

Prod. J., Vol. 44, No. 11/12, 1994, pp. 45–50.

[85] Zelinka, S. and Rammer, D., "Review of Test Methods Used to Determine Corrosion Rate of Metals in Contact with Treated Wood," General Tech. Report FPL-GTR-156, U.S. Dept. Agriculture, Forest Service, Forest Products Laboratory, 2005.

[86] Malloy, D., "Exposed Subfloors and Galvanized Bolts?: Not Any More," *Build* (ISSN: 0110 4381). Bldg. Research Assn. of New Zealand, Feb./March 2005.

[87] MacLean, H. and Gardner, J., "Deterioration of Wooden Dry Kilns Used for Drying Western Hemlock Lumber," *The Lumberman*, Vol. 78, No. 12,1951, pp. 88–90.

[88] Baker, A., "Degradation of Wood by Products of Metal Corrosion," Research paper FPL 229, U.S. Dept. of Agriculture, Forest Service, Forest Products Laboratory, 1974.

[89] Thompson, W., "Effect of Chemicals, Chemical Atmospheres, and Contact with Metals on Southern Pine Wood: A Review," Research Report #6, Forest Products Utilization Laboratory, Mississippi State Univ., 1969.

[90] Highley, T., Scheffer, T., and Selbo, M., "Wood Minesweepers are Sound After 15 Years of Service," *For. Prod. J.*, Vol. 21, No. 5, 1971, pp. 40–48.

[91] Emery, J. and Schroeder, H., "Iron-Catalyzed Oxidation of Wood Carbohydrates," *Wood Sci. Technol.*, Vol. 8, 1974, pp. 123–127.

[92] Cole, I., Trinidad, G., and Chan, W., "Prediction of the Impact of the Environment on Timber Components: A GIS-Based Approach," *Proceedings, Durability of Building Materials and Components-8*, M. Lacasse and D. Vanier, Eds., National Research Council Canada (ISBN 0-660-17737-4 (Volume 1)), 1999.

[93] Imamura, H. and Kiguchi, M., "Prediction of Wood Decay in the Exterior Wall of Wooden Houses by the Deterioration of Nails," *Proceedings, Durability of Building Materials and Components-8*, M. Lacasse and D. Vanier, Eds., National Research Council Canada (ISBN 0-660-17737-4 (Volume 1), 1999.

[94] Flannigan, B. and Miller, J. D., "Humidity and Fungal Contaminants," *Proceedings of the Moisture Control Workshop: Bugs, Mold & Rot II*, W. Rose and A. TenWolde, Eds., Nat'l Institute of Bldg. Sciences, Washington, DC, 1993.

[95] Viitanen, H. and Salonvaara, M., "Chapter 4: Failure Criteria," *Moisture Analysis and Condensation Control in Building Envelopes ASTM MNL-40*, H. Trechsel, Ed. (ISBN 0-8031-2089-3), ASTM International, West Conshohocken, PA, 2001.

[96] Zabel, R. and Morrell, J., *Wood Microbiology*, Academic Press, (ISBN 0-12-775210-2), 1992.

[97] Gaby, L. and Duff, J., "Moisture Content Changes in Wood Deck and Rail Components," USDA Forest Service Research Paper SE-190, 1978.

[98] Hunt, G. and Garratt, G., *Wood Preservation*, 1st ed., McGraw-Hill Book Co. L.O.C. #TA422.H85, 1938.

[99] Griffin, D., "Water Potential and Wood-Decay Fungi," *Annual Reviews Phytopathology*, Vol. 15, 1977, pp. 319–329.

[100] Viitanen, H., "Modeling the Time Factor in the Development of Brown Rot Decay in Pine and Spruce Sapwood—The Effect of Critical Humidity and Temperature Conditions," *Holzforschung*, Vol. 51, No. 2, 1997, pp. 99–106.

[101] Carll, C. and Highley, T., "Decay of Wood and Wood-Based Products Above Ground in Buildings," *J. Test. Eval.*, Vol. 27, No. 2, 1999, pp. 150–158.

5

Moisture, Organisms, and Health Effects

Harriet A. Burge[1]

Introduction

HISTORICALLY, MANKIND BEGAN THE SAGA OF structure occupancy in caves, which were undoubtedly virtual gardens of mold, bacteria, and pests. 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, mice, cockroaches, and probably mold were allowed to proliferate in occupied environments, and straw was used to absorb all kinds of organic material on the floors of both castles and hovels. These conditions led to the black death (spread by rat fleas), exposure to intestinal bacteria and viruses, and the consumption of mycotoxins. During these times, outdoor air, in spite of rain, snow, and hail, was far healthier 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 fungal spores, bacteria, and other particles in outdoor air.

However, 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 more tightly constructed, resulting in reduced air exchange rates. Water generated by occupants and water migration through slabs on grade can contribute to increased indoor humidity.

In addition, millions of square feet of commercial office space are being constructed each year. 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. Materials used in these buildings are increasingly bio-based. These materials include particle board (wood chips or sawdust bound together with organic glues); ceiling tiles (waste paper solidified with organic binders); gypsum board (gypsum and starch sealed between sheets of paper). Fireproofing and insulation are made of borate-impregnated paper and ventilation systems are lined with glass fiber, which can trap moisture and dirt.

Because outdoor air enters our buildings and because we use materials that can readily support microbial growth, strong sources of microorganisms 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

Animals, plants, fungi, and bacteria belong to four separate kingdoms, all of which are essential to life on earth. All have evolved together and grown into an inextricable interdependence.

When members of these kingdoms invade human habitats they are considered pests. Thus, fungi growing in buildings are called mold or mildew; wild plants invading gardens are called weeds; and insects and other arthropods that colonize houses are called pests. The organisms that colonize buildings in response to excess water include fungi, bacteria, dust mites, and (to some extent) cockroaches.

The Nature of the Fungi

The fungi are filamentous organisms composed of long branching chains of cells. The chains of cells are called hyphae, and a mass of hyphae is called a mycelium. A few fungi (e.g., the yeasts) are unicellular. These morphologies provide an enormous surface to volume ratio putting all cells of the fungus into intimate contact with its environment. The fungal cell is bounded by a rigid cell wall composed of chitin (an *n*-acetyl-glucosamine polymer) fibrils bound together by 1,3 B-d glucans.

The majority of fungi produce spores, each of which can reproduce the entire organism. Spores may be produced as genetically identical clones (asexual spores or conidia), or following genetic recombination (sexual spores). A single fungus may produce both spore types during its lifecycle. Fungi are classified by their mode of sexual spore production. They are named with a binomial (genus and species). Many fungi have been called by two separate names because the two life cycle stages have not been recognized as coming from a single fungus (e.g., *Aspergillus repens/Eurotium repens*).

Fungal Physiology

Unlike green plants, which use chlorophyll to 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 accom-

[1] *EMLab P&K, 1150 Bayhill Dr., Suite 100, San Bruno, California 94066.*

plish this digestion by secreting enzymes that break down complex materials into simple sugars. Many fungi produce enzymes (called cellulases) that digest cellulose, which is the major structural material in most plants. A few produce ligninase (lignin is a major structural carbohydrate in wood) and most produce enzymes that digest starch, sugars, and other compounds that plants use for food storage. During the process of digestion, the fungi produce "extraneous" compounds that may be released into the environment. These include volatile organic compounds, mycotoxins (relatively low molecular weight non-volatile compounds), acids, proteins, antibiotics, and many others. Some of these have proven useful to man; others are important poisons.

Fungal Ecology

The fungi can live wherever air, food and water are present, and where temperature conditions are appropriate. Because so many spores are produced by each fungus, even rare mutations become common in the environment, allowing the fungi to readily adapt to new environmental conditions (including food sources). Because the fungi are adaptable, they can often "learn" to produce a specific enzyme to degrade almost any complex carbon-containing substance, including (for example) petroleum products. They are among the natural remediators of toxic pollutants and are added to soils to process petroleum products [1,2]. Fungal degradation of many exotic substrates has been reported, including destruction of compact discs [3].

Moisture is probably the most important factor controlling fungal and bacterial growth on all materials. Water is present on all surfaces, at least at the molecular level. The first layer of water molecules is tightly bound to the surface, and is not available for supporting life. As these molecular layers increase in number, the ease with which the water can be removed increases, until there is liquid water on the surface.

Most fungi (with the exception of some yeasts and some aquatic fungi) 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 generally do 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. Fungal water requirements are complex, and not susceptible to simple measurement (Fig 1).

The term "water activity" is sometimes used as an indicator of the moisture conditions needed for specific fungi. Water activity represents the amount of water in a material that is actually available for use by the fungus. Fungi that can grow at low water activity are considered xerophilic, while those that require higher water activities are mesophilic. Water activity cannot be equated with humidity, although there is sometimes an indirect relationship between the two. Also, water activity is not simply a measurement of the amount of water present, but takes into account the solute concentration in the water. For example, many fungi can grow on jams and jellies, which contain a great deal of water in which high concentrations of sugar are dissolved. The water activity in this situation is quite low (<0.7) and the fungi that grow under these conditions are xerophilic. Thus it is probably true that the amount of solute (rather than the

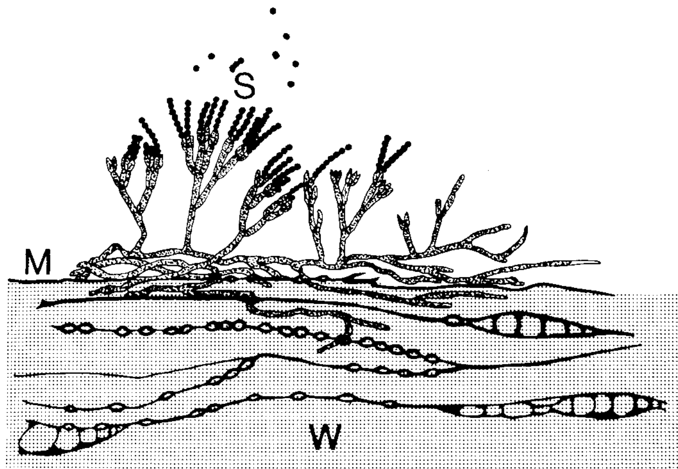


Fig. 1—Diagrammatic representation of fungal growth and population in and on the surface of wood: M=mycelium, S=spores, W=wood.

amount of water) that controls the type of fungi that grow on a specific substrate. Persistent condensation on a dusty metal surface is likely to result in the growth of mesophilic fungi such as Cladosporium, while condensation on fiberboard in which sugars are present in the binder may lead to growth of xerophiles.

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 [4]. 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 [5]. 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 is present (e.g., skin scales).

Fungal decay of wood has been well-studied, and 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 [6]. 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.

Fungal colonization of any substrate also depends on temperature. At a suitable moisture level, fungal growth rate is directly related to temperature up to an optimum [which is often between 18 and 30°C. Above the optimum, growth rate again declines, and the fungus may die. Cold temperatures slow and sometimes halt fungal growth, but often do not cause death.

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

Fungal Aerobiology

The fungal spore is designed for disseminating the organism. Fungal spores may be transferred to new sites in many ways, depending on the mode of spore production and on the nature of the spores. There are generally two groups of "indoor" spores with respect to dispersal: hydrophilic spores that wet easily and are often sticky, and hydrophobic spores that are dry, waxy and often have spiny ornamentation on their outer walls.

Hydrophilic spores are spread by droplet splash, other forms of water transfer, and by arthropods and other animals to which the spores tend to stick. Ascospores are primarily of this type. When rain begins (especially in the spring) ascospores are often released in great abundance, and remain in the air as long as the rain continues. Also included in this group of spores is the infamous Stachybotrys, which produces its spores in wet clusters. These spores are not readily airborne, and, though the fungus is very common in outdoor environments, the spores are present only occasionally in outdoor air. In indoor environments, the spores only become airborne when disturbed during cleaning or remediation activities. Other common fungi in this group include Acremonium, Fusarium, and Chaetomium.

Hydrophobic spores are designed to travel through the air on dry sunny days. Some hydrophobic spores are injected into the air by active spore discharge mechanisms. This group includes basidiospores (released from mushrooms and shelf fungi (including the brown and white rot fungi). The spores are forcibly discharged when the dew point at the spore bearing surface is reached. The spores are then transported through dry air. Many of the common indoor fungi produce hydrophobic spores (Cladosporium, Penicillium, Aspergillus, and many others). These fungi generally do not have "active" discharge mechanisms, but the spores are readily released by air currents and minimal disturbance.

Bacteria

Bacteria are microorganisms that differ from fungi, plants and animals by having no organized nucleus and no complex membrane systems in their cells. 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 contain peptidoglycans and 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 (e.g., Staphylococcus, Micrococcus), and the genus Bacillus which produces very resistant structures called endospores. The organism causing anthrax is a Bacillus species (*Bacillus anthracis*). Some actinomycetes also produce endo-spores, including members of the genus Thermoactinomyces, which grow at high temperatures and are known to contaminate HVAC components [7]. Mycobacterium, a bacterial genus that include organisms that cause tuberculosis and leprosy, and that are suspected to cause hypersensitivity pneumonitis, are also Gram positive. A second staining procedure (the acid fast procedure) is used to separate these from other Gram-positive organisms.

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 and Water, Temperature and Light

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 dose response relationships are complex, and bacterial endospores are resistant.

Bacterial Aerobiology

Bacteria are 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 may cause deterioration of building products and human disease. Bacteria 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 [8,9]. In addition, the thermophilic actinomycetes can contaminate elements of heating systems where water is available and where temperatures consistently reach 50 °C [10].

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 [11]. Mites can use human skin scales for food, so that food is always present. However, mites absorb water directly from the air, and will not survive when relative humidity is consistently below 50% [12].

Human Health Effects [13]

Hypersensitivity Diseases

Many of the biological agents that contaminate buildings cause hypersensitivity disease, a term that will be used here to refer to both immunoglobulin E (IgE) and cell-mediated reactions. These diseases are caused by exposures to complex molecules called allergens. There are two general forms of allergic disease: IgE-mediated, and cell mediated. IgE mediated disease occurs when allergens stimulate over time the production of allergen specific IgE molecules which then attach to MAST cells. Subsequent allergen exposures then cause the MAST cells to break open to release histamine. If the upper airways are inflamed by the histamine, then hay fever symptoms result. If the lungs are involved, then the person develops symptoms of asthma. Cell mediated hypersensitivity also results from (usually intense) exposure to very small particle allergens. In this case, cells in the lung become activated, and subsequent exposures lead to the release of several different inflammatory agents, resulting in the symptoms of hypersensitivity pneumonitis (fever, chest tightness, cough, progressing to pulmonary fibrosis). Note that all allergic diseases involve two steps: sensitization, which prepares specific cells or circulating molecules to recognize specific foreign material (e.g., a particular allergen), and subsequent exposure to the same foreign material, which elicits symptoms. Frequent, often long-term, exposure is required for sensitization. IgE-mediated sensitization and exposure may occur in normal outdoor air as well as in buildings where allergen producing organisms are living. Common organisms that release potent allergens into the environment include dust mites, cockroaches, cats, dogs, mice, and fungi. Cell-mediated hypersensitivity is much more uncommon than IgE-mediated allergy, and is most often caused by occupational exposures to allergen aerosols. However, bacteria in humidifiers, thermophilic actinomycetes in heating systems, and fungi in hot tubs have all been reported as sources for these allergen aerosols.

Evidence for the role of moisture-related organisms in hypersensitivity disease is strong. Case reports, experimental evidence, and epidemiological evidence form a body of proof for the connections. Approximately 40% of the world population has the ability to develop IgE-mediated allergy. Dust mites and cockroaches are responsible for a large part of the morbidity associated with allergy and asthma. In addition, at least 10% of the population (80% of asthmatics) are sensitized to fungal allergens and many of these have particularly severe asthma. Several epidemiological studies have related dampness indicators with respiratory illness in children, although the role of allergy in these relationships remain unclear. Studies regarding actual exposure to fungi and symptoms of allergy in damp homes are less common, and documented levels of mold often are not correlated with dampness.

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. Cryptococcus is another fungus that grows on bird droppings, especially in dry environments (e.g., attics). Cryptococcus is an opportunistic fungus, but infection can occur in immunocompetent people with sufficient exposure. Infections with other 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, some cancer patients, people on long term steroid treatment for severe asthma). Bacterial infections known to be related to moisture and structural contamination of indoor environments are Legionnaires' disease and (rarely) other opportunistic bacterial infections [14]. 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

Fungal growth on substrates in buildings may lead to the presence of fungal toxins in the indoor environment. The mycotoxins, in particular, have been the focus of much attention recently, especially in the courts. Mycotoxins are nonvolatile fungal metabolites that are formed by some fungi under some conditions. Most of the fungi produce one or more mycotoxins under some conditions. The production of the toxins is dependent on the species of fungus, genetic pattern of the specific strain of the species, and environmental conditions. The most important environmental factor is probably the chemical nature of the food source. Without the proper building blocks, these toxins cannot be produced. Thus, *Aspergillus flavus*, the well-known producer of the potent carcinogen aflatoxin B1, produces abundant toxin on rice, peanuts and soybeans, but none on wall board.

Although mycotoxins clearly have serious health effects when ingested, very little data support a role for them in inhalational disease. This is not an indication that the toxins could not have an effect by inhalation. In fact, experimental evidence clearly indicates that such effects do occur in laboratory animals. However, doses by inhalation that are large enough to result in sufficient toxin to cause disease have not been reported in the home or office environment, and only very rarely in agricultural environments where toxin-containing spore exposure may range into the billions per cubic meter of air.

The initial cause of serious concern with mycotoxins in homes was the result of a CDC study that initially made a connection between exposure to *Stachybotrys chartarum* and pulmonary hemosiderosis in babies in a poor section of Cleveland. This finding was widely publicized in the press and other media, leading to fear and panic in some. A subsequent study that demonstrated that the connection had not been made, and that other factors were as or more likely to have been involved did not make the national press and has been essentially ignored by the public. Although a great deal of money and time and energy has been spent on attempts to document mycotoxicoses related to indoor air exposure, to date, no published studies convincingly make a case for the connection, and most studies have the serious flaw that in-

TABLE 1—Summary of well-documented diseases caused by organisms that grow in buildings.

Disease Type	Disease Name	Symptoms	Agents	Environmental Sources
Infections	Legionellosis	Pneumonia	Bacteria	Hot water
Allergies	Hay fever Asthma	Congestion Wheeze	Allergens from fungi, dust mites, cockroaches, etc.	Outdoor air; Damp surfaces & materials; dust
Pneumonitis	Hypersensitivity pneumonitis, allergic alveolitis	Flu-like; chest tightness, cough	Highly reactive antigens from fungi, bacteria,	Warm damp material; humidifier, sauna, hot tub water
Toxicoses	Humidifier fever	Fever, chills, mucous membrane and airway inflammation	Endotoxin	Water, wet surfaces, humidifiers, saunas, other water reservoirs

sufficient exposure has been documented in natural situations, or that very high concentrations of spores have been used in experimental settings. At this point, my belief is that mycotoxicosis related to inhalational exposure in residential and office settings is extremely rare, and has never been clearly documented to have occurred. Until solid evidence is available documenting such effects, concentration should be placed on the real and important effects of the fungi in allergic and other hypersensitivity diseases.

Volatile organic compounds that cause characteristic odors can be released from fungal growth. Although the odors themselves are irritating, actual physical effects of these compounds have not been clearly documented, and measurements of the actual compounds have indicated that odor thresholds are very low, and concentrations even in the presence of extensive fungal growth are unlikely to cause serious illness. However, very few studies have been reported to date, and it is possible that further effort will reveal some health connections.

Bacterial endotoxin [15] 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.

Prevention of Microbial Growth in 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 (Table 1).

Dust mites absorb water from the air, and dust mite populations can essentially be controlled if humidity is kept below 50%. This fact is documented in studies of inner city Boston homes where winter temperatures indoors tend to be high, forcing relative humidity down. In these homes, cockroaches tend to abundant, but dust mites and their allergens may be essentially absent. In homes where humidity cannot be kept below 50%, controlling exposure is the best approach. This is usually accomplished by covering mattresses and bedding with “allergen-proof” encasings, washing bedding in hot water, and keeping carpeting and stuffed toys and furniture to a minimum. Cockroach populations respond to the combination of available food and liquid water. Good housekeeping, combined with high-quality maintenance of plumbing, and sealing of access points from one room or one apartment to another are appropriate control measures.

Fungi and bacteria are especially a problem since they are ubiquitous in outdoor air, and readily enter buildings along with ventilation air. 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 85–90%. 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 [4]. 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 occupancy, 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 de-

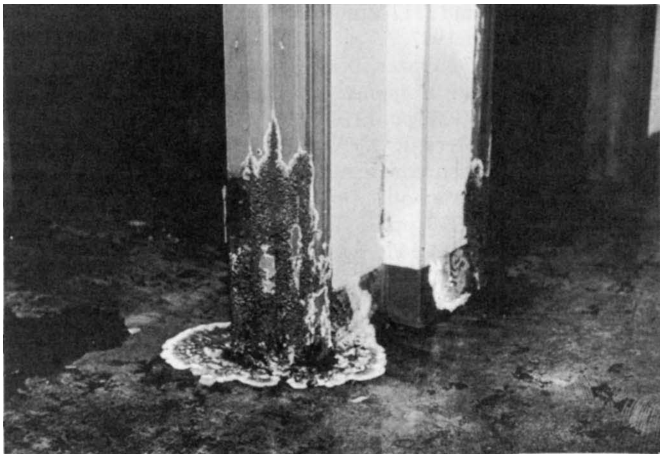


Fig. 2—*One of the white rot fungi* contaminating flood-damaged wood and particle board. Photo courtesy of Adrienne Oudbler.

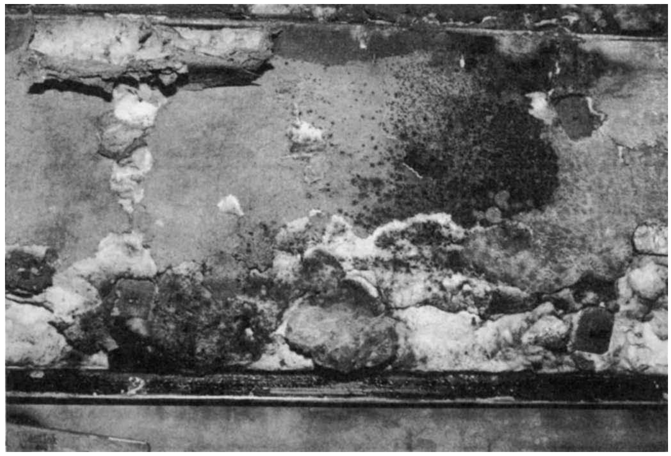


Fig. 3—*Cladosporium* and other fungi contaminating sound lining in an air handling system.

sign (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 and direct exposure to the water (for example during cleanup) could lead to infectious disease. However, these organisms do not grow in the indoor environment, and die relatively quickly once the environment is dry. Once dead, the organisms are of no further concern. This isn't to say that sewage spills should not be cleaned. However, panic is not indicated providing cleanup is done by professionals who know how to manage the risks. Also, it is generally not necessary to discard sewage-contaminated materials provided that they can be thoroughly washed or otherwise cleaned. 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 used that are not highly susceptible to fungal rot (e.g., hardwood or inorganic 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 very 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.

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 75%, 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 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. Biocide treatment will not prevent the return of fungal or bacterial growth. If the water condition that allowed the growth to occur returns, then so will the organisms. Also, dead organisms may be as hazardous as living ones. Biocides are the purview of the infectious disease world where killing the organism renders it innocuous. For most organisms that grow in buildings, this is not the case. Biocides that bind to surfaces may slow the development of growth following a new water event.

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.

Porous materials can usually also be cleaned, although moldy carpeting will have to be removed for cleaning, a process usually more expensive than simple replacement. Materials that have been degraded by microbial growth do have to be replaced. Unfortunately, the fungi growing on wall board do use the cellulose for food. If the growth is attacked quickly, simple washing and painting may solve the problem. However, long-standing growth will lead to deterioration of the surface of the board. 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.

REFERENCES

[1] Pan, F., Q. Yang, et al., "Biodegradation of polycyclic aromatic hydrocarbons by Pichia anomala." *Biotechnol. Lett.*, Vol. 26, No. 10, 2004, pp. 803–806.

[2] Zheng, Z., and J. P. Obbard, "Oxidation of polycyclic aromatic hydrocarbons by fungal isolates from an oil contaminated refinery soil." *Environ. Sci. Pollut. Res.*, Vol. 10, No. 3, pp. 173–176.

[3] Garcia-Guinea, J., V. Cardenes, et al., "Fungal bioturbation paths in a compact disk." *Naturwiss.*, Vol. 88, No. 8, 2001, pp. 351–354.

[4] Aisner, J., Schimpff, S. C., Bennett, J. E. et al., "*Aspergillus* Infections in Cancer Patients: Association with Fire Proofing Materials in a New Hospital," *J. Am. Med. Assoc.*, Vol. 235, 1976, pp. 411–412.

[5] Merrill, W. and French, D. W., "Decay in Wood and Wood Fiber Products by *Sporotrichum pruinosum*," *Mycologia*, Vol. 58, 1966, pp. 592–596.

[6] Frankland, A. W. and Hay, M. J., "Dry Rot as a Cause of Allergic Complaints," *Acta Allergol*, Vol. 4, 1951, pp. 186–200.

[7] Koneman, E. W., Allen, S. D., Dowell, V. R., Jr., Janda, W. M., Sommers, H. M., and Winn, W. C., Jr., *Color Atlas and Textbook of Diagnostic Microbiology*, 3rd ed., J. B. Lippincott, Philadelphia, 1988.

[8] Burke, G. W., Carrington, C. B., Strauss, R., Fink, J. N., and Gaensler, E. A., "Allergic Alveolitis Caused by Home Humidifiers," *J. Am. Med. Assoc.*, Vol. 238, 1977, p. 2705.

[9] Fraser, D. W., "Sources of Legionellosis," in *Legionella, Proceedings of the 2nd International Symposium*, C. Thomsberry, A. Balows, J. C. Feeley, and W. Jakubowski, Eds., American Society of Microbiology, Washington, DC, 1984, pp. 277–280.

[10] Fink, J. N., Resnick, A. J., and Salvaggio, J. E., "Presence of Thermophilic Actinomycetes in Residential Heating Systems," *Appl. Microbiol.*, Vol. 22, 1971, p. 730.

[11] Bernton, H. S. and Brown, H., "Cockroach Allergy II: The Relation of Infestation to Sensitization," *South Med. J.*, Vol. 60, 1967, pp. 852–855.

[12] Arlian, L. G., "Biology and Ecology of House Dust Mites, *Dermatophagoides ssp* and *Euroglyphus ssp*," *Immunol. Allergy Clinics North Am.*, Vol. 9, No. 2, 1989, pp. 339–356.

[13] Burge, H. A., "Bioaerosols: Prevalence and Health Effects in the Indoor Environment," *J. Allergy Clin. Immunol.*, Vol. 86, No. 5, 1990, pp. 687–701.

[14] Burge, H. A., "Indoor Air and Infectious Diseases," *Occupational Medicine: State of the Art Reviews*, S. E. Cone and M. Hodgson, Eds., Vol. 4, No. 4, 1989, pp. 713–721.

[15] Milton, D. K., Gere, R. J., Feldman, H. A., and Greaves, I. A., "Endotoxin Measurement: Aerosol Sampling and Application of a New *Limulus* Method," *Am. Ind. Hyg. Assoc. J.*, Vol. 51, No. 6, 1990, pp. 331–337.

6

Exterior Climate Data for Hygrothermal Analysis

John F. Straube[1]

THE GOAL OF THE PROPOSED CHAPTER IS THE presentation of climatic loading information appropriate for the hygrothermal (heat, air, and moisture) design and analysis of building enclosures (primarily above-grade walls, windows, and roofs). Building design professionals currently have very little guidance about regionally varying hygrothermal loads (such as driving rain, solar radiation, and night sky cooling) for enclosures. The result is often inappropriate enclosure designs or products for some climates, which result in rot, mold, corrosion, decay, freeze-thaw, and other damage. The growing use of computer-based building enclosure models also demands more and different climate information.

Although it is both the difference and absolute value of the exterior and interior conditions that influence the load on the enclosure, this chapter will focus on the exterior conditions. The interior and exterior environmental conditions can conveniently be studied as separate entities, but it must be borne in mind that internal activities and processes can have a significant impact on the interior environment (e.g., stack effect pressures and interior humidity) and they combine with exterior conditions to create the difference that is the load on building enclosures.

Introduction

North American climatologists have been collecting certain basic weather data for well over a century. The most important environmental measures for building enclosure design purposes (see Figs. 1 and 2) can be listed as:

- temperature (both absolute and differences),
- humidity [both absolute and relative humidity (RH)],
- solar insolation [infrared, visible light, and ultraviolet (UV) radiation],
- wind (speed, direction, and the resulting pressure differences), and

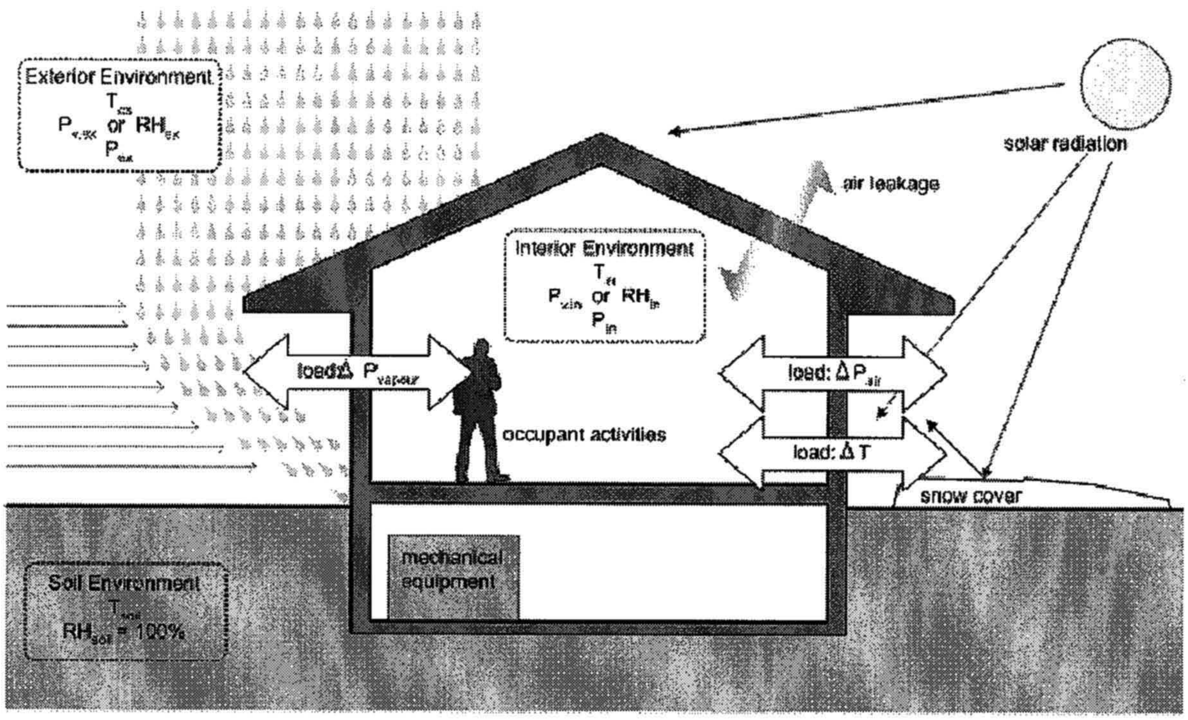


Fig. 1—Environmental factors influencing enclosures [1].

[1] *Building Science Corp., 70 Main St., Westford, CT 01886.*

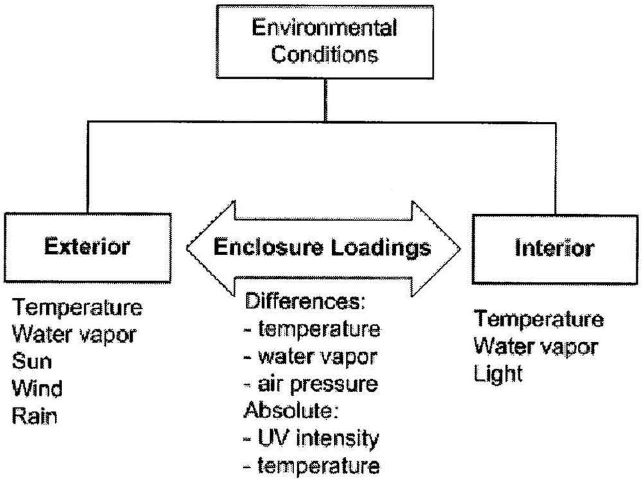


Fig. 2—Environmental conditions and enclosure loadings [1].

- precipitation (in the form of rain, snow, hail, sleet, etc.).

Many other building-related measures are important, such as the number of freeze-thaw cycles, the amount and direction of wind driven rain, and time-of-wetness, but these can be derived from the other five primary measures. In fact, even the five primary determinants listed above are highly correlated—for instance, extensive rainfall typically implies little sun, high humidity, and above-zero temperatures.

Although some research has been conducted to relate the durability and performance of enclosures to specific interior and exterior environmental factors (i.e., the IEA Annex 24, and the Institute for Research in Construction MEWS project), these attempts presume a certain type of enclosure and/or ignore potentially important environmental elements. The approach taken in this chapter is to define the primary environmental loads independent of enclosure type. The designer or analyst can then use such information to assess, for example, the exposure and susceptibility of a specific enclosure to certain types of performance problems, and enter the data themselves into computer models.

The environmental conditions around a building can vary significantly in both space and time. For example, the outdoor temperature is usually quite different in, say, Miami from Minneapolis and usually also differs at any given location between winter and summer. Subsequent sections will deal with the exterior building environment from both a temporal and a spatial perspective.

Spatial Climate Considerations

Exterior Climate

Exterior environmental conditions can vary dramatically and often unpredictably. Various terms are used to define different scales in time (e.g., climate versus weather) and different spatial scales (e.g., climate zone versus microclimate). Climatologists and meteorologists have developed most of the terms, but the focus of these professions is somewhat different from that of building or enclosure designers. Hence, a review and some building-specific definitions are necessary.

Weather refers to the collective meteorological conditions at a specific location at a specific time whereas climate is a descriptor of average weather conditions over the long term [2]. Both climate and weather typically refer to conditions over at least several square kilometers in normal usage. The term microclimate is used for relatively small-scale differences. Microclimate may be used to describe the weather or climate conditions within, for example, a small valley, or on the south slope of a hill, or on a wall locally sheltered by an overhang.

Any precise definition of environmental conditions must incorporate both a temporal and a spatial scale. Six categories of spatial scale are proposed in Table 1 for the exterior environment; each is considered to be relevant to the study of building enclosures. Each of these climate scales is briefly discussed below.

The macroscale is a climatic zone, e.g., the Prairies, hot-dry areas, etc., and has a scale of several hundreds to thousands of kilometers [3,4]. In design with climate, Olgyay [5] recommended a total of only four regions to cover all of North America, based primarily on the Koeppen classification. Koeppen's classification was first proposed in 1900, and it is based on the response of flora to a range of variables.

Lstiburek [6] uses modified definitions of these regions to define six North American climate zones: Hot-humid, Hot-dry/Mixed-dry, Mixed-humid (or Temperate), Cold (or Heating), Severe cold and Arctic (Fig. 3). This classification, one of the more widely used by designers and practitioners,

TABLE 1—Spatial climate variations [1].

Prefix	Synonym	Approximate Dimension	Example	Modifiers
Macro	Zone	500 to>1000 km	Gulf Coast, Prairies	Ocean currents, vegetation (type, coverage)
Meso	Region	1–500 km	New York City, Great Lakes	Topography, vegetation, elevation, development intensity
Micro	Site	10 m to 10 km	Leeside of south facing hill	Slope, terrain, vegetation water bodies, orientation
Micro	Building	1 to >100 m	East face, behind row of trees	Massing, shape, solar absorption, vegetation, overhangs, and orientation
Micro	Enclosure surface	0.1–10 m	Below a window sill	Orientation, surface features, color
Nano	Detail	1–100 mm	At a screw hole or drip edge	Texture, cracks, grooves, shadows

Fig. 3—Lstiburek's climate zone classification [6].

is primarily based on his wide experience with housing across North America.

The mesoclimate or local climate, e.g., the climate of a city or county, may be defined as the subset of the macroclimate that is commonly affected by local topography, vegetation, and human activity [3,4]. For building design purposes, mesoclimates tend to have a range of about 1 km to as much as 100 km. The spatial scale of the mesoclimate varies dramatically with topographical features—local climates can vary significantly within 2–5 km in a valley, along a coast, etc., but may be quite similar at locations 50 km apart as on the Prairies and in the desert. Most long-term climate data are collected in open grassed areas at airports. The mesoclimate is rarely modified by a single building, but it can be modified by intense urban development, deforestation, etc. For example, the so-called "heat island effect" commonly causes average summertime temperature increases of 3–5°C near the center of large cities.

The site-specific microclimate, with a scale from a few tens to several hundreds of meters is often very important for building design. Specific site features such as wind breaks, earth berms, ground cover, etc., modify the climate at each building site differently. Together, the site-specific and building-specific microclimates may be considered to represent the building's "exposure."

The building-specific microclimate, is that climate caused by direct interaction of the site microclimate with the built facility itself, i.e., the size, shape, massing, color, reflectivity, etc. For example, the brick cladding on a wall may store solar energy and warm the air near the building; the

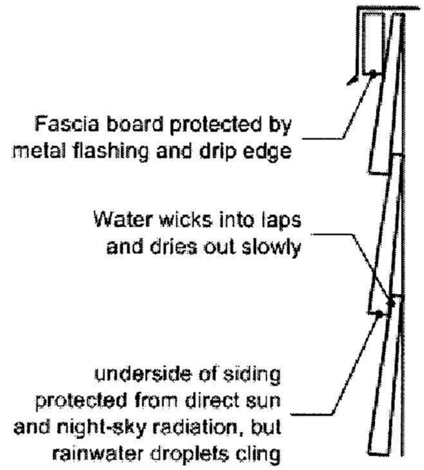


Fig. 4—Nanoclimate at lapped siding [1].

two parts of a built facility may channel snow or wind between them; or a courtyard shaded by a building can be protected from sun and wind.

The enclosure-specific microclimate is that climate on or very near the surface of the enclosure caused by direct interactions with the building enclosure itself and has a scale of a tenth of a meter to as much as 10 m. For example, overhangs influence the deposition of rain and solar radiation on the wall below, and roof parapets influence the local wind pressures both in front and behind them.

The nanoclimate [1] has a spatial scale ranging from less than a millimeter to nearly a meter. This environmental scale is primarily of interest for assessing and understanding local material deterioration. For example, the environmental conditions experienced by the area just below a lap in hardboard siding, the area around a nail, and the underside of a projecting fascia board are quite different. They apply to areas from less than one to several square meters (Fig. 4).

Time Scale of Exterior Conditions

The time scale of the exterior climate has already been used to distinguish climate from weather, but there are other aspects to consider as well. Typical data sets (often based on a 30-yr set of data), include:

- annual average, annual average extreme, and extreme values,
- seasonal mean (e.g., summer or winter),
- mean and average daily maximum and minimum of coldest and hottest months, or of January and July,
- daily mean, annual, or extreme maximum, minimum, and range (the difference of the maximum and minimum),
- hourly average, 15-min samples, peak values.

Different scales apply to different building and enclosure analysis problems. For example, average annual values may be useful for choosing deep basement exterior temperatures, whereas values for peak summer temperatures (which are coincident with high humidity) are necessary for the design of air conditioning equipment. Hence, no single temporal scale is the most appropriate for an enclosure analysis.

ASHRAE has defined design conditions as being based on the percentage of hours exceeded on an annual basis. Hence, the 0.4 % temperature used for cooling design is that temperature exceeded for 0.4 % of 8,760 h (35 h/yr), and the 99 % temperature used for heating design is that temperature below which only 1 % of hours fall per year (88 h). Since these values are climate data (averaged over 15 to 30 yr), a given year may have more or fewer hours above and below a certain threshold. The ASHRAE *Handbook of Fundamentals* [7] provides such data for hundreds of locations throughout North America and the world.

Although extreme values for mechanical equipment sizing are the most commonly available climate data, they are almost never useful for most building enclosure analysis. The use of extreme cold or hot conditions to assess, for example, condensation is inappropriate since condensation rarely causes problems if it occurs for only a few hours. In fact, for simple enclosure analysis the average monthly temperature may be one of the most useful basic data sets. Because of the emphasis on equipment sizing in design, average temperatures are not as readily available to design professionals.

The National Climatic Data Center (NCDC) of the National Oceanic and Atmospheric Administration (NOAA) is a source of more detailed climate data. Monthly average temperatures based on 30-yr records are available for thousands of sites.

Hourly data are almost mandatory for most hygrothermal enclosure modeling. These data are not as widely available, but the National Renewable Energy Laboratory produces a CD of hourly test meteorological years (TMY2). These files are synthetic weather data calibrated to result in average energy consumption. For many building design purposes, such hourly TMY2 files provide sufficiently representative data to be useful.

Exterior Climate Elements

Meteorologists define a climate element as one property or condition of the atmosphere that helps specify and describe the weather. Many climate elements are measured at weather stations around the world at hourly or daily intervals, including temperature, humidity, wind, rain, snow, sunshine, water balance, etc. The elements most important for building enclosure design and assessment are considered below.

Temperature

The most commonly quoted climate measure is temperature. Temperature may not be as important as some other climatic constituents, but it is easy to measure and has been recorded for well over a century.

Temperature is important for assessing the potential for air leakage condensation, diffusion, energy consumption, drying, and other enclosure performance issues. In most cases average monthly temperatures are sufficient to assess this kind of behavior. Hourly temperatures are needed for detailed and/or dynamic analysis.

Heating and cooling degree days (HDD and CDD) provide an annual integrated temperature difference across the enclosure of an assumed building type. These readily available measures are not very useful for the hygrothermal analysis and design of enclosures but do identify broad climate zones.

Moisture Content of the Air

The moisture content of the outdoor air is important to the performance of building enclosures because the enclosure can be a source of moisture or a sink for the removal of unwanted moisture.

Moisture in the outdoor air is generated from rainfall and stored in plants, soil, and surface bodies of water. Hence, locations with high rainfall and vegetation cover tend to have high RH. Since the capacity of air to hold moisture varies dramatically with temperature locations with high temperatures and rainfall (one description of a tropical climate) also tend to have very high air moisture contents.

The moisture content of the outdoor air can be calculated from measurements of dewpoint temperature, vapor pressure, or a combination of temperature and RH (using equations given in various texts). One of the most useful measures of air moisture content is the humidity ratio. Given average monthly temperatures, average RH can be calculated from the humidity ratio.

Maps and statistical descriptions of derived measures directly useful for designing building enclosures are not readily available. For example, to assess the potential for dew forming on exterior surfaces of enclosures, the air moisture content, the night air temperature, and clearness of the sky need to be combined. This information is not readily available.

Sun

The Sun is one of the two primary sources of energy on the Earth (stored energy from the molten core being the other). Understanding its behavior is therefore important to the performance of enclosures and the energy consumption of buildings.

For enclosure design, knowledge of the quantity of solar radiation is important for both the heating and the UV exposure of the exterior cladding. Solar heating dramatically increases the drying of all parts of the enclosure (particularly the exterior), increases the drying capacity of ventilation, reduces the potential for cold weather condensation, and can redistribute moisture from rain wetted cladding inward.

Solar heating can be calculated given the solar energy delivered to a surface oriented in any arbitrary manner using techniques described in numerous textbooks [8] and handbooks [7].

Weather files, such as TMY2, often provide the solar radiation on a horizontal surface. This is useful as a measure of climate and directly provides information for roof exposure but does not indicate the exposure of different orientations. The north face receives much more radiation in southern latitudes than northern latitudes, for example.

Wind

From both a structural and a hygrothermal design point of view, a critically important climatic element to consider is the wind. Because of its importance to building design, wind behavior has been studied extensively by others especially for structural design purposes.

Although many wind engineering resources are available, this section reviews wind pressures primarily as they relate to the hygrothermal aspects of building enclosure design.

Wind pressure on a building varies with wind speed as

$$p = C_p \frac{1}{2} \rho V^2$$

where p is the stagnation pressure (Pa),
ρ is the air density (kg/m^3),
C_p is a pressure coefficient, and
V is the air velocity (m/s).

The pressure on a building surface varies in time and space. The temporal variation is largely random, but the spatial variation depends on factors such as the angle of attack, upstream roughness, and building shape. The ASHRAE Handbook [7] provides a range of typical pressure coefficients (C_p) for simple building shapes and different angles of attack.

The average monthly wind speed and direction can be converted into pressure using the above equation. The average pressure allows the analyst to predict how much pressure will be acting to drive air through the building enclosure or how much wind pressure is available to drive natural convection. Finally, the wind pressure during rainfall provides data of the pressure available to drive rainwater past the cladding.

Driving Rain

Driving rain can be an important, even dominant, moisture load for building enclosures, especially those with absorbent claddings and leaks. Dynamic computer models that include moisture storage require hourly driving-rain data but practical limitations exclude present CFD driving-ran models from design offices. Hence, simple but reasonably accurate methods would be useful.

As a climatic measure, the quantity of driving rain that passes through a vertical plane 10 m above grade can be accurately calculated [9] on an hourly basis as

$$r_v = \mathrm{DRF}(r_h) \cdot V(h) \cdot r_h$$

where r_v is the driving rain (mm/m^2),
DRF is the driving-rain factor,
V is the wind speed at 10 m, and
r_h is the rainfall rate or intensity on a horizontal plane (mm/m^2/h)

has been shown to accurately predict this is suggested as a simple approximate means of predicting driving-rain deposition on a building face from hourly weather records of wind speed, direction, and rainfall. The value for the DRF for a particular raindrop size can be calculated quite precisely from rainfall data using [10]:

$$1/\mathrm{DRF}(\varnothing) = -0.166033 + 4.91844 \cdot \varnothing - 0.888016 \cdot \varnothing 2$$
$$+ 0.054888 \cdot \varnothing 3 \leq 9.20$$

and

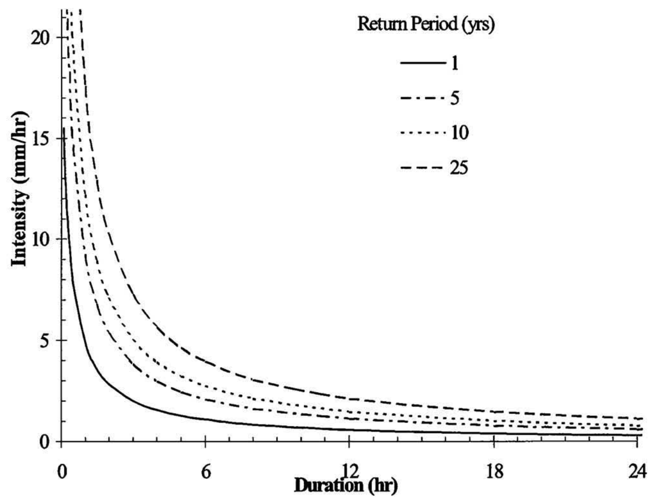


Fig. 5—Intensity-duration-frequency curves for Waterloo, Canada.

$$F(\varnothing) = 1 - \exp\left\{ -\left(\frac{\varnothing}{1.30 r_h 0.232} \right) 2.245 \right\}$$

where $F(\varnothing)$ is the cumulative probability distribution of drop diameters for a given rainfall intensity, and $\varnothing$ is the equivalent spherical raindrop diameter (mm).

These equations are used to calculate the DRF from the median drop diameter using the rainfall intensity at every hourly interval. In lieu of this detailed calculation, a DRF of between 0.20 and 0.25 can be chosen for most locations (as Lacy [11], Kuenzel [12], and Frank [13] have).

To assess the amount of rain on a building facade, the calculated r_v should be modified for the height, shape, exposure, and terrain. The rain deposition factor is used to estimate the impact of these factors (see also ASHRAE 160P and Ref. [14]):

$$r_{bv} = \mathrm{RDF} \cdot \cos(\theta) \cdot r_v$$

where r_{bv} is the driving-rain deposition on a wall (kg/m^2 or mm/m^2),
RDF is the rain deposition factor, and
θ is the angle of the wind relative to the wall orientation in question.

For a 10-m tall square building with a flat roof, the RDF equals 1.

Rainfall intensity is related to the duration of the rain event and likely occurrence of the event. Short rain events can be more intense, and rain events that deliver a large amount of rain in a short period of time are rare. These relationships are defined by intensity-duration-frequency curves, often available for specific location because of their importance for the design of stormwater management systems. These are useful for the definition of extreme (once per year or less often) rain events that may stress certain enclosure systems. (See Fig. 5.)

Climate Data Sheets

Important and sometimes difficult to find design information has been summarized for ten North American cities in the building enclosure design data sheets at the end of this chapter. The primary source of these data was TMY2 hourly data files. Climate normals from Environment Canada and NOAA were also used, along with data from the ASHRAE Handbook. Information such as monthly average temperatures, humidity ratio, solar radiation, wind speed, etc., are simply calculated averages from the hourly records. The driving-rain data were calculated using the equations given earlier.

The wind rises show the average annual wind speed from each direction of a 16-point compass. The frequency of occurrence of wind from each direction is shown as a percentage of all hours. The percentage of hours when the wind was calm is shown in the bottom right corner of this plot.

The amount of driving-rain deposition expected at the top of a fully exposed three storey millimeters building oriented in one of 16 directions is shown in millimeters per year (equivalent to liters per square meter) in the upper right plot of the data sheet.

The number of hours per year that fall within 2 °C (3 °F) and 10 % RH bins are shown in the central figure of the data sheet. Since the humidity ratio and vapor pressure can easily be calculated for the conditions of each bin, this plot can also be used to estimate the number of hours at specific air moisture contents.

The tabulated data at the end of the paper provide monthly values of temperature, RH, humidity ratio, wind speed, and wind speed during rainfall. The total monthly snowfall, rainfall, driving rain (the sum of all directions), and hours of rain are also provided. Finally, to provide an assessment of solar radiation, the total energy delivered to five surfaces—vertical walls facing the cardinal direction and a horizontal surface—in kWh/m^2 are listed.

Conclusions

Understanding environmental conditions is a critical part of understanding and predicting the performance of building enclosures. Builders of vernacular buildings were often well attuned to their exterior environment and intentionally manipulated the microclimate to their benefit. The design of enclosures for modern buildings, especially complex and large buildings, demands a thorough and often detailed understanding of environmental conditions. This chapter has provided a short overview of some of the environmental conditions that play a significant role in enclosure design and analysis.

References

[1] Straube, J. F. and Burnett, E. F. P., *Building Science for Building Enclosure Design*, Building Science Press, Westford, MA, 2005.

[2] Barry, R. G. and Chorley, R. J., *Atmosphere Weather and Climate*, 6 ed., Routledge, New York, 1992.

[3] *Penguin Dictionary of Physical Geography*, E. J. Whittow, Ed., Penguin Books, London, 2000.

[4] *A Dictionary of Geography*, Susan Mayhew, Ed., Oxford University Press, Oxford, 1997.

[5] Olgyay, V., *Design with Climate*, Van Nostrand Reinhold, New York, 1992.

[6] Lstiburek, J., *Builders Guide to Cold Climates*, Building Science Press, Westford, MA, 2005.

[7] *ASHRAE Handbook of Fundamentals*, American Society of Heating Refrigeration and Air-conditioning Engineers, GA, 2001.

[8] Duffie, J. A. and Beckman, W. A., *Solar Engineering of Thermal Processes*, John Wiley and Sons, New York, 1980.

[9] Straube, J. F., "Moisture Control and Enclosure Wall Systems," Ph.D. Thesis, Civil Engineering Department, University of Waterloo, Waterloo, Canada, 1998.

[10] Dingle, A. N. and Lee, Y., "Terminal Fall Speeds of Raindrops," *Journal of Applied Meteorology*, Vol. 11, August 1972, pp. 877–879.

[11] Lacy, R. E., "Driving-Rain Maps and the Onslaught of Rain on Buildings," *Proceedings of RILEM/CIB Symposium on Moisture Problems in Buildings*, Helsinki, Building Research Station Current Paper 54, HMSO Garston, U.K., 1965.

[12] Künzel, H. M., *Regendaten für Berechnung des Feuchtetransports*, Fraunhofer Institut für Bauphysik, Mitteilung 265, 1994.

[13] Frank, W., *Entwicklung von Regen and Wind auf Gebaeudefassaden*, Verlag Ernst & Sohn, Berichte aus der Bauforschung, Vol. 86, 1973, pp. 17–40.

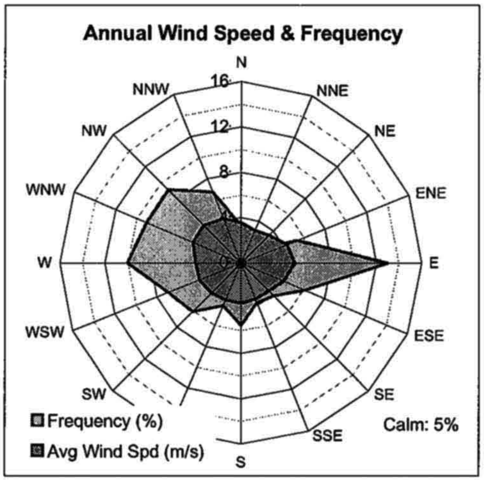
[14] Straube, J. and Schumacher, C. J., "Driving Rain Data for Canadian Building Design," *Proceedings of the 10th Canadian Building Science and Technology Conference*, May, 2005.

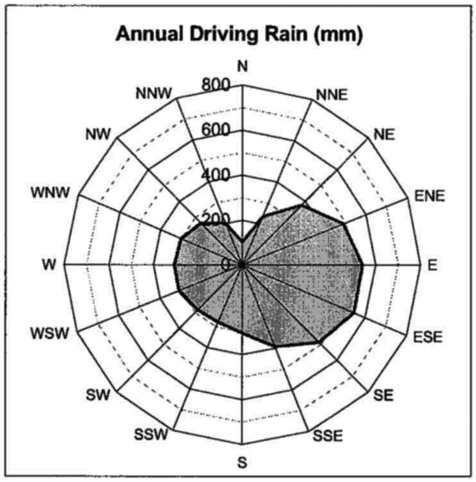
Climate Summary for Building Design — Atlanta, GA USA

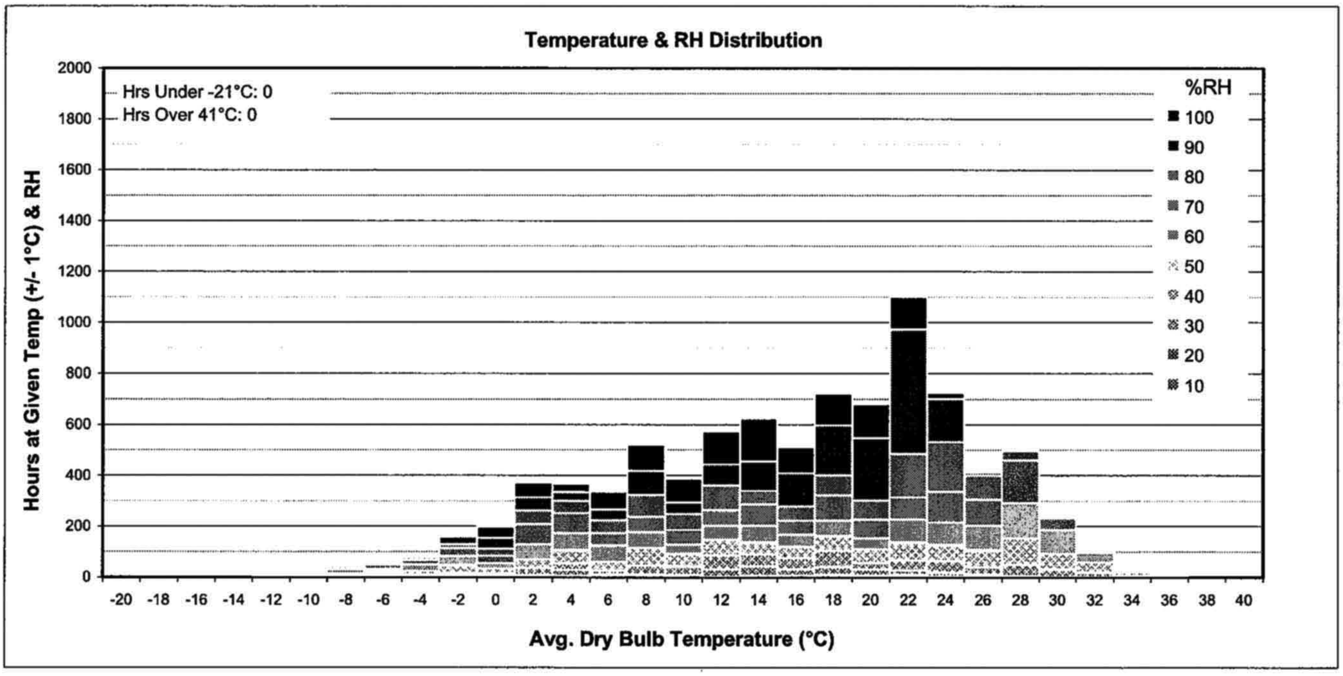
Location	
City	Atlanta
State/Prov	GA
Country	USA
Lat (°)	33.7
Long (°)	-84.4
Elev (m)	315
Time Zone (hrs)	-5

Design Temperatures	
Heating (°C)	-4.9
Cooling (°C)	32.6

Degree Days	
HDD (18°C)	1571
CDD (10°C)	2909







Averages	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec	Year
Temperature (°C)	4.7	6.6	11.6	16.1	21.0	24.1	25.2	24.5	22.6	16.5	10.5	6.6	15.8
RH (%)	69	61	62	62	64	64	74	75	79	70	69	68	68
Humidity Ratio (g/kg)	3.88	4.13	5.28	7.23	9.85	11.86	14.54	14.28	13.39	8.34	5.73	4.53	8.59
Wind Speed - All Hours (m/s)	3.5	3.9	4.9	4.6	4.3	4.0	3.1	2.8	3.7	4.1	3.5	5.0	3.9
Wind Speed - During Rain (m/s)	4.6	4.3	6.2	5.8	5.0	3.2	3.9	3.6	4.7	4.4	4.2	5.9	4.6

Totals		Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec	Year
Snowfall (cm)		2.5	1.3	1.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.5	5.3
Rainfall (mm)		125	118	136	92	100	92	130	93	104	79	104	97	1270
Driving Rain (mm/m²)		113	97	151	90	92	56	102	56	84	59	83	110	1092
Hours with Rainfall (hrs)		84	64	58	20	45	16	56	19	31	23	47	55	518
Solar Radiation (kWh/m²)	N	18	19	30	35	48	53	50	43	35	23	19	17	389
	E	43	50	66	75	87	84	93	89	63	60	47	39	795
	S	92	90	90	75	62	55	58	70	77	108	99	92	967
	W	41	48	66	86	83	84	74	73	68	66	45	40	775
	Horiz	80	96	137	178	196	194	196	180	141	129	89	75	1692

Design Temperatures: ASHRAE HOF 2001
Degree Days: NCDC Climate Normals
Rainfall: NCDC Climate Normals, TMY2
T, RH, Wind, Sun: TMY2

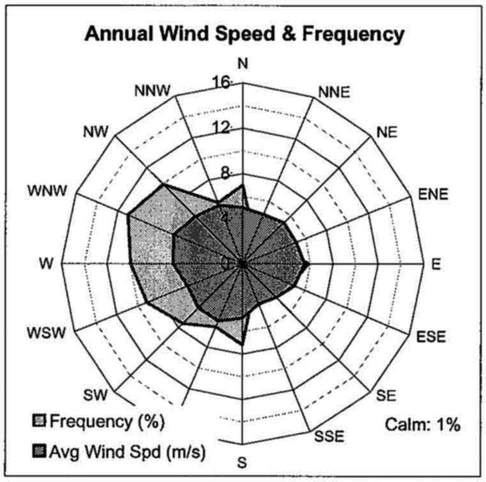
2005.06.07
V 1.0

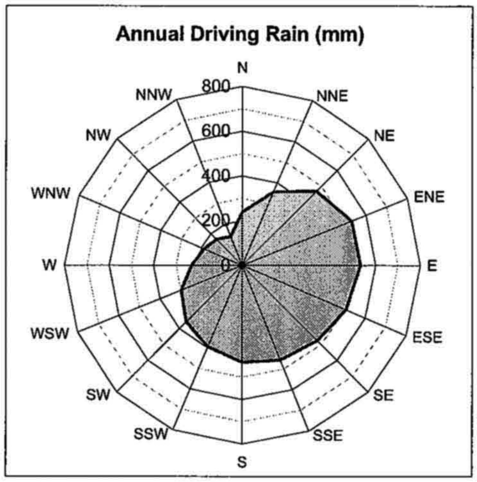
Climate Summary for Building Design — Boston, MA USA

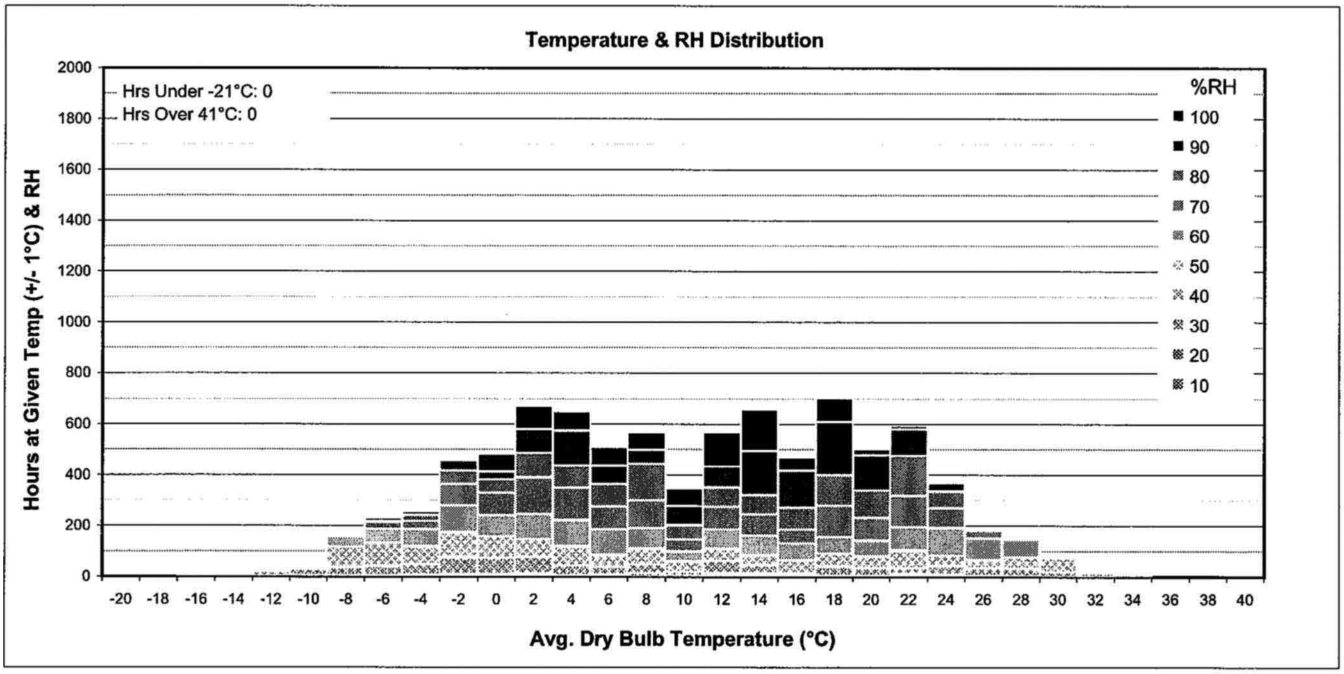
Location	
City	Boston
State/Prov	MA
Country	USA
Lat (°)	42.4
Long (°)	-71.0
Elev (m)	5
Time Zone (hrs)	-5

Design Temperatures	
Heating (°C)	-11.3
Cooling (°C)	30.7

Degree Days	
HDD (18°C)	3128
CDD (10°C)	1656







Averages	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec	Year
Temperature (°C)	-1.5	-0.5	2.5	7.4	14.9	19.3	22.6	21.5	18.1	12.3	5.7	1.2	10.3
RH (%)	56	58	63	70	69	70	68	66	69	69	68	62	66
Humidity Ratio (g/kg)	2.07	2.24	2.86	4.58	7.36	9.65	11.51	10.50	9.00	6.26	4.14	2.93	6.09
Wind Speed - All Hours (m/s)	6.4	5.9	6.1	5.5	5.5	4.2	4.9	4.5	4.6	5.7	6.0	5.7	5.4
Wind Speed - During Rain (m/s)	8.1	5.0	6.3	5.2	7.7	3.4	4.9	4.2	5.0	7.7	8.0	6.2	6.0

Totals		Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec	Year
Snowfall (cm)		32.0	30.2	20.6	2.3	0.0	0.0	0.0	0.0	0.0	0.0	3.3	19.8	108.2
Rainfall (mm)		68	54	77	89	82	82	78	86	88	96	98	75	972
Driving Rain (mm/m²)		96	54	103	98	141	59	78	68	83	137	158	90	1165
Hours with Rainfall (hrs)		22	28	65	115	100	73	50	36	72	44	66	62	733
Solar Radiation (kWh/m²)	N	14	19	24	34	42	49	47	39	28	20	15	13	345
	E	33	41	61	65	79	83	88	79	64	52	30	29	705
	S	83	84	89	74	70	64	69	81	87	99	71	74	945
	W	32	42	56	67	76	81	79	79	60	49	29	27	679
	Horiz	57	77	116	137	173	181	187	168	127	96	56	49	1424

Design Temperatures: ASHRAE HOF 2001
Degree Days: NCDC Climate Normals
Rainfall: NCDC Climate Normals, TMY2
T, RH, Wind, Sun: TMY2

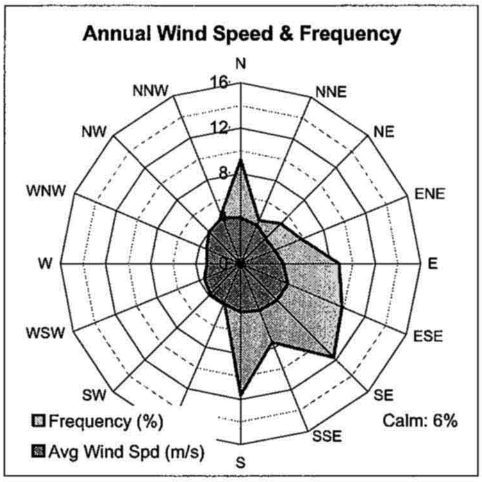
2005.06.07
V 1.0

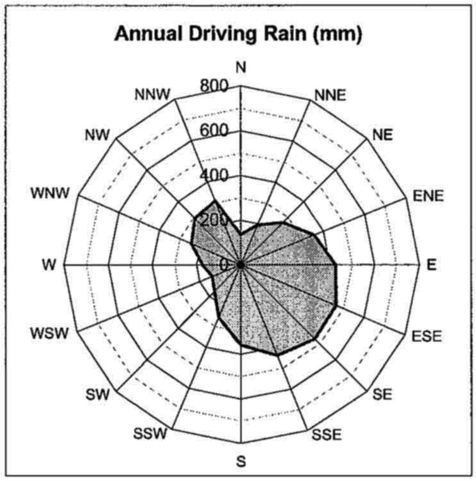
Climate Summary for Building Design — Houston, TX USA

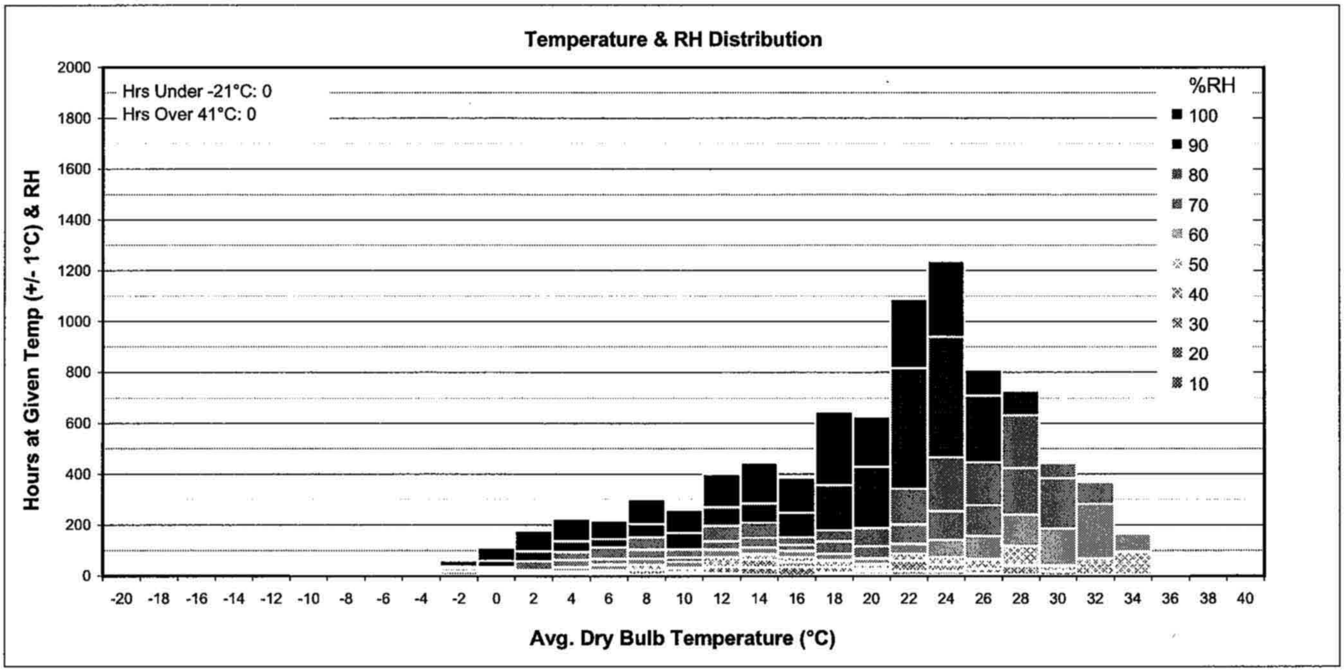
Location	
City	Houston
State/Prov	TX
Country	USA
Lat (°)	30.0
Long (°)	-95.4
Elev (m)	33
Time Zone (hrs)	-6

Design Temperatures	
Heating (°C)	1
Cooling (°C)	34

Degree Days	
HDD (18°C)	652
CDD (10°C)	4255







Averages		Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec	Year
Temperature (°C)		11.9	10.9	16.2	20.5	23.9	26.5	28.0	27.3	25.3	20.9	17.1	11.4	20.0
RH (%)		73	79	69	75	74	74	75	75	73	81	76	79	75
Humidity Ratio (g/kg)		7.36	6.76	8.33	11.41	13.83	15.83	17.56	16.86	14.69	12.51	9.64	7.35	11.84
Wind Speed - All Hours (m/s)		4.5	3.7	4.6	3.9	4.1	3.2	3.5	3.2	3.6	3.5	3.7	3.8	3.8
Wind Speed - During Rain (m/s)		5.1	4.8	5.8	4.4	4.3	2.9	4.7	7.4	3.5	5.8	6.1	4.8	5.0

Totals		Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec	Year
Snowfall (cm)		0.5	0.5	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	1.0
Rainfall (mm)		93	75	85	91	131	136	81	97	110	114	106	94	1214
Driving Rain (mm/m²)		81	55	91	66	96	51	68	91	63	96	111	77	945
Hours with Rainfall (hrs)		41	51	55	33	50	5	24	32	19	31	31	49	421
Solar Radiation (kWh/m²)	N	20	23	29	38	44	53	51	42	32	25	20	19	396
	E	41	41	58	63	72	76	81	79	65	62	45	38	721
	S	83	72	79	60	50	49	53	60	77	95	91	77	847
	W	43	48	64	66	77	83	77	77	67	62	46	38	747
	Horiz	84	93	131	147	174	184	182	171	146	129	94	75	1611

Design Temperatures: ASHRAE HOF 2001
Degree Days: NCDC Climate Normals
Rainfall: NCDC Climate Normals, TMY2
T, RH, Wind, Sun: TMY2

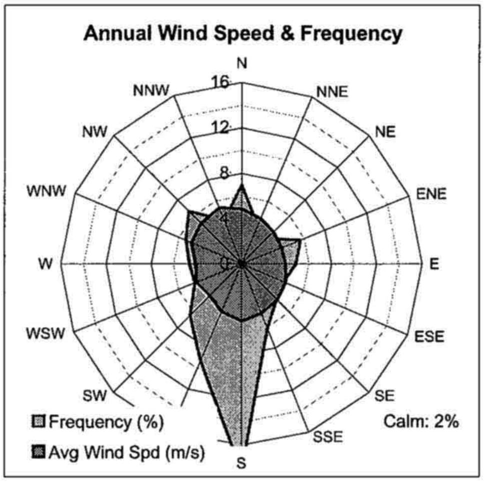
2005.06.07
V 1.0

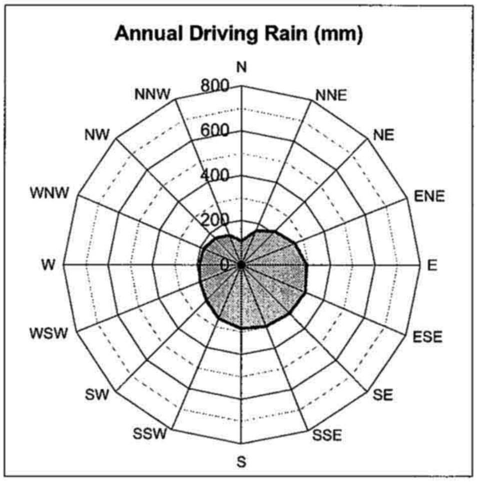
Climate Summary for Building Design — Kansas City, MO USA

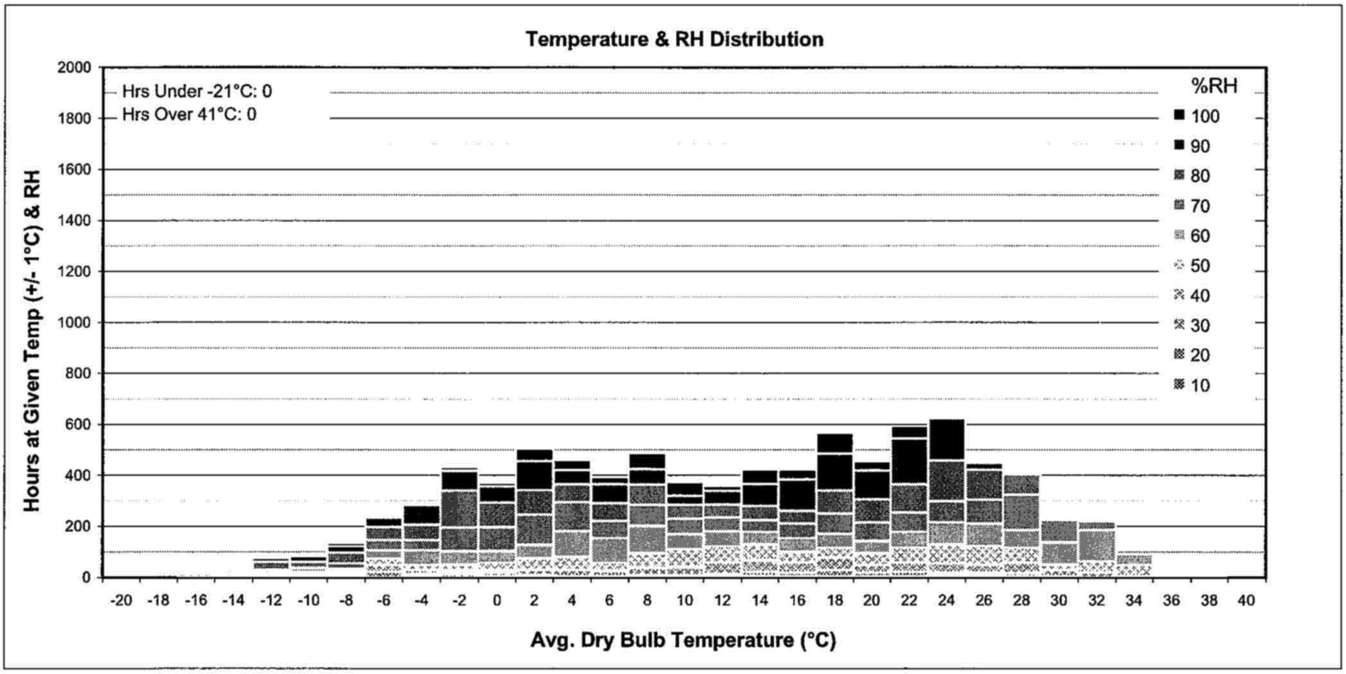
Location	
City	Kansas City
State/Prov	MO
Country	USA
Lat (°)	39.3
Long (°)	-94.7
Elev (m)	315
Time Zone (hrs)	-6

Design Temperatures	
Heating (°C)	-15.4
Cooling (°C)	33.8

Degree Days	
HDD (18°C)	2916
CDD (10°C)	2188







Averages		Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec	Year
Temperature (°C)		-2.6	0.1	5.1	14.6	17.9	23.3	27.6	24.2	19.8	15.2	5.7	0.4	12.6
RH (%)		69	55	59	57	64	74	62	74	69	65	72	65	65
Humidity Ratio (g/kg)		2.22	2.22	3.16	6.06	8.09	13.30	14.21	13.95	9.89	7.26	4.29	2.73	7.28
Wind Speed - All Hours (m/s)		4.5	4.2	5.0	5.2	4.7	3.9	4.1	4.7	3.4	4.4	4.9	4.7	4.5
Wind Speed - During Rain (m/s)		5.2	4.1	5.5	6.5	4.9	4.5	3.9	5.1	3.0	5.1	4.6	5.5	4.8

Totals		Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec	Year
Snowfall (cm)		14.0	11.4	8.6	2.0	0.0	0.0	0.0	0.0	0.0	0.3	3.3	10.9	50.5
Rainfall (mm)		15	22	53	84	137	113	112	90	118	84	55	31	914
Driving Rain (mm/m²)		13	18	55	91	103	77	75	81	53	82	44	36	729
Hours with Rainfall (hrs)		3	14	48	19	19	34	29	26	26	31	27	23	299
Solar Radiation (kWh/m²)	N	15	19	27	33	43	48	46	35	28	20	15	14	343
	E	40	41	61	74	82	90	85	83	65	55	36	31	742
	S	97	83	91	77	68	60	65	77	88	108	85	84	983
	W	38	41	63	74	85	81	96	82	67	57	36	32	751
	Horiz	68	80	126	155	189	194	203	181	135	107	67	58	1564

Design Temperatures: ASHRAE HOF 2001
Degree Days: NCDC Climate Normals
Rainfall: NCDC Climate Normals, TMY2
T, RH, Wind, Sun: TMY2

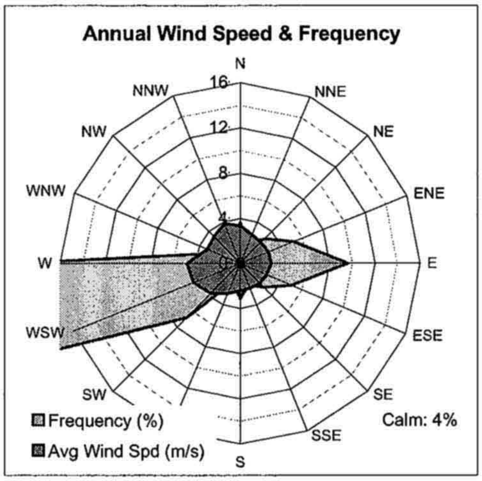
2005.06.07
V 1.0

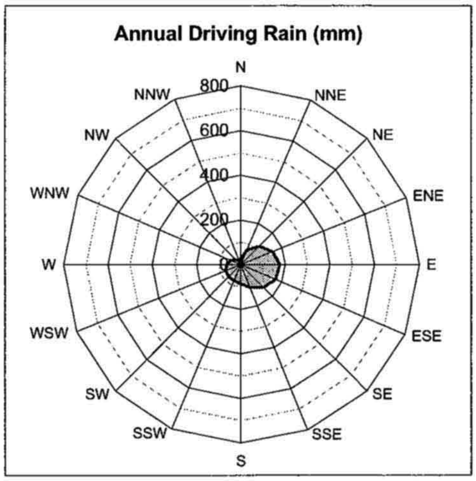
Climate Summary for Building Design — Los Angeles, CA USA

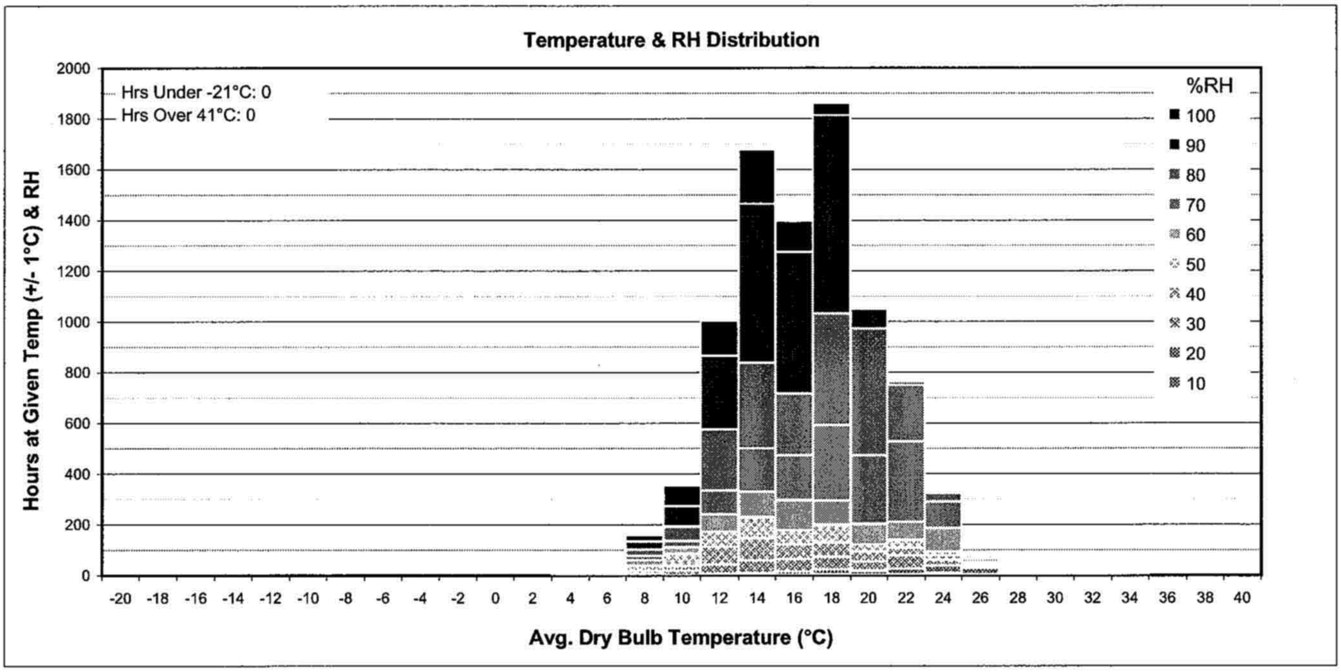
Location	
City	Los Angeles
State/Prov	CA
Country	USA
Lat (°)	33.9
Long (°)	-118.4
Elev (m)	32
Time Zone (hrs)	-8

Design Temperatures	
Heating (°C)	7.4
Cooling (°C)	27

Degree Days	
HDD (18°C)	708
CDD (10°C)	2709







Averages	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec	Year
Temperature (°C)	13.4	13.3	14.6	15.5	17.0	17.6	19.8	20.1	19.9	18.1	16.0	14.4	16.6
RH (%)	59	67	67	70	75	79	75	77	72	72	68	60	70
Humidity Ratio (g/kg)	5.41	6.19	6.71	7.49	8.99	9.85	10.77	11.28	10.23	9.31	7.58	5.92	8.31
Wind Speed - All Hours (m/s)	3.3	3.8	4.1	3.8	3.8	3.4	3.9	3.8	3.4	3.5	3.2	2.8	3.6
Wind Speed - During Rain (m/s)	6.2	5.3	4.0	4.4	2.2	0.0	3.5	0.0	0.0	3.9	4.2	4.5	3.2

Totals		Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec	Year
Snowfall (cm)		0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
Rainfall (mm)		76	79	61	16	6	2	1	4	7	9	29	45	334
Driving Rain (mm/m²)		85	63	47	13	3	0	1	0	0	9	24	38	283
Hours with Rainfall (hrs)		26	10	32	10	6	0	9	0	0	17	23	26	159
Solar Radiation (kWh/m²)	N	18	19	29	32	45	46	46	36	29	24	19	16	359
	E	44	49	66	72	73	64	82	83	62	54	46	43	738
	S	104	101	93	77	63	55	59	76	86	106	107	111	1038
	W	43	56	69	83	96	93	94	85	73	63	48	42	846
	Horiz	89	107	147	172	203	204	217	204	153	127	95	84	1802

Design Temperatures: ASHRAE HOF 2001
Degree Days: NCDC Climate Normals
Rainfall: NCDC Climate Normals, TMY2
T, RH, Wind, Sun: TMY2

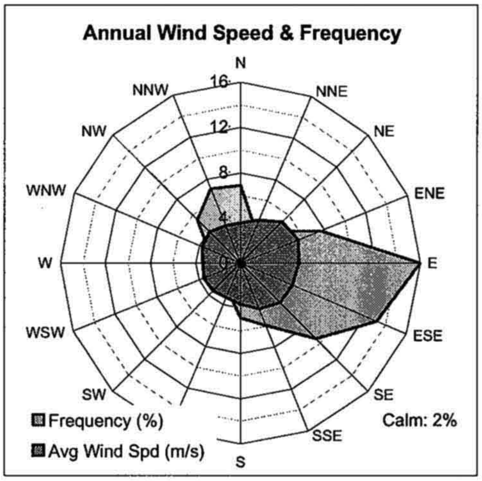
2005.06.07
V 1.0

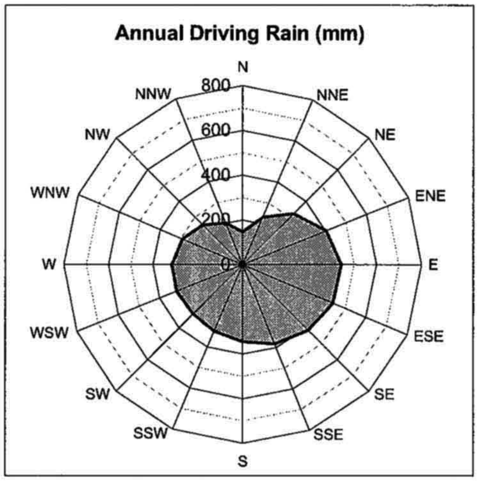
Climate Summary for Building Design — Miami, FL USA

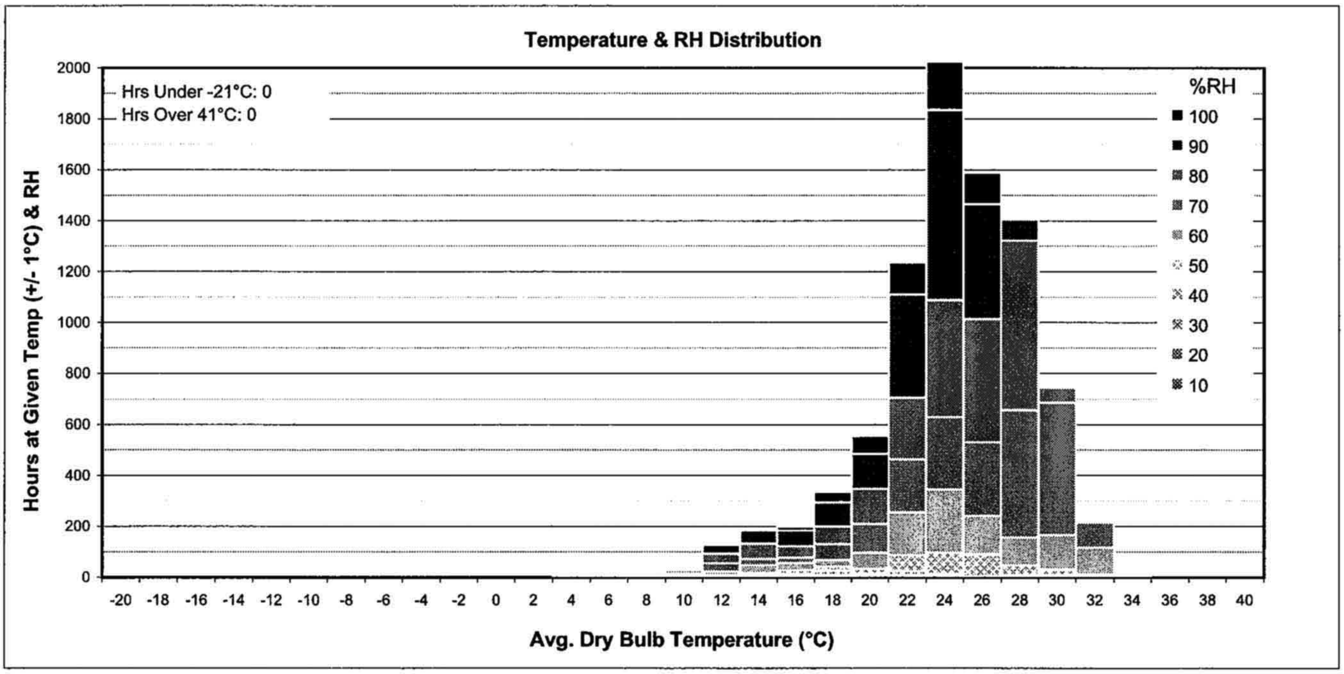
Location	
City	Miami
State/Prov	FL
Country	USA
Lat (°)	25.8
Long (°)	-80.3
Elev (m)	2
Time Zone (hrs)	-5

Design Temperatures	
Heating (°C)	9.8
Cooling (°C)	32.2

Degree Days	
HDD (18°C)	83
CDD (10°C)	5394







Averages	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec	Year
Temperature (°C)	20.0	20.8	21.6	24.5	25.8	27.3	28.0	27.9	26.9	25.1	23.2	20.6	24.3
RH (%)	75	71	68	63	76	72	76	74	78	77	70	70	73
Humidity Ratio (g/kg)	11.34	11.22	11.42	12.29	15.83	16.33	17.92	17.35	17.28	15.32	12.53	10.67	14.12
Wind Speed - All Hours (m/s)	4.3	4.8	5.6	5.6	4.5	3.6	3.9	4.0	3.0	3.5	4.8	4.4	4.3
Wind Speed - During Rain (m/s)	4.9	4.1	6.0	5.1	4.1	3.7	4.5	4.5	3.6	4.1	4.8	6.4	4.6

Totals		Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec	Year
Snowfall (cm)		0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
Rainfall (mm)		48	53	65	85	140	217	147	219	213	157	87	55	1487
Driving Rain (mm/m²)		47	42	66	64	85	133	128	147	142	85	71	46	1057
Hours with Rainfall (hrs)		32	26	14	8	35	45	38	30	70	22	22	2	344
Solar Radiation (kWh/m²)	N	22	23	32	36	48	54	55	49	36	31	24	22	434
	E	54	57	76	78	85	80	84	77	66	64	53	48	821
	S	101	92	84	62	48	47	50	60	67	87	92	102	892
	W	51	55	75	79	76	69	75	79	61	61	48	47	776
	Horiz	107	122	159	184	186	173	185	175	146	133	105	103	1780

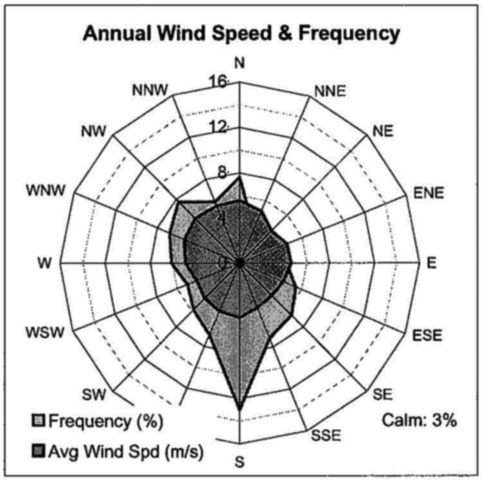
Design Temperatures: ASHRAE HOF 2001
Degree Days: NCDC Climate Normals
Rainfall: NCDC Climate Normals, TMY2
T, RH, Wind, Sun: TMY2

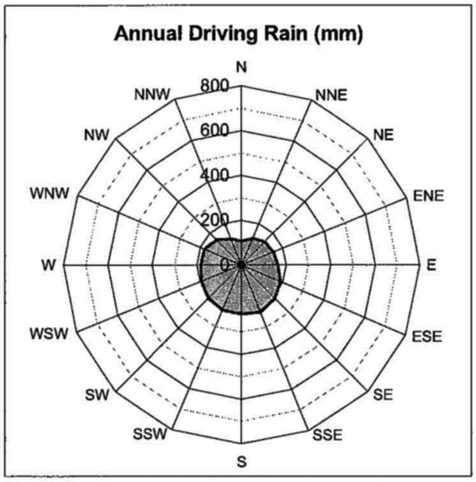
Climate Summary for Building Design — Minneapolis, MN USA

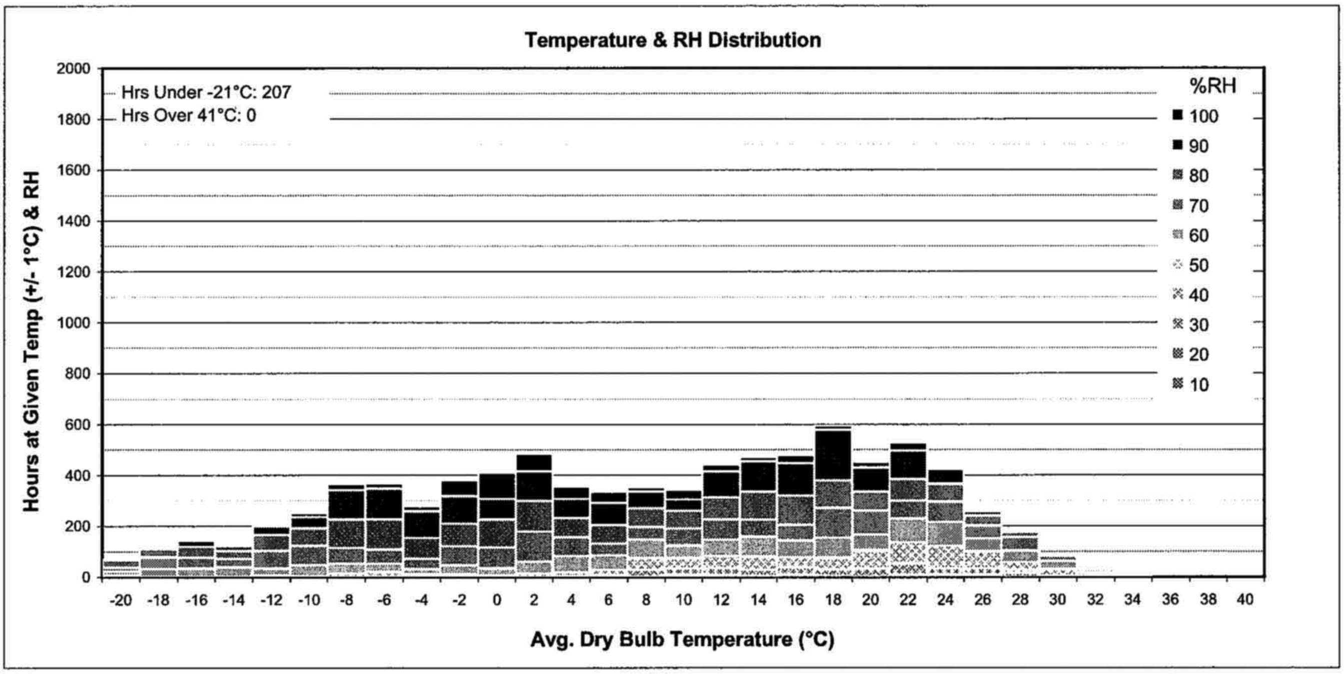
Location	
City	Minneapolis
State/Prov	MN
Country	USA
Lat (°)	48.6
Long (°)	-93.4
Elev (m)	255
Time Zone (hrs)	-6

Design Temperatures	
Heating (°C)	-23.7
Cooling (°C)	31.1

Degree Days	
HDD (18°C)	4376
CDD (10°C)	1510







Averages	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec	Year
Temperature (°C)	-11.8	-8.1	0.3	8.7	16.0	20.5	22.0	21.6	16.1	8.7	0.7	-8.2	7.2
RH (%)	76	69	67	62	61	65	70	72	73	65	78	75	69
Humidity Ratio (g/kg)	1.38	1.54	2.83	4.43	7.05	9.85	11.70	11.54	8.34	4.63	3.20	1.70	5.68
Wind Speed - All Hours (m/s)	4.8	4.4	5.4	5.2	4.7	4.2	4.4	4.2	4.1	4.9	4.5	4.6	4.6
Wind Speed - During Rain (m/s)	0.0	0.0	6.8	6.3	5.0	4.9	5.6	4.7	4.9	7.3	5.0	7.7	4.9

Totals		Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec	Year
Snowfall (cm)		27.2	20.6	26.7	7.1	0.3	0.0	0.0	0.0	0.0	1.3	19.8	23.9	126.7
Rainfall (mm)		0	0	21	52	82	110	103	103	68	52	29	2	622
Driving Rain (mm/m²)		0	0	28	77	70	99	91	77	60	68	28	3	599
Hours with Rainfall (hrs)		0	0	55	80	17	11	15	15	27	16	14	2	252
Solar Radiation (kWh/m²)	N	14	19	27	32	43	47	47	37	26	20	14	13	339
	E	34	44	59	70	87	90	92	83	61	48	30	26	722
	S	95	95	97	80	83	77	81	89	96	96	67	70	1028
	W	35	44	58	66	83	83	91	81	66	47	28	27	708
	Horiz	53	74	110	133	182	193	195	165	121	82	48	41	1396

Design Temperatures:	ASHRAE HOF 2001
Degree Days:	NCDC Climate Normals
Rainfall:	NCDC Climate Normals, TMY2
T, RH, Wind, Sun:	TMY2

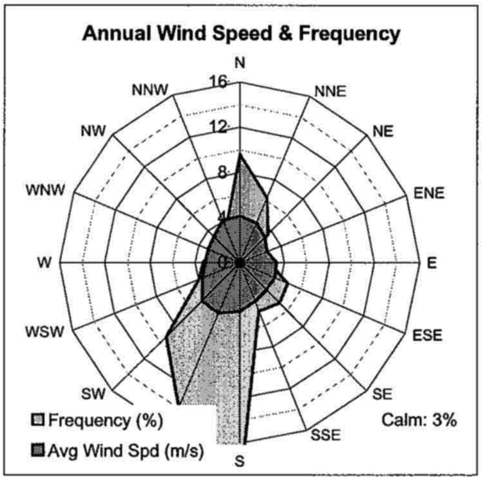
2005.06.07
V 1.0

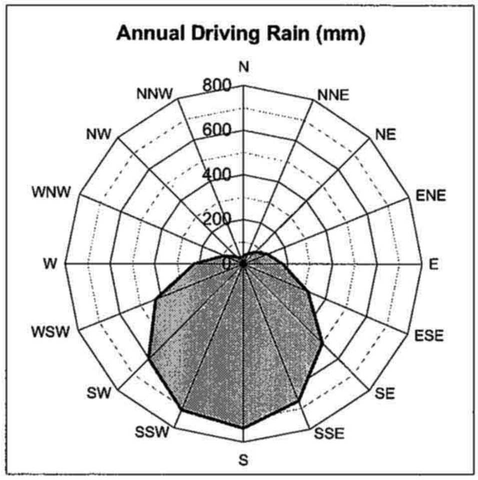
Climate Summary for Building Design — Seattle, WA USA

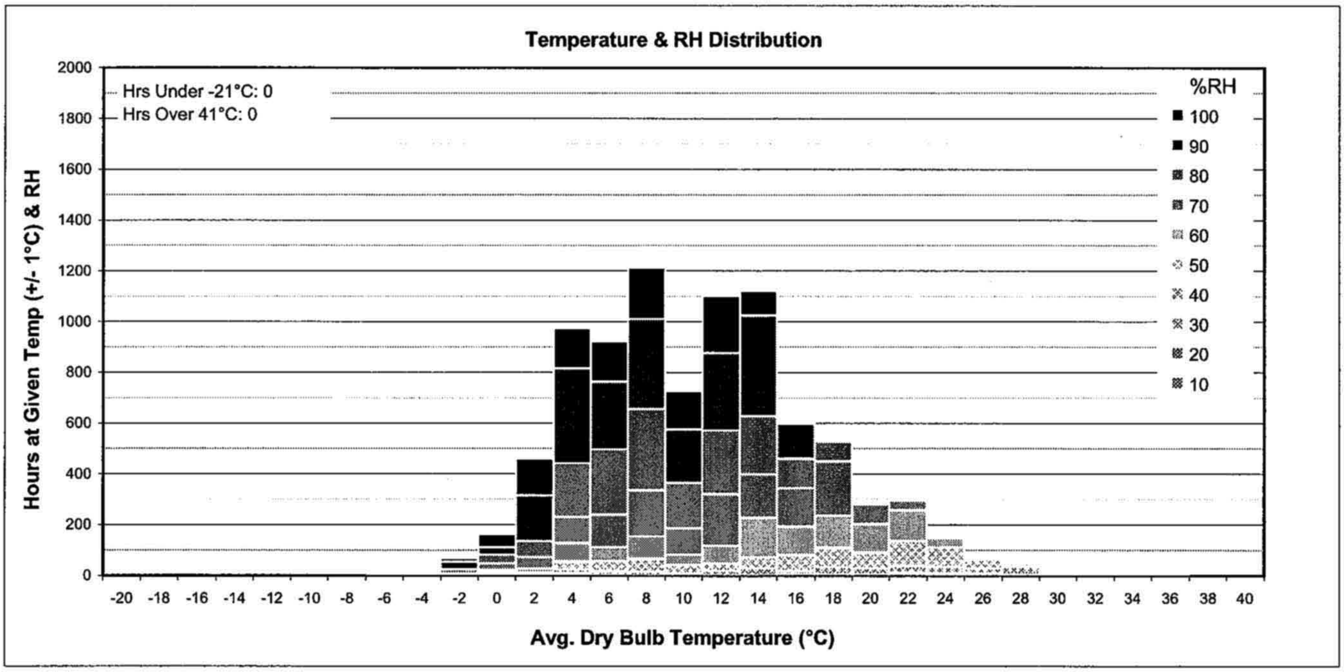
Location	
City	Seattle
State/Prov	WA
Country	USA
Lat (°)	48.0
Long (°)	-124.6
Elev (m)	122
Time Zone (hrs)	-8

Design Temperatures	
Heating (°C)	-2.2
Cooling (°C)	27.4

Degree Days	
HDD (18°C)	2665
CDD (10°C)	1113







Averages		Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec	Year
Temperature (°C)		4.5	6.7	7.0	9.5	13.0	15.2	17.7	18.0	15.4	11.4	7.1	4.8	10.9
RH (%)		77	70	72	71	72	67	65	70	73	80	76	85	73
Humidity Ratio (g/kg)		4.07	4.20	4.52	5.21	6.54	7.03	7.96	8.75	7.62	6.67	4.94	4.61	6.01
Wind Speed - All Hours (m/s)		4.1	3.5	3.5	4.9	3.9	3.7	3.8	3.7	3.8	3.7	4.9	3.3	3.9
Wind Speed - During Rain (m/s)		5.1	4.3	4.6	5.6	3.8	3.7	4.3	4.9	4.0	4.7	5.6	3.8	4.5

Totals		Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec	Year
Snowfall (cm)		12.4	4.1	3.3	0.3	0.0	0.0	0.0	0.0	0.0	0.0	2.8	6.1	29.0
Rainfall (mm)		118	102	92	66	45	38	20	26	41	81	147	137	913
Driving Rain (mm/m²)		126	98	101	90	41	29	19	20	36	84	181	122	948
Hours with Rainfall (hrs)		110	126	150	129	81	40	25	10	52	96	170	192	1181
Solar Radiation (kWh/m²)	N	10	14	23	33	46	47	42	39	20	18	13	9	312
	E	18	26	48	60	75	80	80	64	55	31	20	13	569
	S	37	49	71	71	79	73	81	82	93	64	37	29	765
	W	14	24	43	57	81	83	92	79	65	38	18	12	606
	Horiz	28	46	88	121	170	182	192	154	114	63	34	23	1213

Design Temperatures: ASHRAE HOF 2001
Degree Days: NCDC Climate Normals
Rainfall: NCDC Climate Normals, TMY2
T, RH, Wind, Sun: TMY2

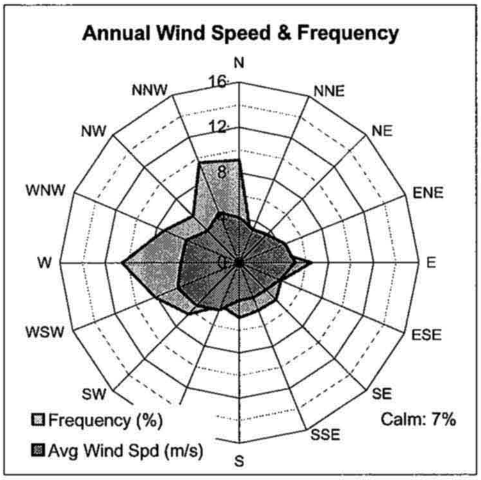
2005.06.07
V 1.0

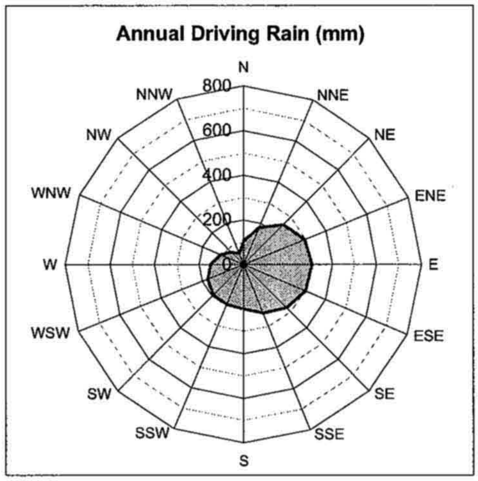
Climate Summary for Building Design — Toronto, ON Canada

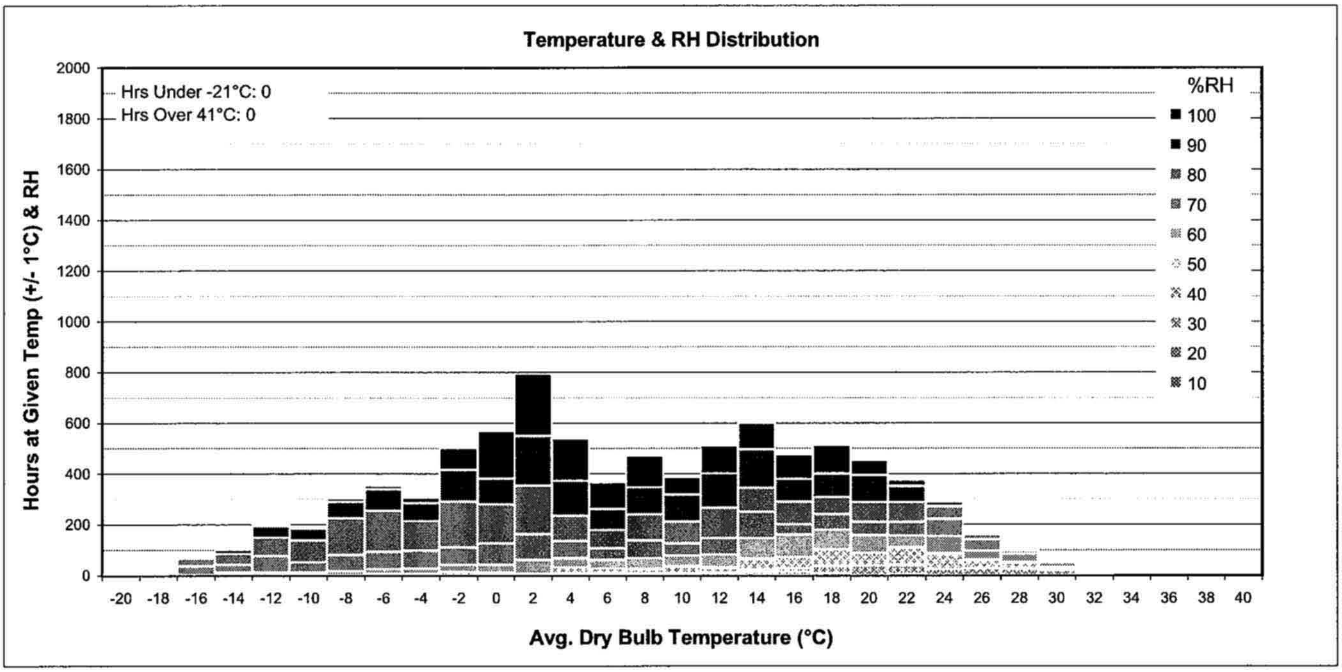
Location	
City	Toronto
State/Prov	ON
Country	Canada
Lat (°)	43.7
Long (°)	-79.4
Elev (m)	173
Time Zone (hrs)	-5

Design Temperatures	
Heating (°C)	-17.2
Cooling (°C)	28.7

Degree Days	
HDD (18°C)	3570
CDD (10°C)	1457







Averages	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec	Year
Temperature (°C)	-5.8	-5.7	-0.7	5.7	12.0	17.7	20.8	19.8	15.0	8.5	3.5	-2.5	7.4
RH (%)	79	75	75	70	62	68	71	71	75	77	83	80	74
Humidity Ratio (g/kg)	2.11	2.02	2.80	4.18	5.50	8.64	10.75	10.31	8.01	5.58	4.22	2.70	5.57
Wind Speed - All Hours (m/s)	4.5	5.3	5.5	4.8	4.3	3.8	3.2	2.1	3.3	4.3	4.4	5.7	4.3
Wind Speed - During Rain (m/s)	4.5	5.8	6.2	5.2	4.8	4.7	3.4	2.3	3.8	4.7	5.3	6.7	4.8

Totals		Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec	Year
Snowfall (cm)		31.1	22.1	19.2	5.7	0.1	0.0	0.0	0.0	0.0	0.5	7.6	29.2	115.5
Rainfall (mm)		25	22	37	62	72	74	74	80	78	63	62	35	685
Driving Rain (mm/m²)		27	31	50	71	71	67	51	33	59	62	75	49	646
Hours with Rainfall (hrs)		44	38	39	70	54	39	46	26	71	51	95	32	605
Solar Radiation (kWh/m²)	N	12	16	23	29	45	51	47	40	26	21	12	9	333
	E	24	32	55	64	94	88	92	80	67	41	19	18	675
	S	65	69	76	73	71	67	69	78	87	75	42	49	820
	W	26	36	46	62	71	81	80	76	58	43	21	18	618
	Horiz	45	63	98	130	174	184	187	159	121	78	39	33	1311

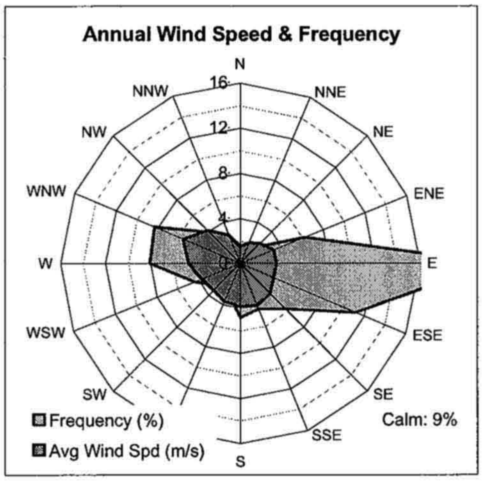
Design Temperatures: ASHRAE HOF 2001
Degree Days: Cdn Climate Normals 1971-2000
Rainfall: Cdn Climate Normals 1971-2000, CWEC
T, RH, Wind, Sun: CWEC

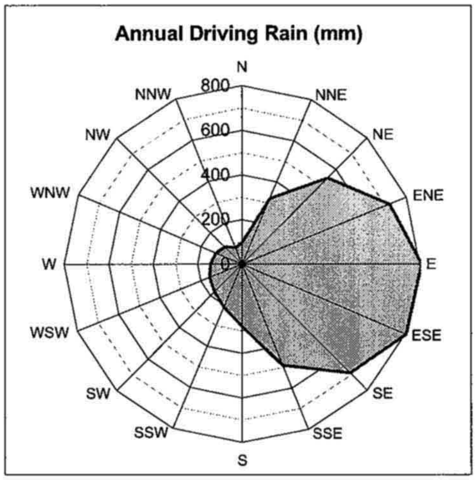
Climate Summary for Building Design — Vancouver, BC Canada

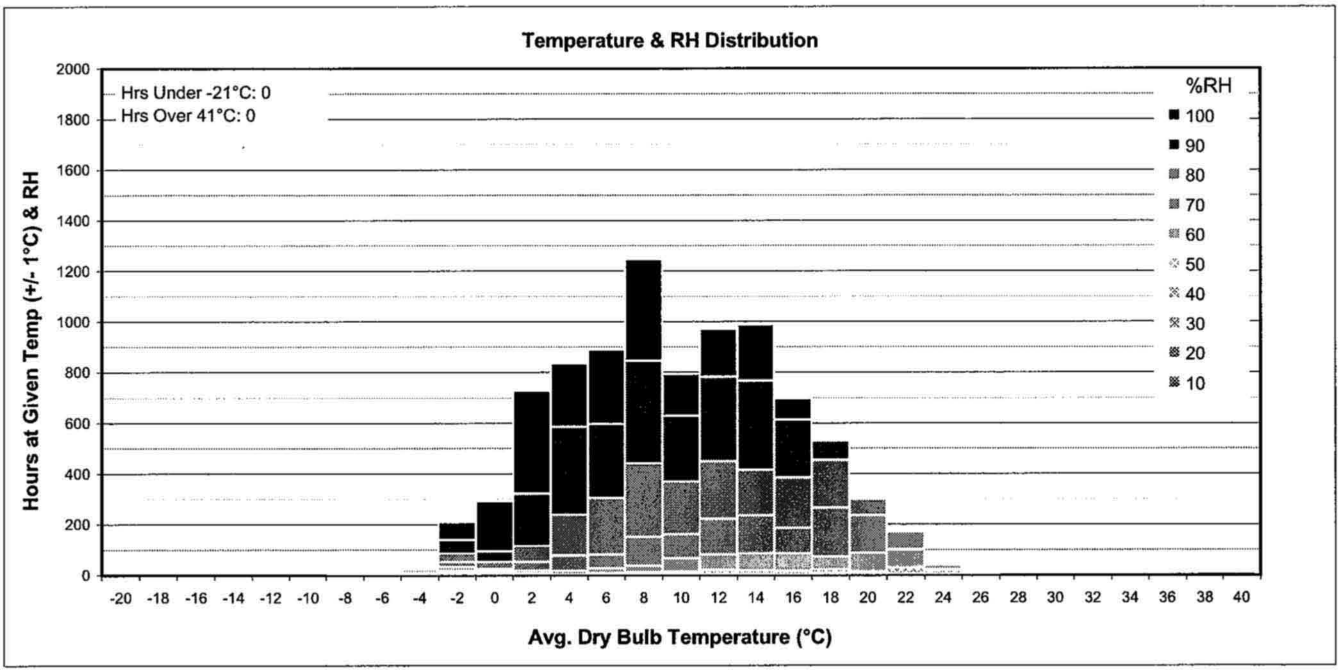
Location	
City	Vancouver
State/Prov	BC
Country	Canada
Lat (°)	49.3
Long (°)	-123.4
Elev (m)	4
Time Zone (hrs)	-8

Design Temperatures	
Heating (°C)	-4.7
Cooling (°C)	23.2

Degree Days	
HDD (18°C)	2927
CDD (10°C)	901







Averages	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec	Year
Temperature (°C)	3.2	5.1	6.1	8.7	11.8	15.1	17.0	17.1	13.8	9.8	5.3	3.6	9.7
RH (%)	87	86	81	73	73	73	76	79	80	82	82	88	80
Humidity Ratio (g/kg)	4.20	4.71	4.77	5.06	6.28	7.77	9.02	9.52	7.86	6.23	4.72	4.40	6.21
Wind Speed - All Hours (m/s)	3.2	2.7	3.4	3.2	3.4	3.0	2.9	3.3	3.8	3.5	3.4	4.3	3.3
Wind Speed - During Rain (m/s)	4.0	4.2	5.0	3.9	3.0	3.2	2.2	3.1	5.4	3.9	4.4	5.3	4.0

Totals		Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec	Year
Snowfall (cm)		16.3	10.4	2.8	0.5	0.0	0.0	0.0	0.0	0.0	0.1	3.2	13.3	46.6
Rainfall (mm)		137	131	115	89	68	58	41	42	70	122	182	183	1239
Driving Rain (mm/m²)		120	118	129	76	45	39	20	28	82	115	165	217	1156
Hours with Rainfall (hrs)		136	115	146	99	73	50	44	41	60	235	140	210	1349
Solar Radiation (kWh/m²)	N	9	11	22	28	43	51	47	35	22	14	9	6	295
	E	13	23	40	64	80	82	89	75	59	31	15	12	583
	S	33	57	69	86	80	72	83	90	95	60	38	33	798
	W	15	26	47	73	91	93	111	82	63	26	16	12	656
	Horiz	25	44	82	136	174	179	203	164	116	54	28	20	1223

Design Temperatures: ASHRAE HOF 2001
Degree Days: Cdn Climate Normals 1971-2000
Rainfall: Cdn Climate Normals 1971-2000, CWEC
T, RH, Wind, Sun: CWEC

7

Moisture Sources

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 2,222 heat degree days (HDD) base 18.8°C (4,000 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 more 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 3,500 h or more during the warmest six consecutive months of the year.
2. A 23°C (73°F) or higher wet-bulb temperature for 1,750 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 (41°F to 48°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 (444 pt) during the mix but with hydration eventually retains slightly less than 120 L (254 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 2,340 L (4,945 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 0.127 pt/day), medium activity from 0.12 to 0.2 (0.25 to 0.42 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),

[1] *Program manager, Building Thermal Envelope Systems and Materials, Oak Ridge National Laboratory, Oak Ridge, TN.*

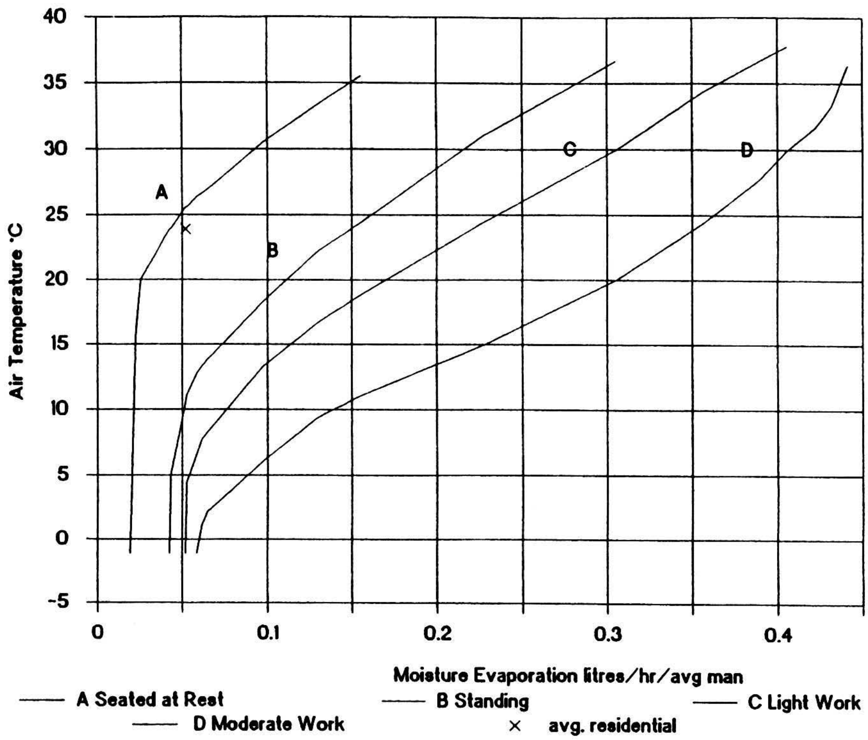


Fig. 1—The moisture released from respiration and perspiration as a function of activity level. One average value from a study of a family of four is plotted with the data assuming a uniform hourly release totaling 1.25 L/day per average-size man.

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 invented mode results in 0.0026 L/h (1,000 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 (0.46 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 [0.38 L/day (0.8 pt/day)], plants, cleaning, and wet clothes [0.4 L/day (0.85 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].

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, particularly in commercial buildings such as gro-

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; not vented outdoors	0+/load (usually nil)
or indoor drying line	2.2 to 2.92/load (more if gas dryer)
Combustion: unvented kerosene space heater	0.95/L per liter 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 then 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	
Respiration and perspiration (family of four, average)	Fraction of human adult weight 0.21/h
Refrigerator defrost	
Saunas, steambaths, and whirlpools	1.03/day (average)
Vegetable storage (large-scale storage is significant)	0 to 1.08+/h
	0+ (not estimated)
NONHOUSEHOLD PRODUCED	
Combustion exhaust gas backdrafting or spillage	0 to 3,200+/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].

cery 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.

$$Me = \frac{H \times A \times (VP_s - VP_a) \times 0.454}{H_L} \quad (1)$$

where

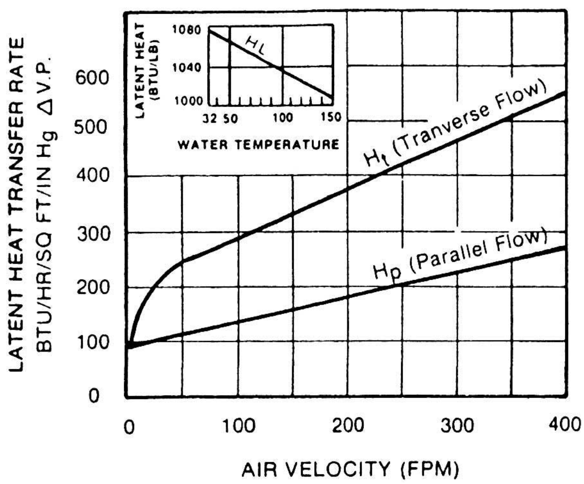


Fig. 2—Used to predict moisture load from wet surfaces.

TABLE 2—Simplified table for use with Eq (3) to estimate moisture evaporation from swimming pools.

Air 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	1,228	982	860	737	614	491	368
15	1,706	1,364	1,194	1,023	853	682	512
20	2,339	1,871	1,637	1,403	1,169	936	702
25	3,169	2,535	2,219	1,902	1,585	1,268	951
30	4,246	3,397	2,972	2,548	2,123	1,698	1,274
35	5,628	4,502	3,940	3,377	2,814	2,251	1,688
40	7,384	5,907	5,169	4,430	3,692	2,954	2,215

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,
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 $\times$ 9.8 m (16 $\times$ 32 ft) has a water surface area of 48 m^2 (516.7 ft^2) and indoor conditions of 50 % relative humidity at 20°C (68°F), (P_a = 1,169) with a water temperature of 25°C (77°F) (P_w = 3,169). The surfaces will produce [0.000145 $\times$ 48 $\times$ (3,169 – 1,169)] 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 49 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.

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/1,000 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

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.

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 (528 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 (4,004 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 (904 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 (41°F to 50°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 (2,099 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 makeup 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 meters per minute) required to maintain a specified positive air pressure [25]

$$Q = 945 \times 0.60 \times A \times SP^{0.65} \tag{3}$$

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 centimeters of water in a water column.

A is derived by assuming an estimated linear cracklike opening for the conditioned space. Once the total ventilation is known, the moisture load from all exterior sources can be calculated by

$$M_e = Q \times d \times 60 \times (M_o - M_i) \tag{4}$$

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. The 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 (152 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 random gas emissions in basement areas. Under a low pressure difference of 10 Pa, water vapor was entering the basement along with randon 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 (14°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 211 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 (1,550 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 (42 to 152 pt/day).

REFERENCES

[1] Mei, H. T., "Moisture Migration in Buildings in Hot/Warm Humid Climates," *Proceedings*, Symposium on Improving Building Systems in Hot and Humid Climates, 3–4 Oct. 1989, Dallas, TX, Energy Systems Laboratory, Department of Mechanical Engineering, Texas A&M University, College Station, TX.

[2] *ASHRAE Handbook of Fundamentals 1989*, American Society of Heating, Refrigerating and Air Conditioning Engineers, Inc., Atlanta, GA, 1989.

[3] Rousseau, M. Z., "Sources of Moisture and Its Migration through the Building Enclosure," *ASTM Standardization News*, November 1984, pp. 35–37.

[4] Quirouette, R. L., "Moisture Sources in Houses," *Condensation and Ventilation in Houses*, National Research Council of Canada, Division of Building Research Humidity, NRCC 23293, Ottawa, May 1984.

[5] Harriman, L. G., III, *The Dehumidification Handbook*, 2nd ed., Munters Cargocaire, Amesbury, MA, 1990.

[6] Erhorn, H. and Gertis, K., "Minimal Thermal Insulation and Minimal Ventilation," *Gesundheit Engineering*, Vol. 107, 1986.

[7] Hite, S. C. and Bray, J. L., "Research in Home Humidity Control," Research Series No. 106, The Engineering Experiment Station, Purdue University, Urbana, IL, November 1948.

[8] Angell, W. J., "Home Moisture Sources," CD-FO-3396, Minnesota Extension Service, Cold Climate Housing Information Center, University of Minnesota, St. Paul, MN, 1988.

[9] Shakun, W., "The Causes and Control of Mold and Mildew in Hot and Humid Climates," *ASHRAE Transactions 1992*, Vol. 98, Pt. 1, Atlanta, GA.

[10] Peart, V., "Mildew and Moisture Problems in Hotels and Motels in Florida," University of Florida Agricultural Extension, Gainesville.

[11] International Energy Agency, *Condensation and Energy Source-book*, Report Annex XIV, Vol. 1, *Energy Conservation in Buildings and Community Systems*, Leuven, Belgium, March 1991.

[12] German Ministry of Housing Building, "Ready Heating and Conditioning—Protection for Health Building Losses," *Heating Technic and Sanitary Engineering 22*, Vol. 1, 1983, p. 18.

[13] "Surface Condensation and Mould Growth in Traditionally-Built Dwellings," *Building Research Establishment Digest*, Vol. 297, Building Research Establishment, Garston, Watford (Max 1985) England.

[14] BS 5250, "Code of Basic Data for the Design of Buildings: The Control of Condensation in Dwellings," 1975 edition (British standard).

[15] Dutz, A. and Le Marie, A., "Energy Conservation and Heat Losses in Buildings," *German Building Technical Notes* (*DBZ*), Vol. 119, No. 10, 1985, pp. 1317–1323.

[16] Lubke, P., "Minimal Ventilation vs Moisture," *Introduction to Practical Basis of* (*the Bases of Building Physics*)*—Minimum Air Streams for Avoidance of Water Condensation at Exterior Corners*, AuPenecken, *Heating, Ventilating, and Building Systems*, Vol. 36, No. 6, 1985, pp. 292–296.

[17] Meyringer, V., "Air Requirements for Avoiding of Water (Moisture) Condensation in Buildings," unpublished manuscript.

[18] Panzhauser, E. et al., "Air Circulation (Frequency) in Austrian Building," Research Report F 287, Austrian Federal Ministry for Building and Technology, Vienna, 1984.

[19] Pfeiler, W., "The Elimination of Water Condensation Soil Mushroom Growing in Building," research report of the Austrian Federation of Public Building Associations, Vienna, Austria.

[20] Stehno, V., "Influence of Insulation, Log-time (Thermal Memory) and Ventilator for Moisture Condensation on the Walls and Ceilings," *Der Ausbau*, Vol. 9, No. 9, 1981, pp. 3509–3561.

[21] Stum, K. R., "Winter Steady-State Relative Humidity and Moisture Load Prediction in Dwellings," *ASHRAE Transactions 1992*, Vol. 98, Pt. 1, Atlanta, GA.

[22] Christian, J. E., "Cooling Season Performance of an Earth-Sheltered Office/Dormitory Building in Oak Ridge, Tennessee," ORNL/CON-151, Oak Ridge National Laboratory, Oak Ridge, TN, July 1984.

[23] Anderson, L. O., "Condensation Problems: Their Prevention and Solution," FPL 132, USDA Forest Products Laboratory, Madison, WI, 1972.

[24] ASHRAE Standard 62-89, "Ventilation for Acceptable Indoor Air Quality," American Society of Heating, Refrigerating and Air Conditioning Engineers, Inc., Atlanta, GA, 1991.

[25] Fan Engineering, Buffalo Forge Co., Buffalo, NY.

[26] "Crawl Space Houses," *Council Notes F4.4*, Vol. 4, No. 2, University of Illinois at Urbana-Champaign and Small Homes Council-Building Research Council, Champaign, IL, 1980.

[27] Jennings, C. W. and Moody, T. L., "Causes and Consequences of Moisture in Earth-Coupled Spaces," *Moisture Control in Buildings*, Building Thermal Envelope Coordinating Council, Workshop Proceedings, Washington, DC, 25–26 September 1984.

[28] Piersol, P. and Fugler, D., "Development and Evaluation of Soil Gas Sampling Techniques," Canada Mortgage and Housing Corporation, Ottawa, Ontario, August 1987.

[29] White, J. H. and Skuor, P., "The House as a Moisture Source," Canada Mortgage and Housing Corporation, draft, personal correspondence from Don Fugler, 10 February 1988.

8

Effects of Air Infiltration and Ventilation

Andrew K. Persily[1] and Steven J. Emmerich[1]

Introduction

THIS CHAPTER DISCUSSES THE ROLE OF AIR INFIL-tration and ventilation in building moisture transport. While water vapor diffusion can be a very important moisture transport mechanism, as discussed in other chapters, bulk air movement via infiltration and ventilation carries far more water vapor into and out of buildings than diffusion, as much as ten times or more under common conditions [1]. Therefore it is important that we understand the phenomena of infiltration and ventilation, and the related building and system features that determine the impacts on moisture transport. This chapter discusses the terminology related to infiltration and ventilation, the driving forces for infiltration, envelope airtightness and its measurement, mechanical ventilation systems, building ventilation requirements and interzone airflows within buildings. Many of these issues are well covered in Chapter 27 Ventilation and Infiltration of the *ASHRAE Fundamentals Handbook* [2], and therefore the material in this chapter reviews that information briefly and focuses on the moisture-specific implications. Other valuable resources for information on infiltration and ventilation include the publications and conference proceedings of the Air Infiltration and Ventilation Centre (AIVC) (*www.aivc.org*), as well as various other ASHRAE publications. In addition, ASTM has held a number of symposia over the years that have resulted in Special Technical Publications (STPs) with a number of useful technical papers [3–5].

Terminology

In discussing the interactions of airflow and moisture transport, it is important to use consistent terminology. However, the relevant terms in the area of building leakage and infiltration are not always used consistently, and therefore several terms are discussed here with reference to Fig. 1. In addition, the AIVC has produced a useful glossary of related terminology that can be consulted for more detailed information [6].

Starting outside the building, *ambient air* refers to the air around a building, which serves as the source of outdoor air (plus water vapor and other airborne substances) brought into a building. *Outdoor air* is the air brought into the building by a ventilation system, which may be impacted by local contaminant sources that do not impact the ambient air. Note that not all buildings have ventilation systems that bring in outdoor air. For example, many low-rise residential buildings in the United States do not have any intentional outdoor air intake, but rather rely on envelope leakage or infiltration for outdoor air. Sometimes outdoor air is referred to as *makeup air*, generally when that air is being used to provide sufficient outdoor air for the proper functioning of exhaust systems and combustion processes. After the outdoor air enters the ventilation system, it is often mixed with *recirculated air*, with the combination referred to as *supply air*. Even if there is no recirculation (so called 100 % outdoor air systems or operating conditions), the ventilation air delivered to the ventilated space is still referred to as *supply air*. Generally, supply air is heated or cooled, humidified or dehumidified, and often filtered. The air pulled back to the system from the ventilated space is referred to as *return air*, some of which is recirculated with the rest exhausted from the building. The air that leaves the building is referred to as *exhaust air* or sometimes *spill air*. Many buildings also have separate exhaust air systems, such as those serving toilets and kitchens. Finally, airflow into and out of the building through leaks in the building envelope is referred to as *infiltration* and *exfiltration*, respectively. As discussed later in this chapter, infiltration is driven by pressure differences across the building envelope caused by indoor-outdoor air temperature differences, wind and the operation of mechanical ventilation equipment and vented combustion devices.

There are other terms of interest relevant to discussions of moisture in buildings that are not depicted in Fig. 1. *Ventilation*, as described in ASHRAE Standard 62.1 [7], is "the process of supplying air to or removing air from a space for the purpose of controlling air contaminant levels, humidity, or temperature within the space." Note that this definition does not refer specifically to outdoor air, which is sometimes a source of confusion. Some people assume that ventilation means outdoor air, while others think of ventilation as supply air, which need not contain any outdoor air at all. Therefore it is a good idea to refer to outdoor air ventilation when discussing outdoor air intake, and supply air or total ventilation when referring to the air delivered primarily for space conditioning. Standard 62.1 defines *mechanical ventilation* as "ventilation provided by mechanically powered equipment such as motor-driven fans and blowers, but not by devices such as wind-driven turbine ventilators and mechanically operated windows" and *natural ventilation* as "ventilation provided by thermal, wind or diffusion effects through doors, windows, or other intentional openings in the building." *Transfer air* refers to airflow from one space to another, which in many cases is done intentionally. For example, bathrooms are ventilated by exhaust, with transfer air from adjoining spaces flowing into the bathrooms, often through grilles in doors, to replace the exhaust air.

[1] *Building and Fire Research Laboratory, National Institute of Standards and Technology, Gaithersburg, Maryland 20899.*

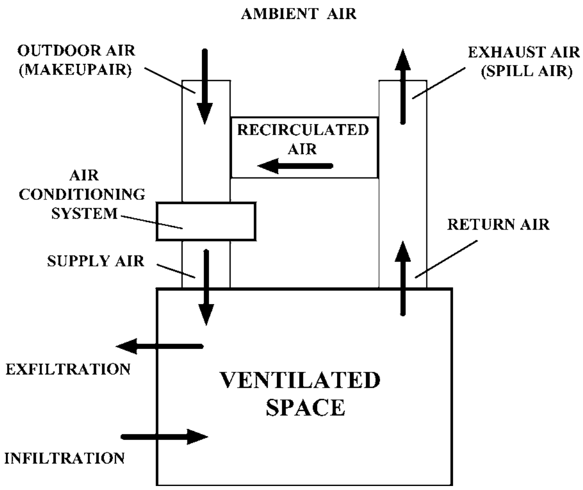


Fig. 1—*Schematic of mechanically ventilated space.*

Another collection of terms is related to the physical porosity or leakiness of the building envelope or its *airtightness*. Often the term *air leakage* is used to refer to this airtightness as a physical attribute of the envelope independent of the weather conditions that lead to airflow through these leaks under normal circumstances. This air leakage or airtightness is measured with a fan pressurization test as described later in this chapter.

The units to describe airflow, infiltration, and ventilation bear some discussion as well. These airflows can be expressed in volumetric airflow units such as L/s, cfm (cubic feet per minute), m^3/s, or m^3/h, but they are also often described in terms of air change rates, which is the volumetric airflow divided by the volume of the space or building of interest. Air change rates are generally expressed in units of air changes per hour or inverse hours, h^{-1}. Some people use ach as a unit for air change rate, but ach is not a proper unit and its use is discouraged. The air change rate of a space or building can be used to describe any of several relevant airflows, total or supply air, mechanical outdoor air intake, infiltration, or total outdoor airflow into a building. In order to avoid confusion it is important to specify which airflow is being discussed when referring to the air change rate of a building or space. Ventilation system airflows are generally referred to in volumetric units, while infiltration rates are almost always presented in air changes per hour or h^{-1}. Ventilation system airflows are sometimes normalized by floor area served, for example commercial building supply airflow rates are often expressed in $L/s \cdot m^2$ or cfm/ft^2.

Infiltration

Infiltration (and exfiltration) through leaks in the building envelope is important to moisture transport for a number of reasons. It is the primary mechanism by which many buildings are ventilated with outdoor air, and by which indoor air leaves the building. The outdoor air change rate determines the indoor moisture level based on indoor moisture generation rates and outdoor conditions, and the indoor moisture level is obviously critical to the potential for condensation and other issues discussed in this book. In addition, infiltration (and exfiltration) carries airborne water vapor into (or out of) the building envelope, where the vapor may encounter temperatures below the dewpoint, leading to condensation. Again as discussed elsewhere in this book, condensation within the envelope can lead to serious problems.

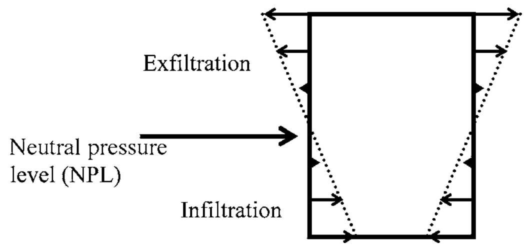


Fig. 2—*Schematic of stack pressures* ($T_{in} > T_{out}$).

Envelope infiltration is driven by pressure differences across openings in the building envelope. This section describes the driving forces for these pressure differences, along with some of the implications for moisture transport, as well as how building leakage is measured. In addition, existing data on building airtightness measurements are summarized for both low-rise residential and commercial buildings.

Driving Forces

The pressure differences that drive infiltration are caused by indoor-outdoor air temperature differences, wind, and the operation of ventilation equipment and vented combustion devices. The physics of these phenomena are well understood and thoroughly discussed in the *ASHRAE Fundamentals Handbook* [2].

When indoor and outdoor air temperatures are different, the resulting indoor-outdoor density difference leads to a change in air pressure with height that is different inside the building than outside. This difference in the air pressure variation with height leads to a pressure difference across the exterior walls, which also varies with height. In the simplest case, with a uniform distribution of leakage over the exterior envelope and no interior obstructions to airflow, indoor-outdoor pressure differences will exist as shown in Fig. 2 under conditions where the indoor air is warmer than outdoors. During such heating conditions, air tends to enter the building through leaks low in the building envelope and then leave or exfiltrate from the higher leaks. This pressure pattern is often referred to as the stack or chimney effect. When the sign of the indoor-outdoor temperature difference is reversed, then the directions of the pressure differences and the airflows are reversed, with air infiltrating high and exfiltrating low. Larger indoor-outdoor temperature differences lead to larger pressure differences. Neglecting internal resistance to airflow, the stack pressure difference at the top and bottom of a building is on the order of 0.02 Pa per m of building height and degree K of indoor-outdoor temperature difference. Therefore for a one-story house (height of 2.5 m) and a 25 K indoor-outdoor temperature difference (cold weather), the stack pressure difference at the top and bottom is about 1.3 Pa. Considering a tall building (20 stories of 4 m each), the stack pressure for this same temperature difference is approximately 40 Pa.

The height at which the pressure difference across the building envelope equals zero is referred to as the neutral pressure level or NPL. The height of the NPL is a function of the vertical distribution of the envelope leakage. If the leakage is uniformly distributed in the vertical extent, then the NPL is one-half the building height. If there is more leakage located high on the envelope, the NPL moves up accordingly. A very high leak, such as a chimney, can raise the neutral pressure plane significantly, even above the roof of the building in extreme circumstances. Operating an exhaust fan also raises the neutral pressure level. The important issue for moisture transport is that outdoor air and the water vapor therein will tend to enter the building at low heights during the heating season and indoor air (at the indoor relative humidity) will flow outwards through the building envelope high in the building. These directional issues are important as the water vapor content of these airstreams interacts with the temperature within the envelope in determining the potential for condensation within the envelope. For example, under heating conditions, the relatively moist indoor air leaving the building at higher points on the wall can encounter cold temperatures in the envelope (particularly when there are insulation defects such as thermal bridges) and condense. In these cases, mold growth may be more likely at these high points, as discussed elsewhere in this manual.

In the more general case of a building with interior partitions such as floors and vertical shafts, and therefore resistance to interior airflow, the stack pressures become somewhat more complicated [8–10]. Generally they will reduce the magnitude of the pressures relative to the idealized case in Fig. 2, but the pattern of infiltration at lower levels under heating conditions remains.

When wind impinges on a building, it tends to cause infiltration on the windward side and exfiltration on the other building sides and the roof. The impact of wind speed and direction on moisture transport will be climate and site specific, depending on the relative consistency of the prevailing wind direction and the exposure of the building. Wind is generally more of an issue in terms of wind-driven rain than infiltration, but wind-induced pressures are a major driving force for infiltration and need to be considered. The wind pressures on the exterior face of a building are a function of the square of the wind speed, as well as the orientation of the face relative to the wind direction and the height on the building. There can also be localized effects, at eaves and corners for example, that can lead to significantly higher or lower wind pressures than the average value over a building wall. Typically at lower wind speed (perhaps 2.5 m/s or less), these exterior wind pressures are on the order of 1 Pa or 2 Pa. At higher wind speeds, for example 10 m/s, wind pressures are on the order of 25 Pa.

When the stack effect and wind act in combination, the pressures add or subtract at each location on the building envelope, resulting in a pressure distribution such as that shown in Fig. 3. This pattern corresponds to a heating situation with the wind blowing from the left-hand side. Note that the neutral pressure is different on the various sides of the building when the wind blows in combination with the stack effect.

The operation of mechanical equipment, ventilation systems, local exhaust fans, and vented combustion appliances also induce indoor-outdoor pressure differences. In the absence of any temperature difference or wind, a net flow into the building will raise the interior pressure above the outdoors at all points on the building envelope. Correspondingly, a net exhaust airflow will lower the interior pressure. When the stack and wind effects exist in combination with these mechanically induced pressure differences, the pressures at each location combine, leading to locally varying and potentially complex pressure patterns. An important impact of these mechanical pressures on moisture relates to climate and whether the building is at a net positive or negative pressure. If the building is positive, the indoor air will exfiltrate out through the building envelope at the interior humidity conditions. Under heating conditions, this can lead to moist indoor air condensing on cold envelope surfaces, even leading to the formation of ice within the wall in colder climates. A host of moisture-related problems can result under these circumstances. On the other hand, a building running negative under cooling conditions will draw moist outdoor air inward through the building envelope where it may encounter cold surfaces and condense. As highlighted elsewhere in this manual, negative building pressures under cooling conditions can lead to some very severe moisture problems, especially if the interior surface of the envelope is relatively impermeable to moisture transport.

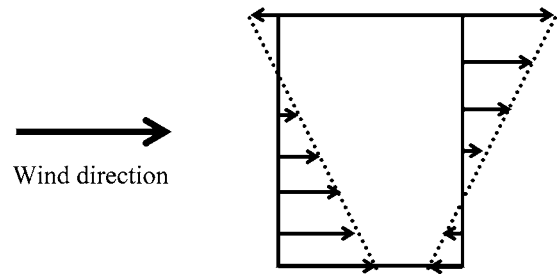


Fig. 3—*Schematic of combined stack and wind pressures.*

Envelope Airtightness

The pressure differences described in the previous section act across openings in the building envelope to cause airflow into and out of buildings. This airflow carries airborne water vapor. Therefore, the airtightness of the building envelope is a critical parameter in discussing and understanding the impacts of infiltration on moisture in buildings. This section discusses envelope airtightness, specifically how it is measured and the range of airtightness values that have been observed in the field.

Measurement

The airtightness of building envelopes is measured using a fan pressurization test in which a fan is used to create a series of pressure differences across the building envelope between the building interior and the outdoors. The airflow rates through the fan that are required to maintain these induced pressured differences are then measured. Elevated pressure differences in the range of 10 Pa to around 75 Pa are used to override weather-induced pressures, such that the test results are independent of weather conditions and provide a measure of the physical airtightness of the exterior envelope of the building.

ASTM Standard E779 [11] is a test method that describes the fan pressurization test procedure in detail, including the specifications of the test equipment and the analysis of the test data. In conducting a fan pressurization test in a commercial building, the building's own air-handling equipment sometimes can be employed to induce the test pressures. A Canadian General Standards Board standard describes the use of a building's air-handling equipment to conduct such a test [12]. In other cases, a large fan can be brought to the building to perform the test. Low-rise residential buildings are often tested with a so-called "blower door" and ASTM Standard E1827 [13] is a test method written specifically for blower doors that employ an orifice approach to measuring the airflow rate.

Fan pressurization test results are generally reported in terms of the airflow rate at some reference pressure difference divided by the building volume, floor area, or envelope surface area. Such normalization accounts for building size in interpreting the test results. In most cases, the pressure and flow data for measurements performed at multiple pressure differences are fitted to a curve of the form:

$$Q = C \cdot \Delta p^{n} \tag{1}$$

where Q is the airflow rate, Δp is the indoor-outdoor pressure difference, C is referred to as the flow coefficient, and n is the flow exponent. Once the values of C and n have been determined from the test data, the equation can be used to calculate the airflow rate through the building envelope at any given pressure difference.

Using Eq (2) below, the airflow rate at a reference pressure is often used to estimate the effective leakage area of the building, which is the area of an orifice that would result in the same airflow rate at the reference pressure difference.

$$\text{ELA} = 10{,}000 \cdot Q_r(\rho/2\Delta p_r)^{1/2}/C_D \tag{2}$$

where ELA is the effective leakage area in cm^2, Q_r is the airflow rate at the reference pressure difference Δp_r in m^3/s, ρ is the air density in kg/m^3, Δp_r is the reference pressure difference in Pa, and C_D is the discharge coefficient (not to be confused with C in Eq (1)). This equation is often used to calculate the effective leakage area at an indoor-outdoor pressure difference of 4 Pa with a discharge coefficient of 1, but other values of the reference pressure and discharge coefficient are sometimes employed. Values of the effective leakage area are then normalized by the envelope surface area or by the building floor area to account for differences in building size.

In addition to the whole building measurement techniques described above, procedures exist to test the leakage of individual building envelope components such as windows, walls, and doors. ASTM E283 [14] and ASTM E783 [15] are test methods for measuring component air leakage in the laboratory and field, respectively. ASTM E1186 [16] describes several techniques for locating air leakage sites in building envelopes and air barrier systems.

Airtightness Data

The importance of envelope airtightness to residential heating and cooling energy use has long been recognized and, thus, the airtightness of many single-family houses has been measured. Often, these measurements have been made as part of weatherization or other energy efficiency programs. Recently, Sherman and Matson [17] reported on a database of airtightness measurements for over 70,000 U.S. homes. While the average leakage for the whole database is quite high, about 20 air changes per hour at 50 Pa (or ACH50), new U.S. homes appear to be constructed tighter, with the average leakage of over 1,000 conventional new houses built since 1993 about half of that average value. As one might expect, energy efficiency construction programs appear to have a significant impact on house leakage as the average reported for new houses under such programs was half that of conventional new houses, or an ACH50 of 5 h^{-1}. Many homes in Canada and various Nordic countries are often constructed with very tight building envelopes, with several countries having standards or regulations for envelope airtightness [18].

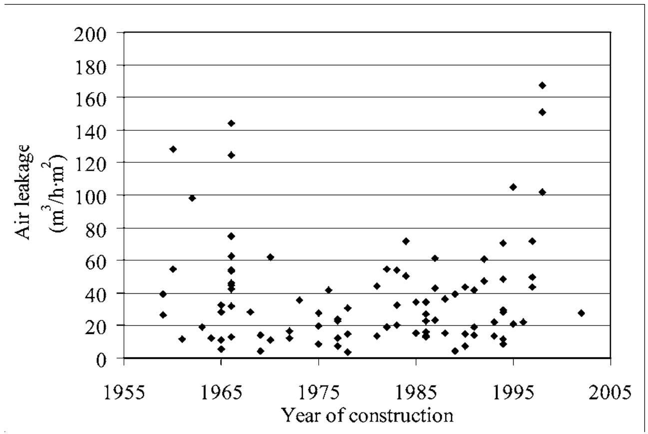


Fig. 4—*Commercial building air leakage (normalized by enclosure area) versus year of construction.*

Many discussions in the popular press and the technical literature still refer to commercial and institutional buildings, and newer buildings in particular, as being airtight. "Tight buildings" are often blamed for a host of indoor air quality problems including high rates of health complaints and more serious illnesses among building occupants. In 1998, Persily published a review of published commercial and institutional building airtightness data that found significant levels of air leakage and debunked the "myth" of the airtight commercial building [19]. More recently, Emmerich and Persily [20] reported on a database of airtightness measurements for 201 commercial and institutional buildings in the United States. The average airtightness for these buildings was found to be 28 m^3/h per m^2 of above grade enclosure surface area at 75 Pa, which is tighter than the average for United States houses but leakier than the average for conventional new United States houses. Unlike the residential airtightness data, the database of U.S. commercial building airtightness shows no indication of a trend toward tightness for newer buildings (see Fig. 4). Although the data show considerable scatter, there are trends indicating taller buildings are tighter on average than shorter buildings and that buildings in colder climates are tighter on average than buildings in warmer climates.

In addition to the whole building airtightness data discussed above, efforts have been made to collect and publish air leakage data for individual components [21]. Data exist for building joints, penetrations, and other leaks. Data also exist for doors and windows; however, those components are generally not significant contributors to total building leakage [22].

Infiltration Measurement and Prediction

Infiltration rates have been measured in many buildings, primarily low-rise residential using tracer gas dilution methods. ASTM Standard E741 [23] describes several tracer gas methods applicable to single zone buildings. These same techniques can be used to determine whole building air change rates in mechanically ventilated buildings, where the test result indicates the combination of infiltration and outdoor air intake. Since infiltration rates are a strong function of weather conditions, varying by a factor of 5 to 1 or even more, it is important to consider those conditions when reporting and interpreting such measurements. And in order to fully understand the infiltration characteristics of a building, many measurements are required under a range of weather conditions. A number of studies of infiltration rates in low-rise residential buildings have been conducted, though they have not involved randomly selected collections of homes [24,25]. Nevertheless, they do provide some indication of variations in infiltration rates as a function of climate and building features such as envelope airtightness.

Models have been developed to predict infiltration rates in buildings as a function of weather conditions, building leakage, and other building features. These range from simple single-zone models that employ a number of assumptions to simplify the calculation process to more complete network airflow analysis models that consider buildings as multizone systems and require more detailed input data [2]. An example of the latter type of program is the CONTAM model [26], which has been widely used to study airflow and indoor air quality in buildings.

Ventilation

Consistent with the definitions in the terminology section, ventilation is considered here to be the purposeful introduction of outdoor air into buildings, which is driven by either natural forces (i.e., natural ventilation), mechanical equipment (i.e., mechanical ventilation), or some combination thereof. While infiltration also introduces outdoor air into buildings, it is not considered to be ventilation per these definitions. The vast majority of residential buildings in the United States rely on infiltration as their primary source of outdoor air, supplemented by use of natural ventilation (e.g., open windows) and mechanical ventilation (e.g., bathroom and kitchen exhaust fans). However, the use of mechanical ventilation as the primary source of outdoor air in single-family houses has been growing in recent years, partially propelled by new ventilation codes and standards. The ventilation picture in United States commercial and institutional buildings is quite different from that in residential buildings, as the dominant practice has long been reliance on mechanical ventilation with infiltration generally considered unwanted and with interest in natural ventilation increasing in recent years.

Natural Ventilation

Natural ventilation's greatest advantage and disadvantage are both derived from the fact that it is driven by natural wind and thermal forces. Since there is no mechanical equipment required, natural ventilation systems typically have lower first costs and no operating cost (not including the costs of heating and cooling the ventilation air). However, since the amount of airflow relies on changing weather conditions, the result can be too little airflow sometimes and too much airflow—causing increased thermal loads—at other times. Many natural ventilation systems also require occupant action (e.g., opening windows or vents) to ensure proper ventilation.

The focus of this discussion of natural ventilation has been on its use as a means of introducing outdoor air for air quality purposes. However, modern buildings with designed natural ventilation often use it as the principal, if not only, source of cooling also. Such natural ventilation systems have significant implications for moisture levels in buildings as those buildings lack the moisture removal provided by mechanical equipment. Therefore, the issue of moisture levels must be considered carefully by the designer if applying natural ventilation to buildings with significant moisture sources or in humid climates.

A recent surge in interest in Europe has led to advanced natural ventilation technology and spurred development of hybrid (or mixed-mode) ventilation systems, which offers the possibility of attaining energy savings in a greater number of buildings through the combination of natural ventilation systems with mechanical equipment. The interested reader can learn more about natural and hybrid ventilation systems from numerous recent publications [27–31].

Mechanical Ventilation

Most U.S. commercial buildings include mechanical systems that supply air made up of a large fraction of recirculated air with a smaller fraction of outdoor air intake. Some mechanical ventilation systems have economizer cycles which provide additional outdoor air for "free cooling" when outdoor temperature or enthalpy conditions fall into an appropriate range. A smaller fraction of U.S. commercial buildings have either 100 % outdoor air systems or dedicated outdoor air systems, which provide conditioned outdoor air without recirculation. With these systems, additional thermal conditioning of the building space is provided by a separate air or water system if needed.

Since residential mechanical ventilation systems are relatively new, at least in the United States, no system can necessarily be called typical. Options include heat or energy recovery ventilators that may be either separate systems or provide supply into a central heating and cooling system, a dampered outdoor air intake connected to the return of a central heating and cooling system, or a whole-house exhaust system with multiple exhaust pick-up locations. These systems are frequently not operated full-time, but have timers to ensure sufficient run-time to meet ventilation needs.

Both residential and commercial buildings also utilize local exhaust systems whose primary purpose is the removal of moisture and odors from spaces such as bathrooms and kitchens. Such systems can be effective at removing moisture from the building before it mixes into the remainder of the building. Typically, local exhaust fans are operated continuously during occupied hours in commercial buildings, but are operated intermittently by occupants in residential buildings. Humidistats are another local exhaust control option and may ensure longer run-times, thus increasing moisture removal.

In addition to directly introducing outdoor air, mechanical systems also have important impacts on building pressures, which may contribute to the infiltration of outdoor air or exfiltration of indoor air through building envelopes. While some of these effects are intentional and expected, such as deliberate provision of greater supply air than return air in an attempt to pressurize a space, just as often such effects may be unintentional through either inappropriate design or lack of thorough testing and balancing. Additionally, even if total supply and return in a building are balanced, individual zones can be pressurized or depressurized due to local supplies and returns, thus resulting in unplanned infiltration or exfiltration.

Similarly, duct leakage can cause unplanned airflows that may result in the introduction of outdoor air from return leaks in humid spaces (e.g., crawl spaces) or through depressurization due to supply leaks outside the building envelope. One study found that residential duct leakage contributed almost 30 % to the total leakage of houses [32].

It is also important to recognize that actual mechanical ventilation system airflows cannot be assumed to equal design flows if such flows are even known. A recent study characterized the ventilation systems serving 100 randomly selected U.S. office buildings [33] including measurement of outdoor airflow rates and comparison to design in the 97 buildings that were mechanically ventilated. The study found that design minimum outdoor air intake values were available for only about half of the mechanical systems. Also, about half of the measured outdoor airflows (under minimum outdoor air intake conditions) were below 10 L/s per person. Under minimum outdoor air intake, about half of the measured outdoor air intake rates were below the requirements in ASHRAE Standard 62-1989 [34], the version of the standard that would have applied at the time they were designed. Similar issues were identified for building exhaust fans as design values were available for 129 of the 159 exhaust fans and the average measured flow in a subset of 41 fans was only 57 % of the design flow.

Outdoor air ventilation rates tend to be higher than might be expected, with a mean value of 49 L/s per person based on the number of occupants and 36 L/s per person based on the number of workstations in the space. Still, 17 % of these measured values (per occupant) are below the 10 L/s per person requirement in ASHRAE Standard 62-1989, and these lower rates occur in 22 of the 97 mechanically ventilated buildings. While these values are high on average relative to the minimum outdoor air requirements in Standard 62, the high outdoor air fractions and the low occupancy relative to the actual number of workstations (and to the default occupancy value in the standard) explains most of the higher values. Adjusting the measured outdoor air ventilation rates to minimum outdoor air conditions and to the occupant density in Standard 62 reduces the mean to 9 L/s per person. Considering only those values that correspond to minimum outdoor air intake, the mean ventilation rate is 14 L/s per person. Adjusting these minimum values for the number of workstations rather than the measured occupancy levels yields a mean of 11 L/s per person, with one-half of these minimum values being below the requirement in ASHRAE Standard 62-1989. In other words, under minimum outdoor air intake, about one-half of the measured outdoor air intake rates are below the requirements in ASHRAE Standard 62-1989 based on the expected occupant levels in the space, and about one-quarter of the rates are below 5 L/s per person, i.e., one-half of the 1989 ASHRAE requirement.

Ventilation Requirements

A number of countries have ventilation requirements in standards or regulations [18]. The most widely recognized ventilation requirements in the United States are ASHRAE Standard 62.1 for commercial buildings and Standard 62.2 for low-rise residential buildings [7,35]. ASHRAE Standard 62.1 has long been adopted by many U.S. codes and provides requirements for ventilation systems and equipment including minimum outdoor airflow rates for spaces including correctional facilities, schools, restaurants, hotels, offices, retail buildings, public assembly spaces, and sports facilities. Standard 62.1 also provides minimum exhaust rates for toilets, commercial kitchens, and other spaces.

ASHRAE Standard 62.2 was first published in 2003 and has not yet been adopted by code in most U.S. jurisdictions. Like Standard 62.1, 62.2 provides requirements for ventilation systems including equipment performance, minimum outdoor airflow rates, and local exhaust rates for kitchens and bathrooms. These latter exhaust requirements are driven primarily by the goal of removing moisture from these spaces.

Interzone Airflows

Consideration of whole building air infiltration and ventilation rates can assist in understanding building moisture issues, but in some cases it is necessary to also consider airflow between buildings zones with potentially different moisture conditions, such as bathrooms, kitchens, and basements. In particular, airflows to and from unconditioned spaces such as crawl spaces, attics, and wall cavities can be more significant due to the generally wider range of temperatures and humidity conditions in these types of spaces. Airflows between these various zones are driven by the same pressures and leakages discussed earlier in the context of whole building leakage, and the same modeling tools such as CONTAM [26] can be used to predict these interzone airflow rates and the associated moisture transport. Tracer gas techniques exist to measure these interzone airflow rates, but they have not been standardized and remain largely in the realm of research. However, it is rarely necessary to measure these airflows to understand the moisture impacts of these spaces in a particular building.

Summary

Infiltration and ventilation airflows can have a major impact on moisture in buildings. They can either be part of the problem or part of the solution, but they cannot be ignored when one is designing, operating, maintaining, or troubleshooting a building. These airflows can directly introduce moist or dry air into a building space, then can create pressures that move moisture into or keep it out of the building envelope, and they can enable or prevent the transport of moist air from one building space to another. In recent decades, the understanding of building airflow fundamentals has improved, measurement methods have been developed and standardized, data have been collected and analyzed, design guidance has been published, and modeling tools have become widely available. There are still unanswered questions and each building still requires consideration of its own unique circumstances, but there is no reason to ignore these effects given the established knowledge.

References

[1] Harriman, L., Brundrett, G., and Kittler, R., *Humidity Control Design Guide for Commercial and Institutional Buildings*, American Society of Heating, Refrigerating, and Air-Conditioning Engineers, 2001.

[2] ASHRAE, *Fundamentals Handbook*, American Society for Heating, Refrigerating and Air-Conditioning Engineers, 2005.

[3] Hunt, C. M., King, J. C., and Trechsel, H. R., Eds., *Building Air Change Rate and Infiltration Measurements, ASTM STP 719*, ASTM International, West Conshohocken, PA, 1980.

[4] Sherman, M. H., Eds., *Air Change Rate and Airtightness in Buildings, ASTM STP 1079*, ASTM International, West Conshohocken, PA, 1990.

[5] Modera, M. P. and Persily, A. K., Eds., *Airflow Performance of Building Envelopes, Components and Systems, ASTM STP 1255*, ASTM International, West Conshohocken, PA, 1995.

[6] Limb, M. J., "Air Infiltration and Ventilation Glossary," AIVC Technical Note 36, Air Infiltration and Ventilation Centre, 1992.

[7] ASHRAE, ANSI/ASHRAE Standard 62.1-2007, "Ventilation for Acceptable Indoor Air Quality," American Society for Heating, Refrigerating and Air-Conditioning Engineers, 2007a.

[8] Tamura, G. T. and Wilson, A. G., "Pressure Differences for a Nine-Story Building as a Result of Chimney Effect and Ventilation System Operation," *ASHRAE Transactions*, Vol. 72, No. I, 1966.

[9] Tamura, G. T. and Shaw, C. Y., "Building Pressures Caused by Chimney Action and Mechanical Ventilation," *ASHRAE Transactions*, Vol. 73, No. II, 1967.

[10] Tamura, G. T. and Wilson, A. G., "Pressure Differences Caused by Chimney Effect in Three High Buildings," *ASHRAE Transactions*, Vol. 73, No. II, 1967.

[11] ASTM Standard E779-03, "Standard Test Method for Determining Air Leakage Rate by Fan Pressurization," *Annual Book of ASTM Standards*, ASTM International, West Conshohocken, PA, 2003.

[12] CGSB CAN/CGSB-149.15-96, "Determination of the Overall Envelope Airtightness of Buildings by the Fan Pressurization Method Using the Building's Air Handling Systems," Canadian General Standards Board, Ottawa.

[13] ASTM Standard E1827-96, "Standard Test Method for Determining Airtightness of Buildings Using an Orifice Blower Door," *Annual Book of ASTM Standards*, ASTM International, West Conshohocken, PA, 2002.

[14] ASTM Standard 2004. E283-04, "Standard Test Method for Determining Rate of Air Leakage Through Exterior Windows, Curtain Walls, and Doors Under Specified Pressure Differences Across the Specimen," *Annual Book of ASTM Standards*, ASTM International, West Conshohocken, PA, 2004.

[15] ASTM Standard E783-02, "Standard Test Method for Field Measurement of Air Leakage Through Installed Exterior Windows and Doors," *Annual Book of ASTM Standards*, ASTM International, West Conshohocken, PA, 2002.

[16] ASTM Standard E1186-03, "Standard Practices for Air Leakage Site Detection in Building Envelopes and Air Barrier Systems," *Annual Book of ASTM Standards*, ASTM International, West Conshohocken, PA, 2002.

[17] Sherman, M. H. and Matson, N. E., "Air Tightness of New U.S. Houses. A Preliminary Report," LBNL-48671, Lawrence Berkeley National Laboratory, 2003.

[18] Limb, M. J., "Ventilation and Building Airtightness: An International Comparison of Standards, Codes of Practice and Regulations, AIVC Technical Note 55," Air Infiltration and Ventilation Centre, 2001.

[19] Persily, A. K., "Airtightness of Commercial and Institutional Buildings: Blowing Holes in the Myth of Tight Buildings," *Proceedings of DOE/ASHRAE/ORNL/BETEC/NRCC/CIBSE Conference Thermal Performance of the Exterior Envelopes of Buildings VII*, 1998, pp. 829–837.

[20] Emmerich, S. J. and Persily, A. K., "Airtightness of Commercial Buildings in the U.S.," *Proceedings of 26th AIVC Conference*, Air Infiltration and Ventilation Centre, Coventry, Great Britain, 2005.

[21] ASHRAE, *Fundamentals Handbook*, American Society for Heating, Refrigerating and Air-Conditioning Engineers. 2001.

[22] Orme, M. and Leksmono, N., *Ventilation Modeling Data Guide, AIVC Guide 5*, Air Infiltration and Ventilation Centre, 2002.

[23] ASTM Standard E741-00, "Standard Test Method for Determining Air Change in a Single Zone by Means of a Tracer Gas Dilution," *Annual Book of ASTM Standards*, ASTM International, West Conshohocken, PA, 2000.

[24] Palmiter, L. S., Brown, L. A., and Bond, T. C., "Measured Infiltration and Ventilation in 472 All-Electric Homes," *ASHRAE Transactions*, Vol. 97, No. 2, 1991, pp. 979–987.

[25] Pandian, M. D., Behar, J. V., Ott, W. R., Wallace, L. A., Wilson, A. L., Colome, S. C., and Koontz, M., "Correcting Errors in the Nationwide Data Base of Residential Air Exchange Rates," *J. Expo Anal Environ. Epidemiol.*, Vol. 8, No. 4, 1988, pp. 577–591.

[26] Walton, G. N. and Dols, W. S., *CONTAMW 2.4 User Guide and Program Documentation* NISTIR 7251, National Institute of Standards and Technology, 2005.

[27] Axley, J. W., "Passive Ventilation for Residential Air Quality Control," *ASHRAE Transactions*, Vol. 105, Part 2, 1999.

[28] Axley, J. W., "Application of Natural Ventilation for U.S. Commercial Buildings: Climate Suitability, Design Strategies & Methods, Modeling Studies," GCR-01-820, National Institute of Standards and Technology, 2001.

[29] BRE, NatVent—CD-ROM, Building Research Establishment, 1999.

[30] Delsante, A. and Vik, T. A., Eds., "Hybrid Ventilation State-of-the-Art Review," International Energy Agency Annex 35 Report, 2000.

[31] Emmerich, S. J. and Crum, J., "Simulated Performance of Natural and Hybrid Ventilation Systems in an Office Building," ARTI-21CR/611-40076-01, Air-Conditioning and Refrigeration Technology Institute, 2005.

[32] Sherman, M. H. and Dickerhoff, D. J., "Air Tightness of U.S. Dwellings," *Proceedings of the 15th AIVC Conference*, 1998.

[33] Persily, A., and Gorfain, J., "Analysis of Ventilation Data from the U.S. Environmental Protection Agency Building Assessment Survey and Evaluation (BASE) Study," NISTIR 7145 – Revised, National Institute of Standards and Technology, 2008.

[34] ASHRAE, ANSI/ASHRAE Standard 62–1989, "Ventilation for Acceptable Indoor Air Quality," American Society for Heating, Refrigerating and Air-Conditioning Engineers, 1989.

[35] ASHRAE, ANSI/ASHRAE Standard 62.2-2007, "Ventilation for Acceptable Indoor Air Quality in Low-Rise Residential Buildings," American Society for Heating, Refrigerating and Air-Conditioning Engineers, 2007b.

9

Heating and Cooling Equipment

Russell M. Keeler P.E.[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 or fins per centimeter 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 ft (6 fins per cm) is a practical upward limit on fin density, with 132 fins per ft (4.3 fins per cm) 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 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 room condition 75°F (23.9°C), DB/50 % RH) selected to be within the human comfort zone. A computation

[1] *Principal, Chason Energy, 1153 Bergen Parkway, Suite M301, Evergreen, CO 80439.*

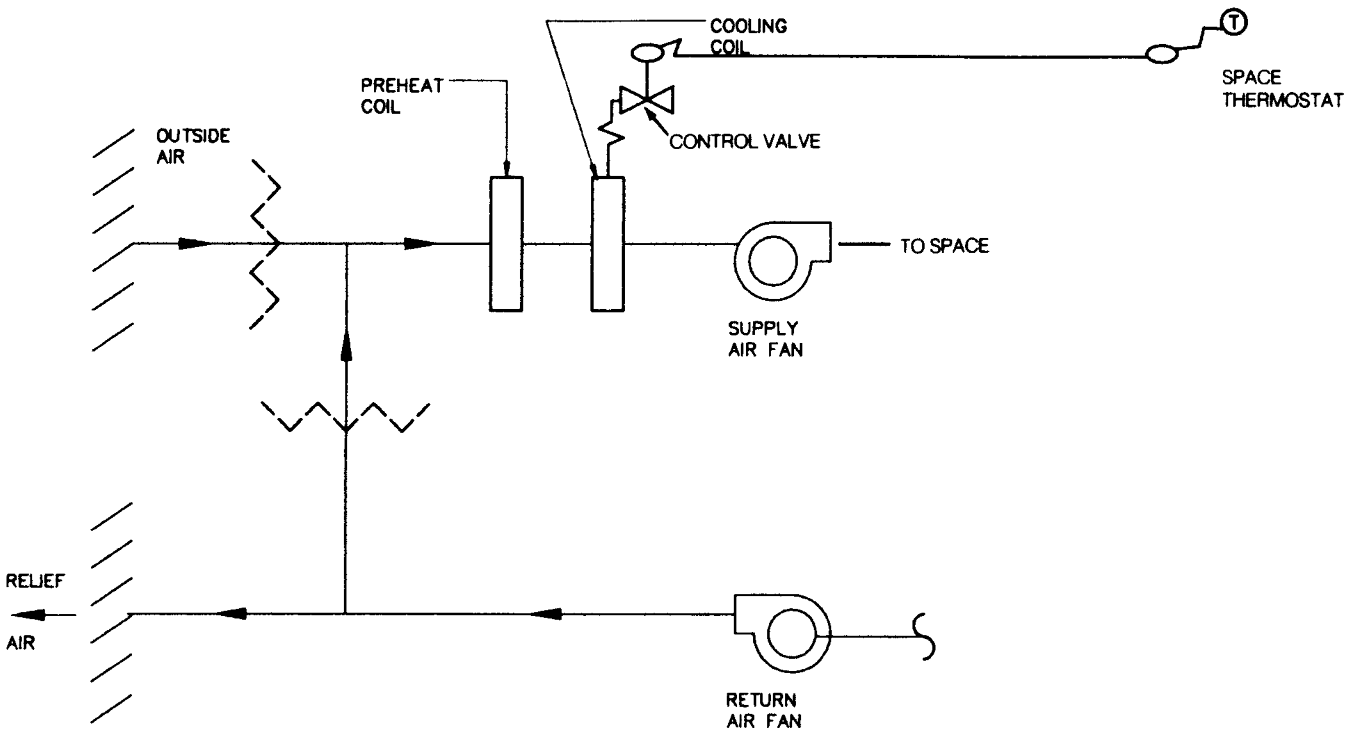


Fig. 1—Simple air conditioning system.

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), little moisture can be absorbed from a room at 75°F (23.9°C) DB/55 % 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 is 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 10 tons of capacity (35 kW) 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 (10 kW), a reasonable equipment selection may be 2 tons (7 kW). Few operating hours at the 3-ton (10 kW) condition will arise during the year, but a substantial part of the cooling duty will be experienced at the 2-ton (7 kW) level. At these lower load times, the system will run more or less continuously, 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 "under sizing" equipment selection approach is quite common in the residential air conditioning market.

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.

In unitary (under 10 tons) systems, there is generally no provision for modulation of cooling capacity. That is, the system is either "On" or "Off". At design load, this control scheme works well, but at part load, such as low sensible load and high humidity, the "On"/"Off" control fails at humidity control.

In small unitary systems, a more appropriate design approach is to provide two units, each at half the design load. By cycling the units so that one operates from the room thermostat with the other idle, full compressor operation is assured, and dehumidification can take place. The second unit only operates when the first is at full capacity, and the room thermostat is not satisfied, calling for full cooling. A time lag of 5–10 min should be programmed into the control sequence to avoid excessive cycling.

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

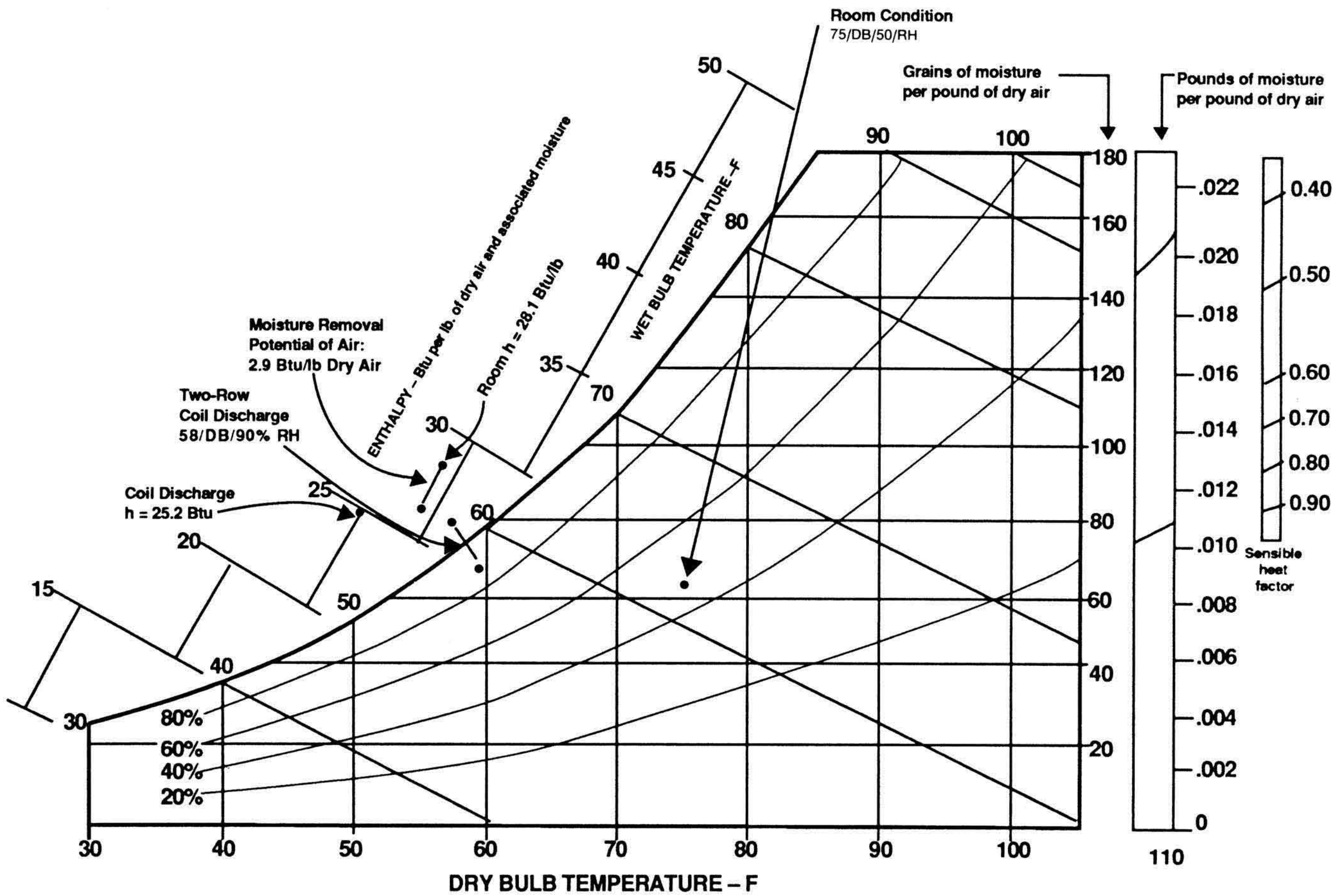


Fig. 2—Psychometric chart.

(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 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 colder conditioned air become mixed with room air before the air stream sweeps the surfaces.

TABLE 1—Shallow coil moisture absorption.

Location	Absolute Humidity Grains/lb Dry Air	Absolute Humidity 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]	70	10.0
Absorbing potential	6	0.86

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 in. (6 fins per cm). Typically for air conditioning applications, fin spacing ranges from eight to fourteen per inch (three to six per centimetre).

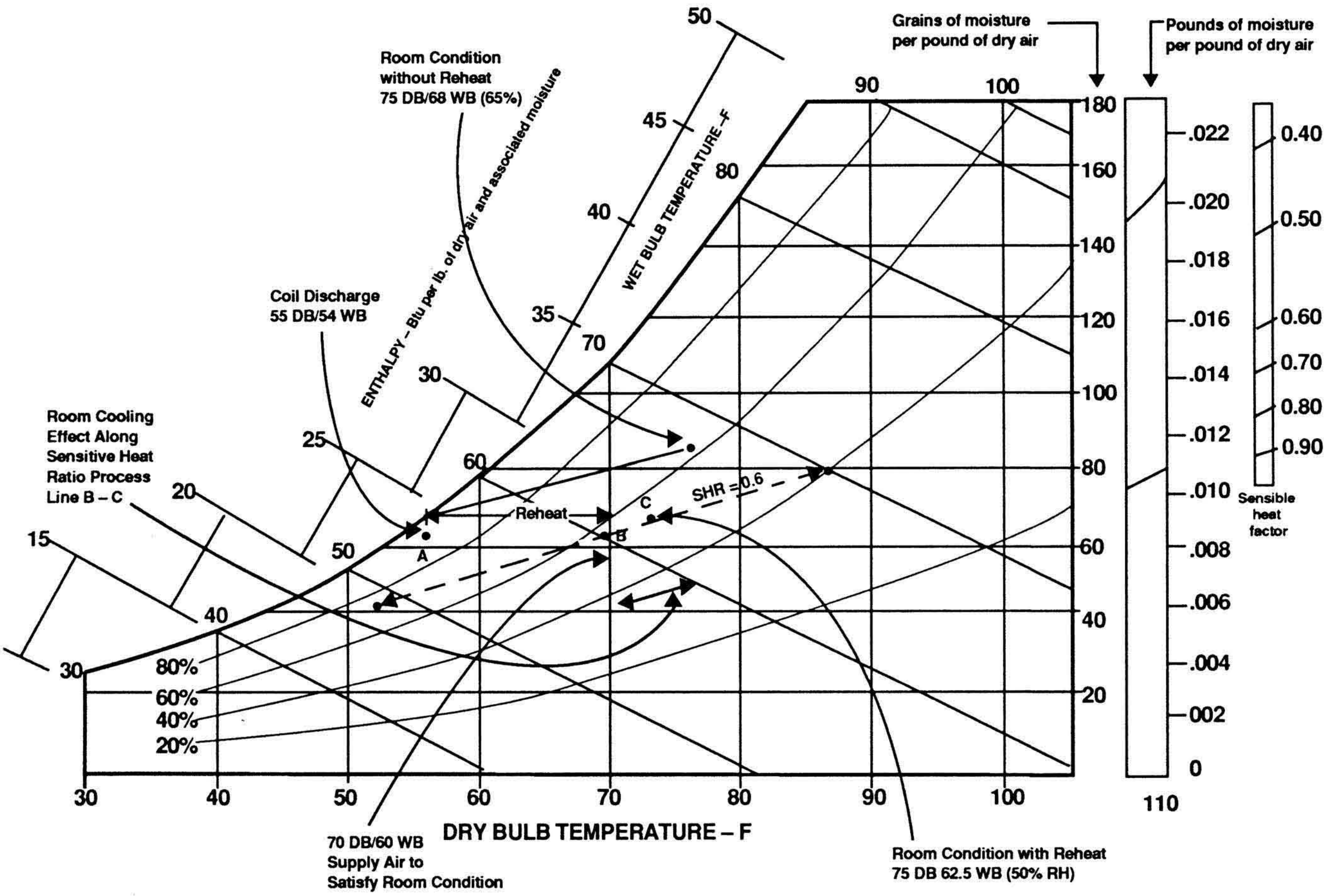


Fig. 3—Psychrometric chart.

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.

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 air stream. 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

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

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

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.

Impact of Sensible Heat Ratio on Condensation

Operational histories with many air conditioning systems in a variety of climates indicate that maintaining 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 a situation 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 (sensible temperature).

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 cooling 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

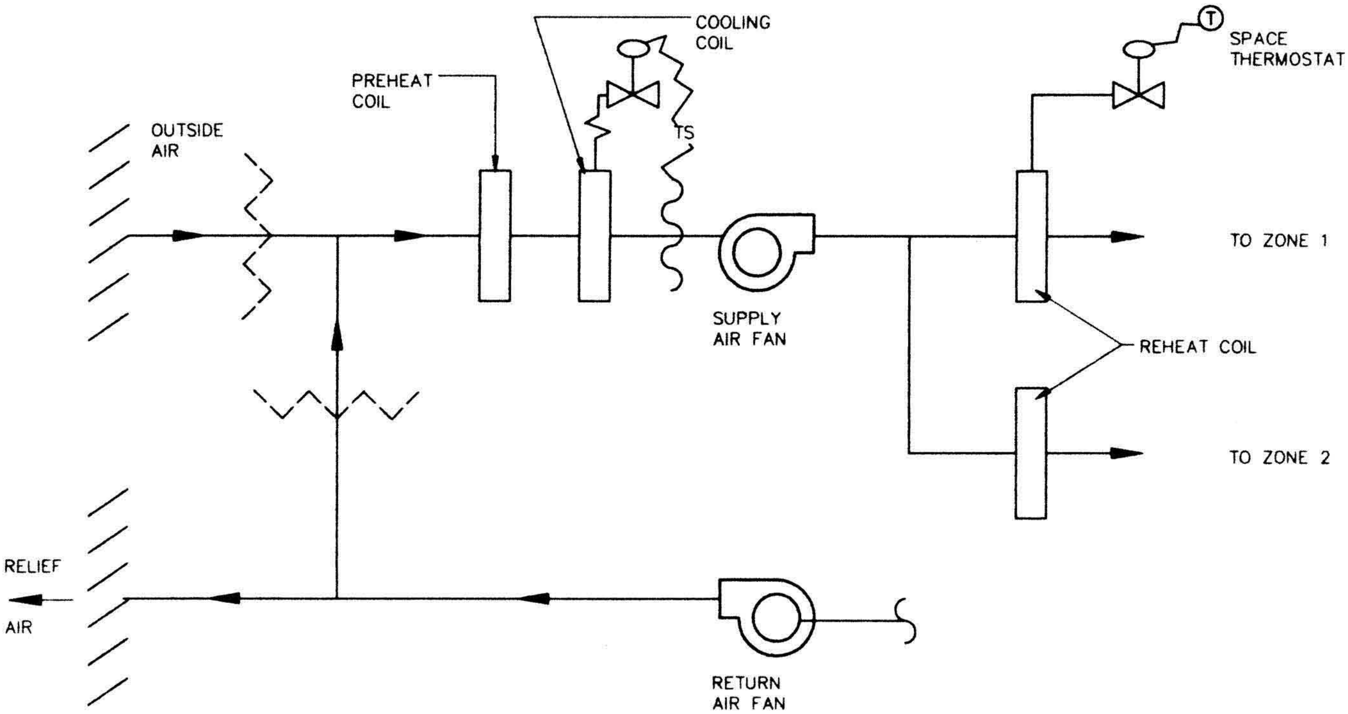


Fig. 4—Constant volume reheat system.

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 to 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 (no control over coil temperature) 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 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 variable volume reheat, and fan-powered induction systems.

Air Distribution

Overhead systems

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.

Under floor air distribution systems

Under floor air distribution systems present a special challenge in dehumidification, as the systems are designed to introduce air to the space at relatively high temperatures of 65–68°F (18–20°C). Coil discharge temperatures in this range will not provide dehumidification. The most reasonable way to dehumidify without the introduction of "new" energy is to employ a face and bypass arrangement in the system. Dehumidification is achieved by passing part of the conditioned air through the coil at a low temperature, and then reheating the air using return air. A deep cooling coil will be required.

In one recent assembly hall installation, we used a 10 row cooling with a discharge air temperature of 42°F. The discharge air was then reheated to 68°F using return air.

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 3,500 h per year or (2) 73°F (22.8°C) or more for 1,750 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. 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. Face and bypass.
3. 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.

Face and bypass reheat

Face and bypass systems use some of the return air as a source of reheat by diverting the air around the cooling coil, then mixing the warmer return with the dehumidified air from the cooling coil. Careful selection of the cooling coil discharge temperature will result in a warmer (but very dry) mixture that can still achieve the dehumidification goal.

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 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 temperature 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

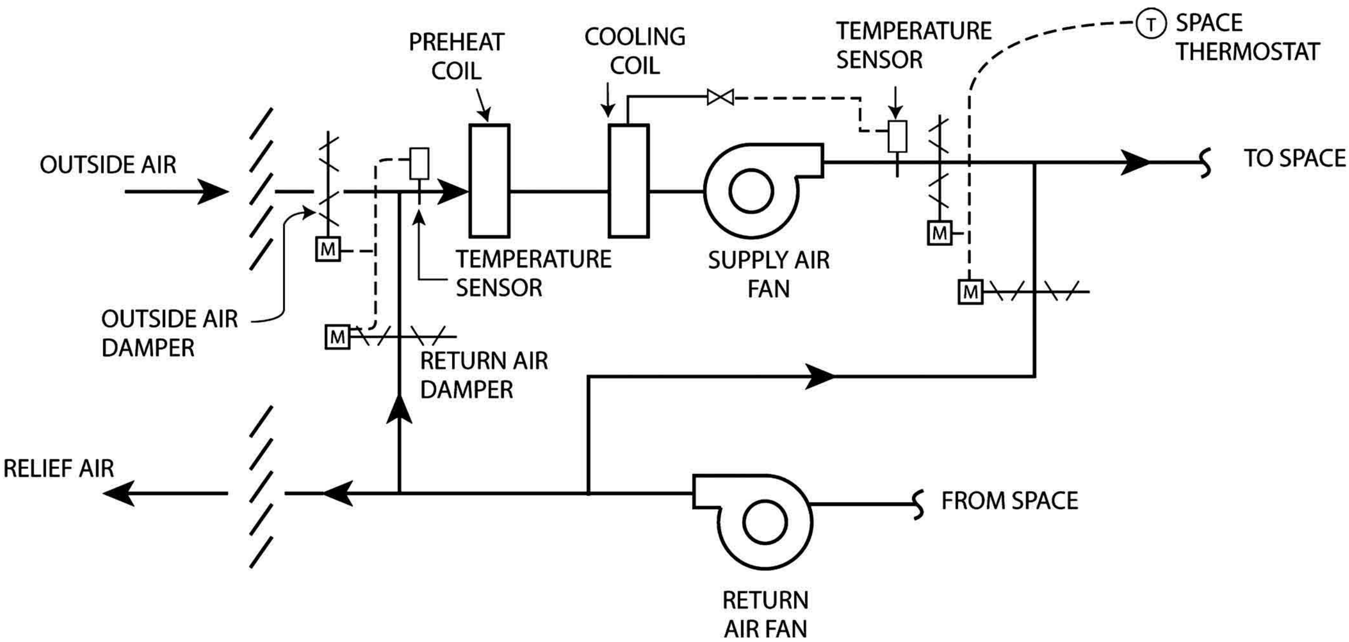


Fig. 5—Face and bypass reheat.

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

[2] Private communication with Heinz Trechsel regarding observations of public housing high-rise buildings.

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.
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 the opposite 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, 2001–2004.

[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.

10

Design Tools

Anton TenWolde[1] and Mark T. Bomberg[2]

Introduction

TO PREVENT POTENTIAL MOISTURE PROBLEMS IN housing in cold climates, various rules of thumb were developed during the 1930s and 40s. In principle they all stated that a "vapor barrier" should be incorporated into exterior walls on the inside (warm in winter side) of the insulation [1]. These rules were later refined to include a statement that the exterior of the wall should have a water vapor permeance five times greater than the interior vapor barrier [2]. Further refinements attempted to include rules for warm and humid climates [3]. By and large, these rules were useful, although they did not cover moisture transport mechanisms other than vapor diffusion which, it was found later, is not the greatest source of moisture transport into and through building envelopes. While these simple rules may be appropriate for extreme cold or extreme warm climates, they ignore the fact that in many locations design rules targeted at one season (summer or winter) may not be appropriate for conditions during the rest of the year.

To account for diffusion mechanisms more effectively, manual, steady-state methods were developed to determine moisture movement in walls and roofs. Being steady-state, based on a single set of assumptions, such as indoor and outdoor temperatures and relative humidities; such methods are of limited value, although their application is a significant improvement over the simple adoption of the rules of thumb previously used. These methods, known as manual design tools, all have severe limitations, and the results are difficult to interpret. However, these methods are widely used by design professionals and have traditionally been used to formulate building code requirements for vapor retarders. The proper use and limitations of these methods are discussed in the first section of this chapter, Manual Design Tools.

In an effort to provide a better understanding of the various mechanisms and interactions of moisture and heat transfer in building envelopes, transient mathematical models were developed. First thought of as strictly research tools, they soon began to be useful tools for designers. In their most simple form, they applied hourly weather data to model moisture diffusion through multilayer envelope sections. In their most sophisticated form they account not only for diffusion, but also for air movement and rainwater wetting of the exterior surface and rainwater leakage.

Today, the designer has several levels of design tools available: Manual, steady-state methods, and transient (nonsteady-state) mathematical models. Manual, steady-state methods are of particular value only when comparing two or more similar designs for their relative propensity to condensation under specific environmental conditions.

Mathematical models are useful tools for a much broader set of design issues, but they too have limitations. It is precisely the sophistication of the models that impose difficulties: The input data required is often difficult to come by in the design stage, but criteria for indoor and outdoor conditions to be used for building design have been developed by ASHRAE Standard Committee 160 [3]. Another difficulty is incorporating air leakage into the design analysis. Including air leakage into the calculations requires an estimate of the air leakage rate through the wall. Although laboratory tests can be performed to give some idea of the leakage rate, the air pressure regimes even in the laboratory will not be the ones experienced in the field. However, when in-service data regarding air leakage rates of similar walls are available, the mathematical models, especially those including air leakages, are very powerful tools.

Overall, despite the lack of exact input data, the use of design tools, including models, is much superior to the simple following of rules of thumbs, and a moisture analysis should be standard procedure for any building envelope design. Exceptions can only be made for buildings in the same climate, similar occupancy, and similar envelope construction. This chapter provides guidance in the use of steady-state, manual methods, and an introduction to mathematical models. A more detailed discussion of mathematical models and modeling is provided in *ASTM MNL40, Moisture Analysis and Condensation Control in Building Envelopes*. Models are still under development and the user is encouraged to consult the various references before starting the use of models.

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,

[1] *Research Physicist (retired), USDA Forest Service, Forest Products Laboratory, One Gifford Pinchot Drive, Madison WI 53726-2398. The Forest Products Laboratory is maintained in cooperation with the University of Wisconsin.*
[2] *Research Professor, Department of Mechanical and Manufacturing Engineering, Syracuse University, Syracuse, NY 13244.*

TABLE 1—Example of a wall with approximate thermal and vapor diffusion properties.

Air Film or Material	Thermal Resistance (h·ft²·°F/Btu)	Thermal Resistance (m²·K/W)	Water Vapor Permeance[a] (perm)	Water Vapor Diffusion Resistance (1/perm)	Water Vapor Diffusion Resistance (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	16.67	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]	329.7[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 limits ventilation of back of siding.
[d]Total diffusion resistance of wall with vapor retarder.
[e]Total diffusion resistance of wall without vapor retarder.

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 [4] is based on the following diffusion equation and definitions

$$w = \delta \Delta p / d \tag{1}$$

where:

w = vapor flow per unit of area, kg/m²·s (grain/ft²·h),
δ = water vapor permeability, kg/m·s· Pa or s (perm · in.),[3]
p = vapor pressure, Pa (in. Hg), and
d = thickness of the material (distance along flow path), m (in.).

This equation is based on Fick's law, which uses concentration gradient as the driving potential, rather than vapor pressure. However, the concentration of water vapor in air is very low, and therefore the ideal gas law can be assumed to apply. This allows us to substitute water vapor pressure for water vapor concentration.

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 diffusion resistance, Z, is the inverse of permeance and is expressed in reps (1/perm) or m/s

$$Z = d/\mu \tag{2}$$

Thus, Eq (1) can also be written as

$$w = \Delta p / Z \tag{1a}$$

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 21.1°C (70°F), 40 % indoor relative humidity, and −6.7°C (20°F), 50 % outdoor relative humidity. The wall in the 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

$$\Delta T_{\text{material}} / \Delta T_{\text{wall}} = R_{\text{material}} / R_{\text{wall}} \tag{3}$$

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 Tables 6(a) and 6(b)

[3] 1 perm=1 grain/ft²·h· in. Hg: 1 grain=1/7000 lb; rep=1/perm.

TABLE 2—Calculation of temperatures and saturation vapor pressures.[a]

Air Film or Material	Temperature, °C (°F) Drop	Surface	Saturation Vapor 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)	473 (0.1394)[b]
Plywood sheathing	1.2 (2.2)		
		−4.3(24.2)	426 (0.1258)[b]
Wood siding	2.0 (3.6)		
		−6.3(20.6)	359 (0.1060)[b]
Surface air film	0.4 (0.6)		
		−6.7 (20)	371 (0.1096)[c]
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.
[b]Saturation vapor pressure over ice.
[c]Saturation vapor pressure over water. Dewpoint temperature or RH, reported in weather data, usually relates to saturation over water, not over ice.

or in psychrometric tables or charts (e.g., Ref. [4], Chapter 6). Table 2 lists the saturation vapor pressures for this example.

Step 3—Vapor pressure drops across each material can be calculated in much the same way as are temperature drops

$$\Delta p_{\text{material}}/\Delta p_{\text{wall}} = Z_{\text{material}}/Z_{\text{wall}} \quad (4)$$

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)

$$Z_{\text{wall}} = 329.73\ 10^9\ \text{m/s}\ (18.94\ \text{perm}^{-1})$$

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).

$$\Delta p_{\text{wall}} = p_{\text{indoor}} - p_{\text{outdoor}} = (40/100)2503 - (50/100)371$$
$$= 1001 - 185 = 816\ \text{Pa}\ (0.2409\ \text{in. Hg})$$

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

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)	
	472 (0.1394)		273 (0.0806)
Plywood sheathing		86.2 (0.0254)	
	426 (0.1258)		187 (0.0552)
Wood siding		1.2 (0.0004)	
	359 (0.1060)		185 (0.0548)
Surface air film		0.04 (0.00001)	
	371 (0.1096)		185 (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.

$$w = \Delta p_{\text{wall}}/Z_{\text{wall}} \quad (5)$$

For this example, $w = 816/(329.73\ 10^9) = 2.510^{-9}\ \text{kg/m}^2\cdot\text{s}$ (0.013 grain/h·ft^2). 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 temperatures (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.

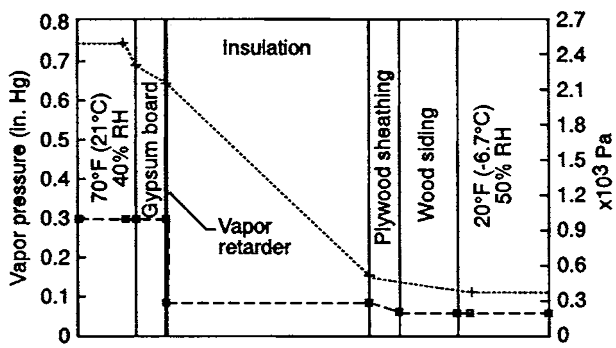


Fig. 1—Dew point method; example of a wall with vapor retarder. Dotted line is saturation vapor pressure; dashed line is calculated vapor pressure.

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)	
	472 (0.1394)		915 (0.2702)
Plywood sheathing		718.9 (0.2123)	
	426 (0.1258)		196 (0.0579)
Wood siding		10.3 (0.0030)	
	359 (0.1060)		186 (0.0549)
Surface air film		0.4 (0.0001)	
	371 (0.1096)		185 (0.0548)
Outdoor air (50 % RH)			
	Final Calculation		
Indoor air			
	2503 (0.7392)		1001 (0.2957)
Surface air film		13.8 (0.0041)	
	2305 (0.6807)		987 (0.2916)
Gypsum board		439.8 (0.1299)	
	2174 (0.6419)		547 (0.1617)
Insulation		75.4 (0.0223)	
	472 (0.1394)		472 (0.1394)
Plywood sheathing		281.7 (0.0834)	
	426 (0.1258)		190 (0.0560)
Wood siding		4.0 (0.0012)	
	359 (0.1060)		186 (0.0548)
Surface air film		0.2 (0.00005)	
	371 (0.1096)		186 (0.0548)
Outdoor air			

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 472 Pa (0.1394 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).

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 walls is

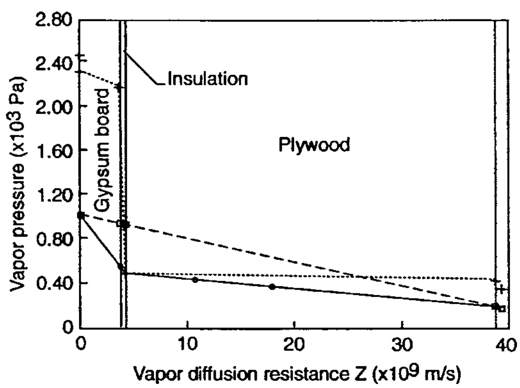


Fig. 2—Dew point method; example wall without vapor retarder. Dotted line is saturation vapor pressure; dashed line is initial calculation of vapor pressure; solid line is final calculation of vapor pressure.

$$\Delta p_1 = 1001 - 472 = 529 \text{ Pa (0.156 in. Hg)}$$

and that over the second part is

$$\Delta p_2 = 472 - 185 = 287 \text{ Pa (0.085 in. Hg)}$$

The vapor diffusion resistances of both parts of the wall are

$$Z_1 = (0.11 + 3.5 + 0.6)10^9 = 4.21\ 10^9 \text{ m/s (0.24 perm}^{-1}\text{)}$$

$$Z_2 = (35 + 0.5 + 0.02)10^9 = 35.52\ 10^9 \text{ m/s (2.03 perm}^{-1}\text{)}$$

The vapor pressure drops can now be calculated from

$$\Delta p_{\text{material}}/\Delta p_i = Z_{\text{material}}/Z_i \quad i = 1,2 \tag{6}$$

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 water (solid or liquid) accumulation.

$$w_c = \Delta p_1/Z_1 - \Delta p_2/Z_2 = 529/(4.21\ 10^9) - 287/(35.52\ 10^9)$$
$$= 118\ 10^{-9} \text{ kg/s} \cdot \text{m}^2 \text{ (0.61 grain/h} \cdot \text{ft}^2\text{)}$$

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:

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 [5,6] 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

$$w = -(\delta'/\mu')\Delta p/d \tag{7}$$

where:

δ' = diffusion coefficient of water vapor in air, s,
μ' = diffusion resistance factor of the material, and
d = distance along the flow path or thickness of the material, m (in.).

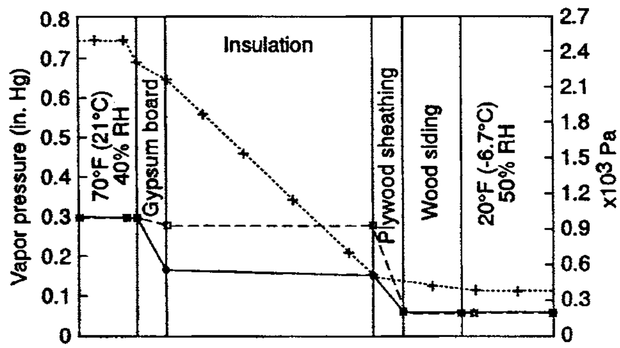


Fig. 3—Glaser diagram for example wall without vapor retarder. See caption to Fig. 2 for line designations.

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

$$\delta = \delta'/\mu' \tag{8}$$

Combining Eqs (7) and (8) 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. [7] and described in greater detail by TenWolde [8]. 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:

$$x_1 = R_1/R_{\text{wall}}$$

$$x_2 = x_1 + R_2/R_{\text{wall}}$$

$$x_n = x_{n-1} + R_n/R_{\text{wall}} \tag{9}$$

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:

$$T(x) = T_i - x(T_i - T_o) \tag{10}$$

where

T_i = indoor temperature °C (°F), and
T_o = outdoor temperature °C (°F).

The vapor diffusion y parameter is defined similarly as

$$y_n = y_{n-1} = Z_n/Z_{\text{wall}} \tag{11}$$

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

$$w_c = \frac{p_i - p_s[T(x)]}{yZ_{\text{wall}}} - \frac{p_s[T(x)] - p_o}{(1-y)Z_{\text{wall}}} = \frac{1}{Z_{\text{wall}}}\frac{p_i - p_s[T(x)] - y(p_i - p_o)}{y(1-y)} \tag{12}$$

where

w_c = moisture accumulation rate, kg/m^2·s (grain/ft^2·h),
p_i = indoor vapor pressure, Pa (in. Hg),
p_o = outdoor vapor pressure, Pa (in. Hg),
$p_o[T(x)]$ = 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

$$w_c Z_{\text{wall}} = \frac{p_i - p_s[T(x)] - y(p_i - p_o)}{y(1-y)} \tag{13}$$

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.

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 point on the curve that penetrates the deepest (i.e., the plywood surface) represents the greatest wetting potential. This point falls between curve d (w_cZ = 1.0 in. Hg or 3386 Pa) and e (w_cZ = 1.5 in. Hg or 5080 Pa). The wetting potential can be estimated by interpolation:

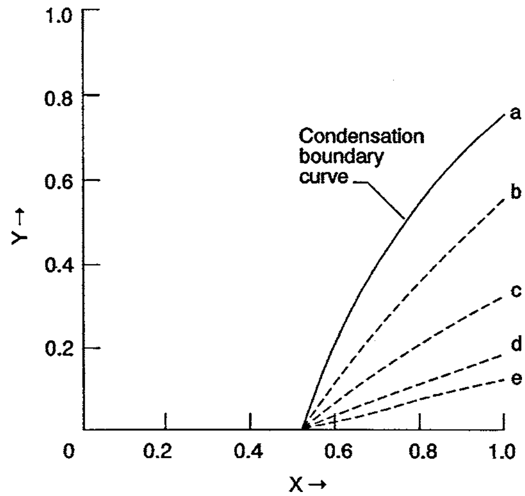


Fig. 4—Kieper diagram: moisture accumulation curves for indoor conditions of 70°F (21°C), 40 % RH and outdoor conditions of 20°F (−6.7°C), 50 % RH. The W_CZ values for the curves are (*a*) 0, (*b*) 0.2 in. Hg (677 Pa), (*c*) 0.5 in. Hg (1693 Pa), (d) 1.0 in. Hg (3386 Pa), and (e) 1.5 in Hg (5080 Pa).

$$w_cZ = 1.4 \text{ in. Hg (4740 Pa)}$$

With Z = 2.27 perm^{-1} (39.710^9 m/s), the estimated rate of condensation is

$$w_c = 1.4/2.27 = 0.62 \text{ grain/h} \cdot \text{ft}^2 \ (12010^{-9} \text{ kg/m}^2 \cdot \text{s})$$

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 [9]. Even small amounts of indoor air leakage into the wall (exfiltration) can more than double the condensation rate during winter [10]. However, where exfiltration increases the potential for wetting, infiltration of dry cold air decreases that potential. If the amount and 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

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/ft^2·h·in. Hg.

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 [11].

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" are not included.

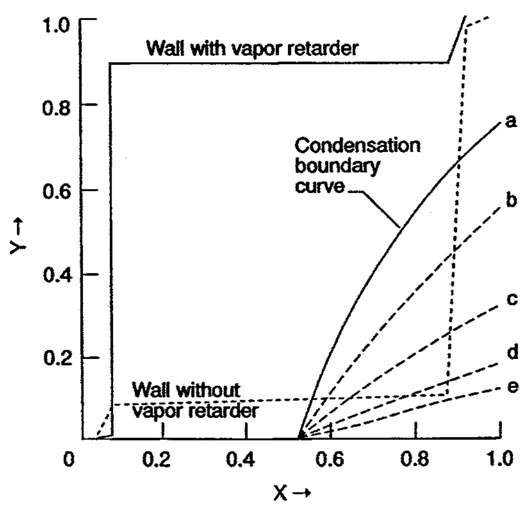


Fig. 5—Kieper diagram: example wall with and without vapor retarder, indoor conditions of 70 °F (21°C), 40 % RH and outdoor conditions of 20°F (−6.7°C), 50 % RH. The $w_C Z$ values for the curves are (*a*) 0, (*b*) 0.2 in. Hg (677 Pa), (*c*) 0.5 in. Hg (1693 Pa), (*d*) 1.0 in. Hg (3386 Pa), and (*e*) 1.5 in. Hg (5080 Pa).

Recommendations for Use

Although manual design tools have many limitations and are based on simplifying assumptions, they have the advantage of being relatively simple. For that reason, they will continue to be used, despite the increased availability of much more sophisticated computer programs. If steady-state tools are used, the authors suggest the following:

- Only use these methods for analyzing airtight construction and in cases where wetting by rain or heating by direct sunlight does not play a significant role.
- Only use these methods to estimate seasonal mean conditions, rather than daily or even weekly mean conditions.
- Use monthly averages for indoor and outdoor temperatures and humidities.
- Results obtained with any of these methods should be considered as approximations and be used with prudent care.

Software for Heat, Air, and Moisture (HAM) Transport

Introduction

There has been a rapid improvement in the capabilities of computer-based moisture analysis tools that can predict the movement and accumulation of moisture in building components and materials. However, there still is a large gap between needs of architects, designers, and practitioners and the heat, air, moisture computer models currently available at the marketplace.

Straube and Burnett [12] discussed HAM models available in the marketplace and suitable for the enclosure design, stating:

> "Structural, mechanical and electrical engineers use various different mathematical models to analyze the response of the modeled system or subsystem and then improve, adjust, or revise the system as needed until a final design is arrived at. The building industry is moving towards a similar situation with building enclosures. However, we in North America still have some way to go in terms of developing a professional

consensus on which models are to be preferred, what analysis procedures are cost and qualitatively effective, and how to develop the necessary experience to use these models properly. Rapidly changing technologies, e.g., materials and interior building environments, combined with higher expectations of performance for both the enclosure and the building, have created a very real need for the development and use of practical hygrothermal analysis methods."

Discussing the reasons for conducting of a hygrothermal analysis, Straube and Burnett [12] highlight the comparative power of HAM modeling:

"Although a simple analysis technique may provide neither absolutely correct nor accurate results, so long as a satisfactory decision can be made (i.e., a safe design) with this information, the technique fills the need. Consider also the situation where conducting a parametric analysis where the accuracy between results (relative results) may be much more accurate than the absolute value of any particular result."

Improvements Needed to Make Software More Useful to Designers

Zhang [13], who discussed the needs of users, stated that combined heat, air, moisture, and pollutants transport in buildings exists in different scales. These scales involve transports in the surroundings of the building, the building enclosure, different zones in the building and local environments around occupants. A system model is needed for simulating these transport processes and their impacts on indoor environmental quality. Components of this system model should include:

- a multi-zonal network flow model for whole building,
- a room model for air and pollutant movement in ventilated spaces,
- a coupled heat, air moisture, (HAM) and pollutant transport model for the building enclosure,
- an HVAC model for describing the dynamics of the heating, ventilating and air-conditioning (HVAC) system, and
- shared databases of weather conditions, transport properties of building materials, and volatile organic compounds (VOCs) emissions from building materials and furnishings.

Discussing multi-zone models Zhang [13] stated:

"A whole building can be divided into multiple zones, each representing a space or aggregated spaces (office workstation, cubical, room, corridor, stair shaft, elevator shaft, etc.) whose environmental conditions can be represented by averaged values, and controlled through a single controller such as a thermostat or an 'airstat.'[4] Lumped parameters are defined for each zone including the pressure, temperature, relative humidity and pollutant concentrations. The primary purpose of the multizonal model is to capture the interactions among the different zones of a building, and the ambient weather conditions, and provide a system level prediction of the building performance. In addition, it should also be able to use the outputs from the other component models in order to predict the building performance more accurately."

Most of HAM models can assist in understanding of moisture response of the building enclosure, particularly in terms of amount of expected condensation in relation to the selected climatic conditions and identification of potential problems. Yet, the designer must modify the material selection and assembly composition to avoid reduction of performance that could be created by rain penetration, construction moisture or moisture carried by capillary or other forces. Current HAM models are suitable for the comparative assessment only.

To expand the use of HAM modeling from the sensitivity studies to the real time performance analysis the following is required:

- Numerical part of the HAM (Heat, Air and Moisture) transport model must be validated;
- Moisture transport characteristics[5] i.e., the moisture storage and permeability (moisture conductivity) must also be validated for each of the materials involved in the analyzed building assembly.
- Detailed information on boundary conditions must be provided, especially on the relevant air pressure differences.

Hagentoft et al. [14], describe requirements for numerical models and their validation, developed by an international group. Work of this group provided a basis for development of a European standard.

Ensuring that moisture transport properties presented in one or other handbook or database are applicable for the analyzed case is more difficult. This difficulty stems from two reasons:

1. Each HAM model uses an individually tailored set of material characteristics
2. Despite many research papers (as an example see Roels [15], Roels et al. [16,17], Carmeliet et al. [18]) and despite the existence of internationally agreed set of requirements for material characterization [19] adequate characterization of materials is not a part of all the recently published North American hygrothermal datasets.

An international group (see Bomberg et al. [19]) required that, independently of what methods are used for the determination of hygrothermal properties, each material must be adequately characterized, and recommended minimum requirements for material characterization. Grunewald et al. [20] proposed a minimal set of parameters for hygrothermal material characterization as input to simulation programs. Perhaps even more importantly, air flow often dominates the flow of moisture in cavity construction (frame construction), especially when it comes to drying of wet assemblies. Detailed information is therefore needed on the typical air flows within and between parts of the envelope, and the pressures that drive them.

ASHRAE Standard Committee 160P (Design Criteria

[4] In analogy to a "thermostat," "airstat" is introduced here as a device with a sensor and information processing algorithm (e.g., compare measured value with a "setpoint" and send our control signals to actuators such as an air cleaning or ventilating device.

[5] The term "material property" implies a physical quantity generaaly independent of the used test method, while the term "material characteristics" highlights that the quantity may vary with changes in the applied test method (see Bomberg et al. [19]).

for Moisture Control in Buildings) is currently developing a standard for hygric design loads that include hourly climatic data (also see draft of a European Standard prEN13013-3 [21]). Nevertheless, there is an urgent need for developing ASTM standards addressing:

- Requirements for validation of HAM models.
- Standard procedures for validation of hygrothermal material characteristics.
- Standard procedures for validation of hygrothermal characteristics of cladding assemblies (this would define the effect of air and moisture venting of the cladding system).

HAM Software Available in Marketplace

A survey of existing HAM models used in different places (IAE Annex 24, 1988) revealed more than 35 different HAM models, out of which at least ten are available in the United States. Instead of repeating the survey, the authors instead present only a few selected hygrothermal models.

Analytical, Simplified 1-D, Steady State Model of Heat and Moisture Transport (COND)

COND is not a simulation tool but a software program for the hygrothermal evaluation of different building envelope designs. It is not able to calculate the real temperature and moisture fields that will be present in the construction. However, similar to the Glaser methods it can provide expected values, which allow for an approximate evaluation of the building envelope. This helps to evaluate the performance of a building envelope under certain climatic conditions, including the prediction of moisture damage. The method of calculation takes into consideration condensation and redistribution of moisture. Therefore, the evaluation of building envelopes will be closer to reality than with steady-state methods based on the conventional vapor pressure profiles (Glaser, dew point, or Kieper methods).

The model works with one-dimensional and steady-state heat and moisture transport through a vapor permeable construction that consists of many layers. The climate is described by constant temperature and relative humidity on the inside and outside of the construction. The temperature difference results in heat flow through the construction and after certain period steady-state heat flow is established. The profile of the temperature associated with steady-state conditions results in a vapor flow through the construction. Here again, a steady vapor flow is reached after a certain time. The profile of the vapor pressure is also calculated. If the calculated vapor pressure exceeds the saturated vapor pressure (which is directly dependent on the temperature), condensation occurs inside the construction.

As soon as condensation water accumulates in the construction, it causes both liquid and vapor fluxes. This is an essential enhancement in comparison to the Glaser dew point scheme, which disregards capillary liquid water transport. Following the global condition of equilibrium, the inward flux of moisture is equivalent to the outward flux. These conditions of equilibrium are defined with various balance equations. The solution of the generated system of equations is the distribution of moisture in the stationary condition. Through consideration of time-dependent transient phenomena, an estimation of the expected distribution of moisture can be made, for the final effect after a considered elapse of time.

COND was developed by the Technical University of Dresden (http://www.bauklimatik-dresden.de/cond/index_en.html) but in North America can be obtained from the Syracuse University, Syracuse, NY, 13244). The use of the software is, however, limited because of lack of hygrothermal material characteristics.

1-D (pseudo 3-D), Transient Model of Heat, Air and Moisture Transport (WALLDRY)

WALLDRY is a relatively simple heat, air, and moisture transport simulation program that uses basic engineering equations to describe the transport phenomena that occur in a siding-clad, wood-framed wall.

The WALLDRY program was created for Canada Mortgage and Housing Corporation (CMHC) to evaluate the drying of wood frame residential wall assemblies clad with sidings (with or without strapping). Of specific interest were the effects of air leakage through the siding and ventilation of the air space created by the strapping. Several unique aspects of the assembly (the siding, the air space created by the strapping and the framing in the inner portion of the wall) are captured in a psuedo-3-dimensional topology. The topology is called "psuedo-3-dimensional" because the wall assembly is divided into a three-dimensional system of elements, but the physical model and numerical solution are not constructed to model transfers between all adjacent elements. Instead, one-dimensional formulations of the physical equations are applied to the elements in one plane and then another. This has permitted treatment of the wall studs as sources or sinks for moisture while airflow within the wall cavity is not addressed.

The airflow model is used to predict the hourly mean air velocity and mass flow of air at each of the nine elements that make up the air space behind the siding. These velocity and mass flow values are used as inputs for the heat flow and moisture transfer models. The airflow model assumes that flows are driven by air pressure differences related to wind pressures and stack effects. Air is introduced to an element from adjacent elements or air leakage through gaps in the siding. Similarly, air leaves an element to adjacent elements or leakage through siding gaps. The continuity of mass principle applies. The definition of joint properties allows consideration of cladding without intermediate joints. The heat and moisture transfer rates are not independent of each other; however, they are calculated independently and the results are used to repeat the calculations for a total of three passes through the heat and moisture transfer sub routines. Each pass through the subroutines makes a small correction to the calculated temperatures and moisture contents. Whereas the original program assumed constant properties for materials, the updated version incorporates moisture sensitive properties, which are adjusted in the iterative solution.

This software is now being updated in Miscrosoft Visual Basic.NET, which permitted numerous modifications to be made. Material properties will be selected from the international database (see previous section) or other sources. Hourly weather files include both laboratory conditions from experiments, as well as real weather files containing:

- Indoor temperatures and relative humidity as fixed or variable histories,
- Outdoor temperature and RH histories,
- Wind speed and direction,
- Solar radiation (on North, East, South and West wall surfaces).

Wind pressure coefficients are currently built into the program but they may be altered for specific cases. Data from field and laboratory experiments have been used to assess if predictions by the model have been adequate. These include test huts in the Atlantic provinces and Ontario, as well as chamber studies in Ottawa and Vancouver. All such comparisons were made on the original version of the software. Past comparisons were not always successful but this had as much to do with difficulties in experimentation as in specifying the material and physical boundary conditions.

The software will not be supported for commercial applications but may be provided on request for research and educational purposes by application to Silvio Plescia, Housing Standards and Technology Group, Canada Mortgage and Housing Corporation, National Office, 700 Montreal Road, Ottawa, Ontario, K1A 0P7.

1-D and 2-D Transient Models of Heat and Moisture Transport (WUFI/ORNL)

Not much information can be added to the chapter in the ASTM manual [12] that describes physical background, equations, and material properties used in WUFI/ORNL software. The software is user friendly and uses an a few engineering simplifications that upon a careful verification show good overall approximations of the moisture transfer phenomena. Those approximation are perhaps less precise during transient, repeated wetting and drying iterations but precise enough for any comparative assessment of building constructions.

The simplifications used in the WUFI model are:

- Material transport properties for wetting of the wall under influence of rain are different from those under moisture redistribution in the material,
- Transport coefficients for moisture contents above the hygroscopic region are approximated with a linear in the logarithmic scale dependence of moisture content. Yet, as this approximation is used between two "characteristic" moisture contents it is therefore not without physical justification.

WUFI provides a good engineering tool for the comparative assessment of constructions. The main weakness of this software is lack of airflow calculating capabilities and the restriction to heat and moisture. The database for materials typically used in North America is limited but rapidly increasing because simple input requirements are more accessible than those more complex that are needed for research models. For the American version of WUFI, called WUFI/ORNL, the contact is the ORNL (e-mail: Karagiozisan@ornl.gov).

1-D and 2-D Transient Models of Heat, Air, and Moisture Transport (CHAMPS/DELPHIN)

In contrast with the three software programs described above, this software is not a practical engineering tool but a more powerful research tool for real time calculations. The material characteristics are much more complex, they include all information used for WUFI and more. Therefore, the determination of material characteristics requires much more effort. An engineering model of material characteristics (Grunewald et al. [20]) would permit using this software for engineering applications. This work is combined with development of the validation procedures for material characteristics.

DELPHIN has been developed by the Technical University of Dresden (http://www.bauklimatik-dresden.de) but a new version that includes air and VOC flows is currently being developed in collaboration between Syracuse University and Technical University of Dresden. This software is not likely to be supported for commercial use but will be available for the collaborating research groups.

Other HAM Software Used by Research Organizations

All leading research groups in Argentina, Belgium, Canada, Finland, Holland, Israel, Japan, Germany, and the United States have HAM models used in-house. In North America, the Oak Ridge National Laboratory and NRC Canada have 2-D models with airflow capability. These model are expanded from the Latenite (the code developed by NRCC together with VTT, Finland). Typically, these research laboratories measure material properties and use them in the appropriate model simulations. One wonders if this is not one of the reasons for such a slow progress in developing material characteristics and validation tools for HAM modeling in public domain.

References

[1] *Conference on Condensation Control in Dwelling Construction*, Housing and Home Finance Agency, May 17 and 18, 1948.

[2] HUD Minimum Property Standards for One and Two-Family Dwellings, 4900.1, 1980 (latest edition).

[3] American Society of Heating, Refrigerating, and Air-Conditioning Engineers, Standard 160, *Criteria for Moisture Design Analysis in Buildings*, ASHRAE, Atlanta, 2009.

[4] American Society of Heating, Refrigerating and Air-Conditioning Engineers, *2005 ASHRAE Handbook, Fundamentals*, ASHRAE, Atlanta, GA, 2005.

[5] Glaser, H., "Graphisches Verfuhren zur Untersuchung von Dif-fusionsvorgangen," (Graphical Procedure for Investigating Diffusion), *Kaltetechnik*, Vol. 11, 1959, pp. 345–355.

[6] Seiffert, K., *Damp Diffusion and Buildings* (*Wasserdampf Diffusion im Bauwesen*), Elsevier Publishing Company, New York, 1970.

[7] Kieper, G. W., Caemmerer, W., and Wagner, A., "A New Diagram to Evaluate the Performance of Building Constructions with a View to Water Vapor Diffusion," CIB W40 Working Group, Con-seil International du Batiment, 1976 meeting in Washington, DC.

[8] TenWolde, A., "The Kieper and MOISTWALL Moisture Analysis Method for Walls," *Thermal Performance of the Exterior Envelopes of Buildings II*, ASHRAE SP 38, American Society of Heating, Refrigerating and Air-Conditioning Engineers, Atlanta, GA, 1983, pp. 1033–1051.

[9] Latta, J. K., "Vapor Barriers: What Are They? Are They Effective?" *Canadian Building Digest*, Vol. 175, 1976.

[10] TenWolde, A., "Steady-State One-Dimensional Water Vapor

Movement by Diffusion and Convection in a Multi-layered Wall," *ASHRAE Transactions*, American Society of Heating Refrigerating and Air-Conditioning Engineers, Atlanta, GA, Vol. 91, No. 1, 1985, pp. 322–342.

[11] Covington, S. A. and Mclntyre, I. S., "Timber Frame Wall Materials, Measurement of Vapour Resistance," *Batiment International*, July/August 1985, pp. 207–210.

[12] Straube, J. F. and Burnett, E. F. P., "Overview of Hygrothermal Analysis Methods, Chapter 5," *ASTM Manual 40*, ASTM International, West Constochocken, PA, 2001.

[13] Zhang, J. S., *Proceedings of 4th Advanced Fluid Information and Transdisciplinary Fluid Integration (AFI/TFI) Conference*, Sendai, Japan, Nov. 11–12, 2004.

[14] Hagentoft, C. E., Kalagasidis, A. S., Adl-Zarrabi, B., Roels, S., Carmeliet, J., Hens, H., Grunewald, J., Kunk, M., Becker, R., Shamir, D., Adan, O., Brocken, H., Kumaran, K., and Djebbar, R., "Assessment Method for Numerical Prediction Models for Combined Heat, Air and Moisture Transfer in Building Components: Benchmarks for One-dimensional Cases," *Journal of Thermal Envelope and Building Science*, Vol. 27, No. 4, April 2004, pp. 307–327–352.

[15] Roels, S., "Modeling Unsaturated Moisture Transport in Heterogeneous Limestone," Ph.D. Dissertation, Leuven: K. U. Leuven.

[16] Roels, S., Elsen, J., Carmeliet, J., and Hens, H., "Pore Volume Distribution Determination of Limestone Combining Mercury Porosimetry and Micrography," *Materials and Structures (RILEM)*, Vol. 34, 2001, pp. 76–82.

[17] Roels, S., Carmeliet, J., Hens, H., Adan, O., Brocken, H., Cerny, R., Pavlik, Z., Hall, C., Kumaran, K., Pel, L., and Plagge, R., "Interlaboratory Comparison of Hygric Properties of Porous Building Materials," *J. of Thermal Envelope and Building Science*, Vol. 27, No. 4, April 2004, pp. 307–325.

[18] Carmeliet, J., Hens, H., Roels, S., Adan, O., Brocken, H., Cerny, R., Pavlik, Z., Hall, C., Kumaran, K., and Pel, L., "Determination of the Liquid Water Diffusivity from Transient Moisture Transfer Experiments," *Journal of Thermal Envelope and Building Science*, Vol. 27, No. 4, April 2004a, pp. 277–305.

[19] Bomberg, M., Carmeliet, J., Grunewald, J., Holm, A., Karagiozis, A., Kuenzel, H., and Roels, S., "Position Paper on Material Characterization and Model Benchmarking," *Nordic Building Physics Symposium* Vol. 1, 2002, pp. 143–150.

[20] Grunewald, J., Häupl, P., and Bomberg, M., "Towards an Engineering Model of Material Characteristics for Input to Ham Transport Simulations—Part 1: An Approach," *Journal of Thermal Envelope and Building Science*, Vol. 26, No. 4, 2003, pp. 343–366.

[21] PrEN13013–3: Hygrothermal Performance of Buildings—Climatic Data—Part 3: Calculation of a Driving Rain Index for Vertical Surfaces from Hourly Wind and Rain Data (prenormative text).

MNL18-EB/Oct. 2009

11

Measurement Techniques and Instrumentation

Vince Cammalleri[1] and Peter L. Lagus[2]

THIS CHAPTER DESCRIBES MEASUREMENT TECH-niques 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 easily obtained 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* [2] contains in excess of 150 entries under the categories of “moisture analysis” 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. [3,4].

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 plays 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 E337-02 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 [5].

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

[1] *Principal, Simpson Gumpertz & Heger Inc., Waltham, MA.*
[2] *Lagus Applied Technology, Inc., Escandido, CA.*

TABLE 1—ASTM standards relevant to moisture or humidity measurement in building investigations.

ASTM Designation	Title
C70-06	STM for Surface Moisture in Fine Aggregate
C128-07a	STM for Density, Relative Density (Specific Gravity), and Absorption of Fine Aggregate
C324-01 (2007)	STM for Free Moisture in Ceramic Whiteware Clays
C566-97 (2004)	STM for Total Evaporable Moisture Content of Aggregate by Drying
C755-03	SP for Selection of Water-Vapor Retarders for Thermal Insulation
C1104/C1104M-00 (2006)	STM for Determining the Water-Vapor Sorption of Unfaced Mineral Fiber Insulation
C1136-08	SS for Flexible, Low Permeance Vapor Retarders for Thermal Insulation
C1263-95 (2005)	STM for Thermal Integrity of Flexible Water-Vapor Retarders
C1258-08	STM for Elevated Temperature and Humidity Resistance of Vapor Retarders for Insulation
C1601-08	STM for Field Determination of Water Penetration of Masonry Wall Surfaces
D644-99 (2007)	STM for Moisture Content of Paper and Paperboard by Oven Drying
D779-03	STM for Water Resistance of Paper, Paperboard, and Other Sheet Materials by the Dry Indicator Method
D1653-03 (2008)	STM for Water-Vapor Transmission of Organic Coating Films
D1860-95 (2000)	STM for Moisture and Creosote-Type Preservative in Wood
D1864-89 (2002)	STM for Moisture in Mineral Aggregate Used on Built-up Roofs
D2216-05	STM for Laboratory Determination of Water (Moisture) Content of Soil and Rock by Mass
D2247-02	SP for Testing Water Resistance of Coatings in 100 % Relative Humidity
D2987-88 (2006)	STM for Moisture Content of Asbestos Fiber
D3017-04	STM for Water Content of Soil and Rock in Place by Nuclear Methods (Shallow Depth)
D3201-08a	STM for Hygroscopic Properties of Fire-Retardant Wood and Wood-Base Products
D4178-82 (2005)	SP for Calibrating Moisture Analyzers
D4230-02 (2007)	STM for Measuring Humidity with Cooled Surface Condensation (Dew-Point) Hygrometer
D4263-83 (2005)	STM for Indicating Moisture in Concrete by the Plastic Sheet Method
D4442-07	STM for Direct Moisture Content Measurement of Wood and Wood-Base Materials
D4444-08	STM for Laboratory Standardization and Calibration of Hand-Held Moisture Meters
D4585-07	SP for Testing Water Resistance of Coatings Using Controlled Condensation
D4643-08	STM for Determining Water (Moisture) Content of Soil by Microwave Oven Method
D4933-99 (2004)	SG for Moisture Conditioning of Wood and Wood-Base Materials
D4944-04	STM for Field Determination of Water (Moisture) Content of Soil by the Calcium Carbide Gas Pressure Tester
D4959-07	STM for Determination of Water (Moisture) Content of Soil by Direct Heating
D5886-95 (2006)	SG for Selection of Test Methods to Determine Rate of Fluid Permeation Through Geomembranes for Specific Applications
D6031-96 (2004)	STM for Logging In-Situ Moisture Content and Density of Soil and Rock by the Nuclear Method in Horizontal, Slanted, and Vertical Access Tubes
D6565-00	STM for Determination of Water (Moisture) Content of Soil by the Time-Domain Reflectometry (TDR) Method
D6701-01	STM for Determining Water-Vapor Transmission Rates Through Nonwoven and Plastic Barriers
D6780-05	STM for Water Content and Density of Soil in Place by Time-Domain Reflectometry (TDR)
D6782-05	STM for Standardization and Calibration of In-Line Dry Lumber Moisture Meters
E96/E96M-05	STM for Water-Vapor Transmission of Materials
E154-08a	STM for Water-Vapor Retarders Used in Contact with Earth Under Concrete Slabs, on Walls, or as Ground Cover
E241-08	SG for Limiting Water Induced Damage to Buildings
E283-04	STM for Determining Rate of Air Leakage Through Exterior Windows, Curtain Walls, and Doors Under Specified Pressure Differences Across the Specimen
E331-00	STM for Water Penetration of Exterior Windows, Skylights, Doors, and Curtain Walls by Uniform Static Air Pressure Difference
E337-02 (2007)	STM for Measuring Humidity with a Psychrometer (the Measurement of Wet- and Dry-Bulb Temperatures)
E398-03	STM for Water-Vapor Transmission Rate of Sheet Materials Using Dynamic Relative Humidity Measurement
E514-08	STM for Water Penetration and Leakage Through Masonry
E547-00	STM for Water Penetration of Exterior Windows, Skylights, Doors, and Curtain Walls by Cyclic Static Air Pressure Difference
E741-00 (2006)	STM for Determining Air Change in a Single Zone by Means of a Tracer Gas Dilution
E779-03	STM for Determining Air Leakage Rate by Fan Pressurization
E783-02	STM for Field Measurement of Air Leakage Through Installed Exterior Windows and Doors
E1105-00 (2008)	STM for Field Determination of Water Penetration of Installed Exterior Windows, Skylights, Doors, and Curtain Walls by Uniform or Cyclic Static Air Pressure Difference
E1186-03	SPs for Air Leakage Site Detection in Building Envelopes and Air Barrier Systems

TABLE 1— (*Continued.*)

ASTM Designation	Title
E1258-88 (2008)	STM for Airflow Calibration of Fan Pressurization Devices
E1424-91 (2008)	STM for Determining the Rate of Air Leakage Through Exterior Windows, Curtain Walls, and Doors Under Specified Pressure and Temperature Differences Across the Specimen
E1554-07	STMs for Determining External Air Leakage of Air Distribution Systems by Fan Pressurization
E1646-95 (2003)	STM for Water Penetration of Exterior Metal Roof Panel Systems by Uniform Static Air Pressure Difference
E1677-05	SS for an Air Retarder (AR) Material or System for Low-Rise Framed Building Walls
E1680-95 (2003)	STM for Rate of Air Leakage Through Exterior Metal Roof Panel Systems
E1745-97 (2004)	SS for Water-Vapor Retarders Used in Contact with Soil or Granular Fill under Concrete Slabs
E1827-96 (2007)	STMs for Determining Airtightness of Buildings Using an Orifice Blower Door
E1907-06a	SG to Methods of Evaluating Moisture Conditions of Concrete Floors to Receive Resilient Floor Coverings (withdrawn and replaced by ASTM F710-08)
E1993-98 (2008)	SS for Bituminous Water-Vapor Retarders Used in Contact with Soil or Granular Fill Under Concrete Slabs
E2099-00 (2007)	SP for the Specification and Evaluation of Preconstruction Laboratory Mockups of Exterior Wall Systems
E2128-01a	SG for Evaluating Water Leakage of Building Walls
E2140-01	STM for Water Penetration of Metal Roof Panel Systems by Static Water Pressure Head
E2178-03	STM for Air Permeance of Building Materials
E2268-04	STM for Water Penetration of Exterior Windows, Skylights, and Doors by Rapid Pulsed Air Pressure Difference
E2319-04	STM for Determining Air Flow Through the Face and Sides of Exterior Windows, Curtain Walls, and Doors Under Specified Pressure Differences Across the Specimen
E2357-05	STM for Determining Air Leakage of Air Barrier Assemblies
F372-99 (2003)	STM for Water-Vapor Transmission Rate of Flexible Barrier Materials Using an Infrared Detection Technique
F1249-06	STM for Water-Vapor Transmission Rate Through Plastic Film and Sheeting Using a Modulated Infrared Sensor
F1869-04	STM for Measuring Moisture Vapor Emission Rate of Concrete Subfloor Using Anhydrous Calcium Chloride
F2170-02	STM for Determining Relative Humidity in Concrete Floor Slabs Using in-situ Probes

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.

the precise instant when dew formation occurs, then this measurement 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 [6,7].

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 D4230-02.

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. 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 [5].

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 temperature 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

TABLE 2—Relative humidity sensors.

Type	Methods 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

TABLE 2— (*Continued.*)

Type	Methods of Operation	Approximate Range	Approximate Uncertainty	Response Time	Primary Output Parameter
Electrolytic	Electrolysis of moisture absorbed on desiccant	−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°F to 86°F (dew or frost point temperature)	2 F (dew or frost point temperature)	Fast	Temperature

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 [15].

Commonly used organic materials are human hair, ny-

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.

lon, 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 [7].

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 1,000 ppm, but can be used with higher humidity [15].

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 that 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 techniques 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 [16]. 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 [17].

Electrical resistance moisture gages are widely utilized in the wood industry [18]. 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 [19,20] in soils and other materials [21] 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 that 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 [22] improve reliability in materials where salts are a problem. Resistance gages have also been applied to concrete using conductive-rubber electrodes [23] and using a wet-cell four-pin surface technique [24].

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 [25]. 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 D4444-08 provides guidance in the use of resistance-type meters for moisture measurements in wood and wood-based products.

Capacitance Techniques

A variety of instruments has 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 [26], 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 [26].

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 [27].

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 [28–30]. 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 backscattered 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 [31] and in field surveys on roofs [32,33]. 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 D3017-05 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 [34], the transient (or "hot-wire" technique) has been applied to firebrick [35], concrete [36], and insulating materials [37]. 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 [38], 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 and Page [39] 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 [40] and wood products [41].

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 [42,43] 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·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. [44].

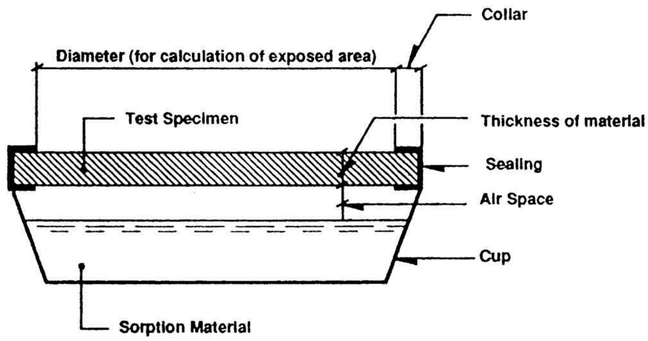


Fig. 1—Test apparatus for wet and dry cup tests.

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 E96/E96M-05. 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 E96/E96M-05 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 [45].

ASTM E96/E96M-05 is actually comprised of two basic methods known as the desiccant method (dry cup method) and the water method (wet cup method). In the desiccant 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 the Appendix 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 desiccant method, particularly for hygroscopic materials. The water method is sensitive to changes in relative humidity and surface resistance on the high relative humidity side [46]. 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 desiccant 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 [47].

In addition to ASTM E96/E96M-05, three additional standards exist for testing water-vapor transmission rates through sheet material. These standards are ASTM F372-99, ASTM F1249-06, and ASTM E398-03. In ASTM F372-99 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 F1249-06 is similar to ASTM F372-99 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 E398-03 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 [48]. 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) [49,50], 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.

ASTM E331-00 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.

ASTM E547-00 is analogous to E331 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, E547 is less reproducible than E331.

ASTM E1105-00 is a method of performing an E331 or E547 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.

ASTM E514-08 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 501.1-05 [51] 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 E1105. 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 ASTM E1105, except that the water spray is not closely controlled and the test, therefore, has poor reproducibility.

AAMA 501.2-03 [50] 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.

All of the above test methods provide procedures for conducting the tests. However, they do not provide end-point criteria. Performance criteria for windows, skylights and glass doors are given in 101/I.S. 2/NAFS-02, co-published by AAMA and WDMA [53], which provides for five performance classes depending on the design wind load as determined in ASCE 7-98 [54].

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 [55], 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 E741-00. 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 ex-

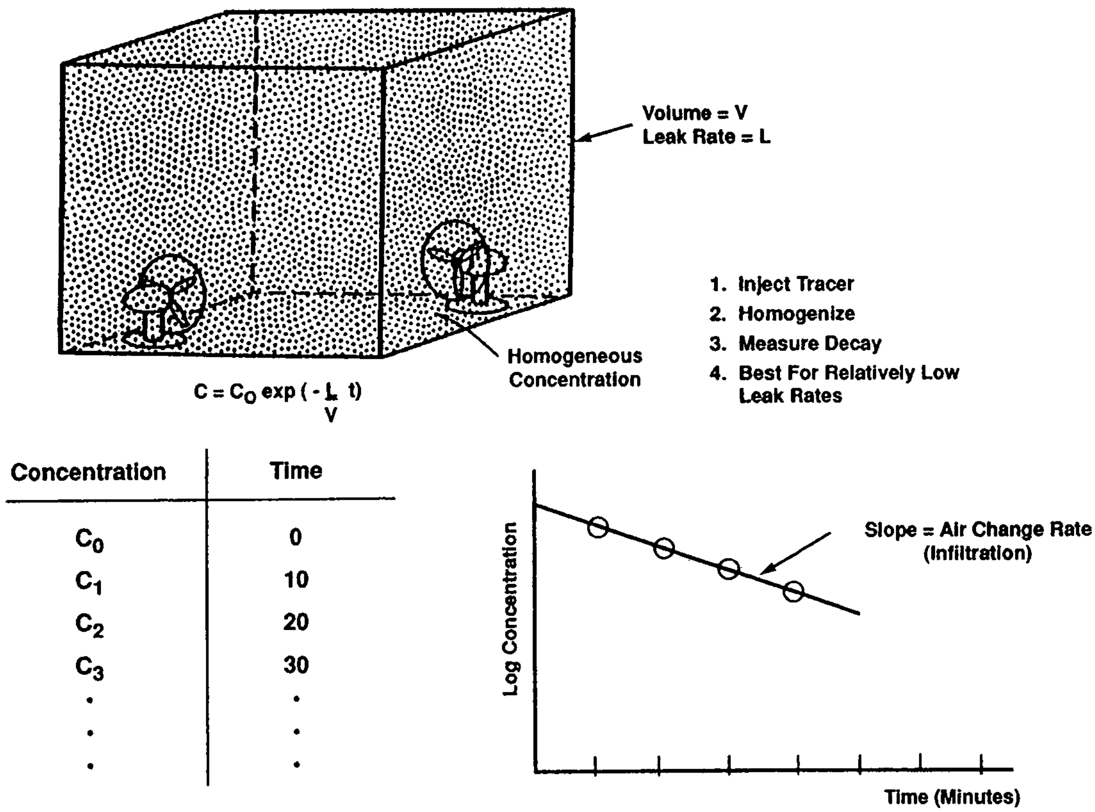


Fig. 2—Essential elements of tracer dilution test.

isting 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) [56]. ASTM E779-03 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

$$\frac{dC(t)}{dt} = F(i) - q(t)C(t) \qquad (4)$$

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,
$F(i)$ 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 [57]. This technique is also the subject of a standardized measurement procedure, ASTM E741-00. 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

$$C = C_0 \exp(-It) \qquad (5)$$

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:

$$I = 1/t \ln(C_0/C) \qquad (6)$$

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 [58,59].

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

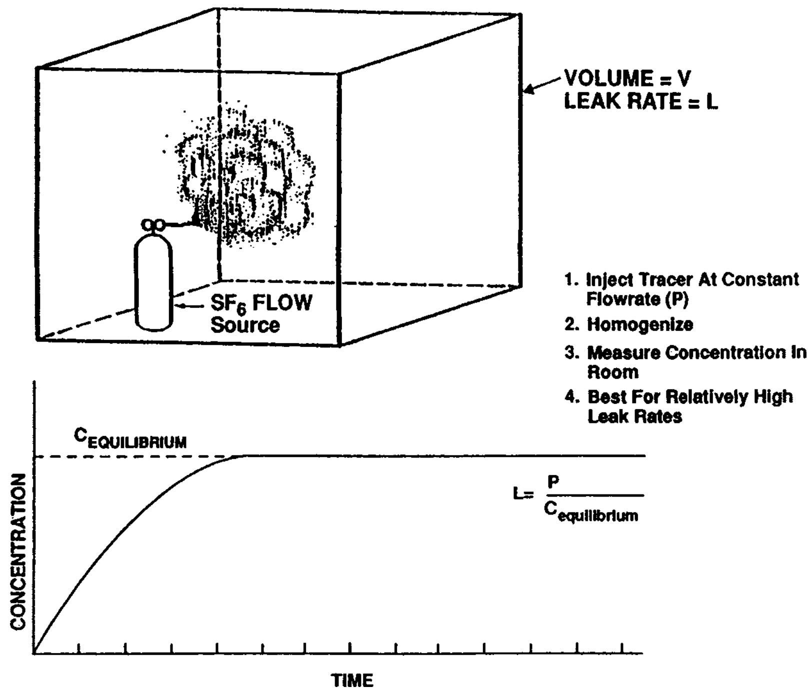


Fig. 3—Essential elements of constant flow injection test.

$$C(t) = F/q \tag{7}$$

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 [60]. 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 [61]. 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

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

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 [62] primarily due to cost considerations. However, measurements have been performed in large buildings using infrared absorption [63,64] and flame ionization detector gas chromatography [65].

Measurement Fundamentals

Referring to Table 4, the thermal conductivity detector was among the first detector types used to perform airflow rate measurements in buildings [66]. 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).

The electron capture detector in conjunction with a chromatographic column exhibits extraordinary sensitivity to halogenated compounds [67]. 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 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, multichamber 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 [68]; however, separate continuous infrared analyzers have also been successfully used for simultaneous analysis of SF_6, CO_2, and N_2O [69].

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 [65,70,71]. 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 [72]. 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 [73]. 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.

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.

TABLE 5—Cost and experience level for various measurement techniques.

Technique	Cost, Dollars	Experience Level
IR absorption, continuous	6 K	Low
Thermal conductivity GC		
Electron capture GC	4 K to 10 K	Moderate
IR absorption GC		
Flame ionization detector GC		
Constant concentration (Princeton)	20 K	High
Multitracer	40 K	High
Residual gas analyzer (LBL)		
Multitracer, multichannel	25 K	High
Electron capture chromatograph		
PFT tracer	200 to 600 samplers	Low
	25 K to 50 K analyzers	High[a]

[a]Analysis done off site in analytical laboratory.

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 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.

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 [74].

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 [75].

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 E783-02 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 E783 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.

The air leakage through the entire surface of exterior or interior walls can be evaluated by a multifan technique. This technique is particularly appropriate for large, multicelled buildings such as multiapartment dwellings [76]. 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

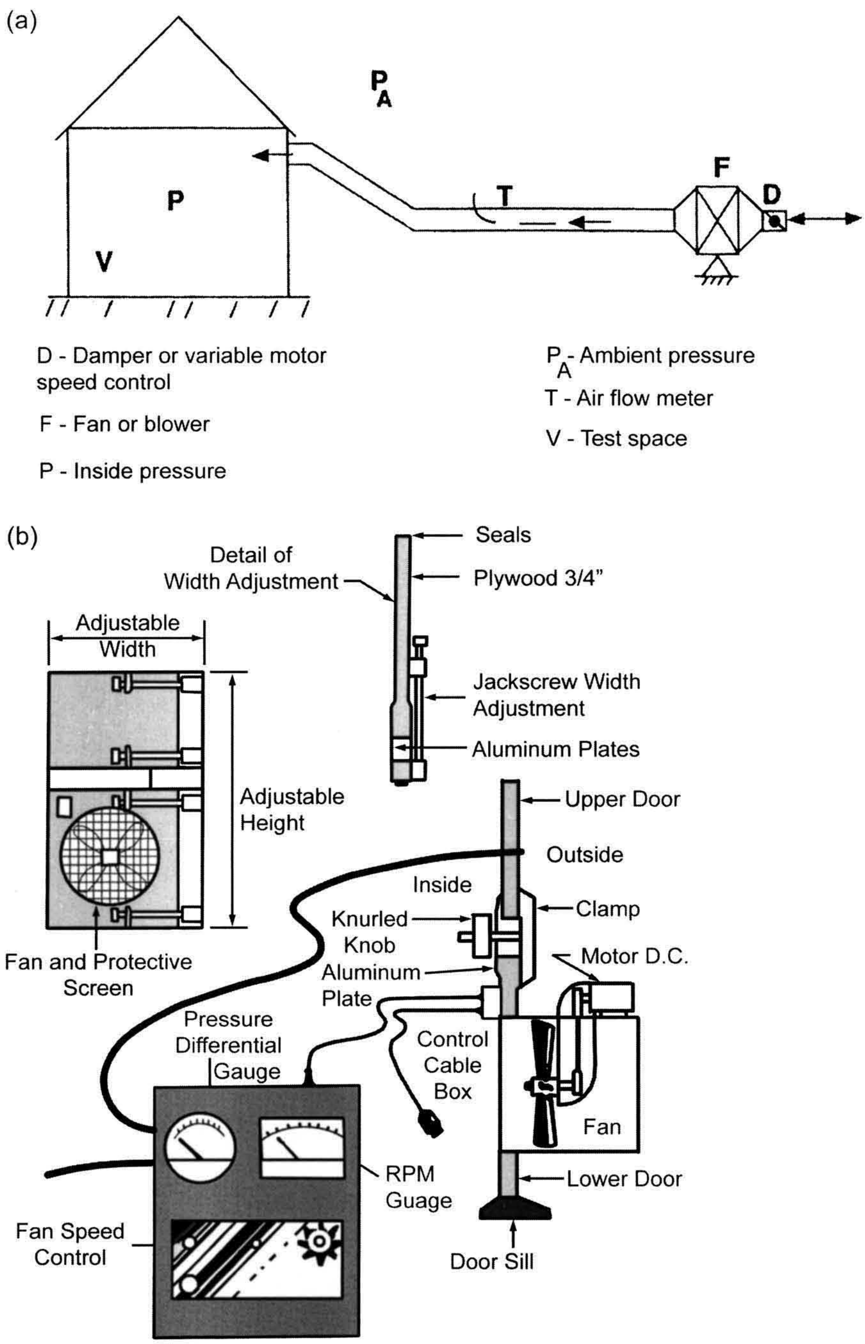


Fig. 4—(a)Generic pressurization test; (b) fan door pressurization device.

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 E1186-03.

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.

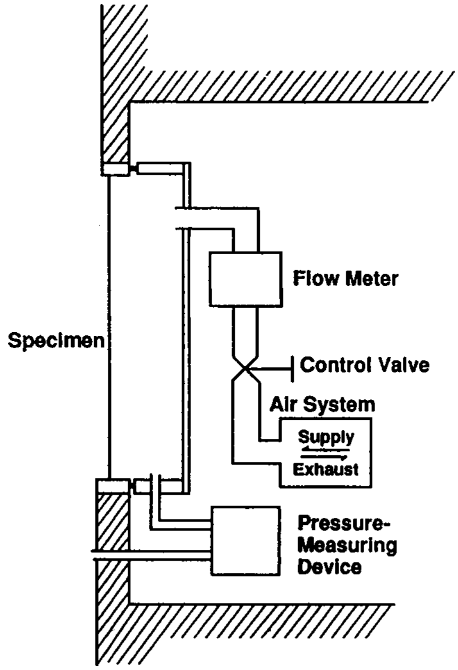


Fig. 5—Apparatus and setup for component leakage test.

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 [77]. 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 as 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 [78]. In addition to providing information about water-vapor transport direction, the comparison of the 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 as long as absorption/condensation phenomena are not considered likely or significant [79]. 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

$$\frac{D_{SF_6}}{D_{H_2O}} = \sqrt{\frac{M_{H_2O}}{M_{SF_6}}} \quad (11)$$

since

$$\frac{\tau_{SF_6}}{\tau_{H_2O}} = \frac{D_{H_2O}}{D_{SF_6}} \quad (12)$$

$$\tau_{H_2O} = 0.35\,\tau_{SF_6} \quad (13)$$

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

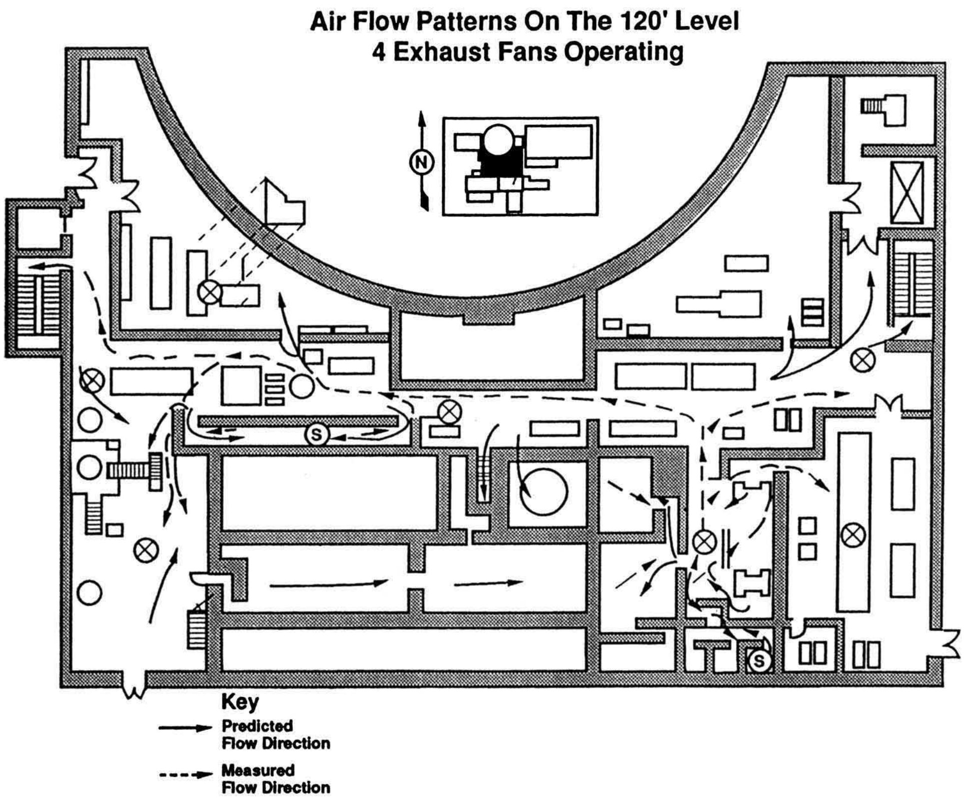


Fig. 6—Flow pattern test.

those that are commercially available for calibration of leak detection or chromatographic systems.

Laboratory versus Field Testing

Most testing standards for building envelope components are developed with the intent of assessing performance of new, often mass-produced products. Performance standards are generally designed to test the product by subjecting it to an arbitrary severe exposure condition as a means of establishing a margin of safety against less severe, but prolonged, actual exposure conditions. In many cases, discrete performance thresholds are used for product certification or classification.

This practice is prudent, but rarely representative of the actual conditions to which the product will be exposed during its service life. The criteria used in assessing product quality merely represent the product's ability to achieve that performance under optimal laboratory conditions of near-perfect workmanship and controlled conditions. The use of laboratory tests developed for evaluating new products under controlled conditions may be inappropriate for use in the field, depending on purpose and context of the field test, and may produce misleading results.

Field testing standards are generally modified versions of their laboratory testing counterparts, adjusted to address some practical limitations of in-situ testing and the variability of ambient conditions. The validity and significance of field tests are subject to professional judgment. Professional judgment is required to establish appropriate expectations for in-situ performance as compared to laboratory values, develop suitable testing parameters and procedures, and to interpret the results.

In-Situ Performance

The in-situ performance of a product can differ from its laboratory performance for reasons unrelated to material quality or workmanship. A product installed as a component of a building enclosure assembly will be affected by the manner in which it is integrated with adjacent construction. The thermal performance and condensation resistance of a window or curtain wall system, for example, can be significantly reduced when it is installed such that the thermal barrier plane of the fenestration product (i.e., the center line of the insulating glass unit) does not align with that of the wall system (insulation). Extruded aluminum starter sills may extend across the thermal break material of the window frame. These short-circuiting effects can reduce the thermal resistance of even the highest performance window systems to marginal, sometimes unacceptable, levels.

Similarly, the perimeter seals used in laboratory testing for air leakage and water penetration resistance of windows and curtain walls is seldom replicated in the field. Air and water seals are typically located at the outboard surface of the specimen frame in a laboratory setup. When a curtain wall is installed in the building enclosure, the wall's air barrier membrane (and back-up waterproofing) will likely extend into the specimen's glazing pocket. Alternatively, a three-sided sill flashing element may be installed that extends through to the interior surface of a window frame. Either way, the air flow patterns around and within the specimen would be altered from what the laboratory conditions evaluated. Field testing the performance of such a specimen could yield different, often lesser, results than those of the laboratory test even if the field specimen was fabricated identical to the laboratory specimen.

In addition to the contextual effects of adjacent construction, a product's performance can be diminished independently after the specimen leaves the factory due to the effects of transportation, storage, handling, and weathering. Degradation of weatherstipping and gaskets, and loss of adhesion of sealant at window corners are inevitable and will, with age, diminish a product's performance.

Field Testing Parameters and Acceptance Criteria

Laboratory testing parameters and acceptance criteria may be unsuitable for field testing. Laboratory testing procedures can be used in the field, but careful modification may be needed to address peculiarities and differences for various components within the enclosure assembly as a whole. The key to establishing appropriate testing parameters, procedures, and acceptance criteria is recognizing the essential purpose of the test.

If the field test is performed for diagnostic or forensic purposes, testing parameters should be developed to replicate conditions the specimen has already experienced. Subjecting the specimen to design conditions or laboratory certification standards would be of limited benefit in helping replicate and isolate the problem or product weakness. In a field investigation intended to determine the cause of water leakage and to develop a remedial plan, for example, water testing parameters such as air pressure differential and test duration should be carefully selected to replicate the reported leakage and not to create leakage that has not occurred in service. Ideally, the building's leakage history, including date and location of observed leakage, should be procured and the prevailing weather conditions during the occurrence approximated with the test as the pertinent exposure. In the absence of detailed documentation of water leakage, weather records can be used to determine an appropriate air pressure differential used to replicate wind-driven rain based on recent rain events [80].

When the purpose of the field testing is to evaluate the adequacy of an installation during its projected service, testing parameters should be based on design conditions for the particular site. Laboratory test pressures and durations used for product certification standards generally represent "proof test" parameters used for prototype development, quality control during manufacturing, and field verification during the construction process. They do not generally reflect the exposure conditions to which the specimen will be subjected with regularity. A product's failure to meet the testing parameters designed for product certification does not necessarily mean the product will fail in service life; a window system can provide years of leak-free performance even if it fails to meet the more rigorous laboratory test acceptance criteria.

Conversely, a product passing even a rigorous laboratory test does not guarantee the product's adequate performance as installed in a building for its entire service life. The quality of a window system assembled and installed under optimal laboratory conditions with kid-glove handling, near-perfect workmanship and controlled ambient conditions simply cannot be replicated in the field. As such, it is reasonable to expect a reduction in performance of a field-installed window as compared to that of the same window product tested in a laboratory. A product that fails a laboratory test is highly unlikely to pass the same test in the field.

The testing parameters used on field tests performed for quality assurance on newly installed products generally resemble those used for laboratory certification testing. The intent of such tests is to help assure that the new product meets the certification criteria. Recent revisions in acceptance criteria for field-tested window and curtain walls have accounted for expected diminished performance associated with effects of transportation, storage, handling, and weathering, allowing for a reduction in performance criteria for water penetration resistance and air leakage. While such allowances may, in concept, be appropriate for reasons mentioned above, the reduction factor remains arbitrary and does not reflect the product's actual performance potential for any given site or building.

This latter issue is often a point of contention with designers and property owners. When new windows or curtain walls fail to meet laboratory-based certification standards in the field, the immediate reaction tends to characterize the window product as deficient and prone to leakage, although the product would not likely be subjected to certification conditions and, as mentioned earlier, can provide years of leak-free service. A valid argument can be made that a fenestration product should achieve the level of performance that was promised and paid for, but the cost of full scale removal and replacement when water leakage is not anticipated in service may fall within the realm of economic waste. Such disputes are sometimes resolved by negotiating an extended warranty with the manufacturer, or providing a monetary reimbursement to the Owner. Such disputes can be avoided, in part, through prudent design practice that quantifies acceptable laboratory and field performance criteria, and provides for early and frequent sampling and testing of installed fenestration products. Designers, for example, should establish minimum field performance criteria, and then increase these criteria for laboratory testing to help assure that the diminished anticipated field performance does not result in a product or system unfit to fulfill its performance expectations over the long term. Acceptable performance reductions for field testing should be based on the type of building, nature of the occupancy, exposure, and topography, and, ultimately, on the Owner's requirements. In the absence of field testing standards that offer rational performance criteria, it is incumbent on the designer to exercise professional judgment and clarity in the specification of laboratory vs. field testing parameters, procedures, and acceptance criteria.

REFERENCES

[1] *The Temperature Measurement Handbook*, Omega Engineering, Inc., Stamford, CT, 2004.

[2] ASTM, *Annual Book of ASTM Standards – Subject Index, Alphanumeric Index:* Vol. 00.01, ASTM International, West Conshohocken, PA, November 2008.

[3] Whiting, D., "Assessment of Potential Techniques for In-Situ Real Time Moisture Measurements in Building Envelope Systems," Report ORNL 83–40122/1, U.S. Department of Energy, Washington, DC, 1984.

[4] TenWolde, A. and Courville, G. E., "Instrumentation for Measuring Moisture in Building Envelopes," *Proceedings, ASHRAE Symposium HI85-22*, ASHRAE, Atlanta, 1985.

[5] *Handbook of Fundamentals*, ASHRAE, Atlanta, GA, 2005, Chap. 14.

[6] Harding, J. C., "Chilled Mirror Dew Point Sensors," *Measurement and Control*, February 1984, pp. 167–175.

[7] Beal, D. B., "Evaluating Humidity Sensors," *Sensors*, Vol. 8, 1991, pp. 76–85.

[8] *Handbook of Fundamentals*, ASHRAE, Atlanta, GA, 1989, Chap. 13.

[9] Buck, A. L., "Variable Path Lyman Alpha Hygrometer," *Bull. Am. Metallurgical Soc.*, Vol. 57, 1976, pp. 1113–1118.

[10] Dunmore, F. W., "An Electric Hygrometer and Its Application to Radio Meteorography," *J. Res. Natl. Bur. Stand.*, Vol. 20, 1939, pp. 701–714.

[11] Whiting, D., "Assessment of Potential Techniques for In-Situ Real Time Moisture Measurements in Building Envelope Systems," Report ORNL 83–40122/1, U.S. Department of Energy, Washington, DC, 1984.

[12] Musa, R. C. and Schnable, G. L., "Polyelectrolyte Electrical Resistance Elements," *Humidity and Moisture*, A. Wexler, Ed., Reinhold Publishing, New York, 1965, Vol. 1.

[13] Stine, S. L., "Carbon Humidity Elements—Manufacture, Performance, Theory," *Humidity Moisture*, Wexler, A., Ed., Reinhold Publishing, New York, 1965, Vol. 1.

[14] "The Brady Array," *Measurement Data*, January 1979, p. 67.

[15] Knight, W. H., "The Piezometric Sorption Hygrometer," *Humidity Moisture*, Wexler, A., Ed., Reinhold Publishing, New York, 1965, Vol. 1.

[16] Pande, A. and Pande, C. S., "Physical Methods of Measuring Moisture—Part I," *Instrum. Practice*, Vol. 16, No. 7, 1962, pp. 896–903.

[17] Bouyoucos, C. J., and Crabb, G. A., Jr., "Measuring Soil Moisture Tension by Electrical Resistance Method," *Agric. Eng.* Vol. 30, No. 12, 1949, pp. 581–583.

[18] "Electrical Moisture Meters for Wood," General Technical Report FPL-6, USDA Forest Service, Washington, DC, 1975.

[19] Bouyoucas, C. J., "More Durable Plaster of Paris Moisture Blocks," *Soil Sci.*, Vol. 76, 1953.

[20] Yoshikatu, F. and Tsutome, N., "Glass Filter Electrical Moisture Block and Self-Recording Moisture Meter for Measuring Soil Moisture," NASA Report TT-F-14292, NASA, Washington, DC, 1972.

[21] British Research Station (BRS), Watford Herts, "The Use of Electrical Resistance Gages for Measuring the Moisture Content of Porous Materials" (Rilem seminar by correspondence 1960), *RILEM Bull.*, Vol. 15, Paris, June 1962, pp. 73–87.

[22] Klein, A. and Trescony, L. J., "Ionic Barrier Moisture Meter for Measurement of Moisture Content and Moisture Distribution in Concrete," Moisture Problems in Buildings, RILEM/CI Symposium, Helsinki, August 1965.

[23] Kondo, J. and Norose, S., "Apparatus for the Measurement of Moisture Content in Mortar of Plaster by Electrical Method," *RILEM Bull.*, Vol. 15, 1962.

[24] Stratfull, R. F., "How Chlorides Affect Concrete Used with Reinforcing Steel," *Mater. Protection*, Vol. 7, No. 3, 1968, pp. 29–34.

[25] Hancox, N. L. and Walker, J., "Influence of Liquid Resistivity on Plaster of Paris Resistance and Capacitance Moisture Gages," *Br. J. Appl. Phys.*, Vol. 17, No. 6, 1966. pp. 827–833.

[26] Pande, A. and Pande, C. S., "Physical Methods of Measuring Moisture—Part II," *Instrum. Practice*, Vol. 16, 1962.

[27] May, J. C. and Vassiliades, J. M., "Tracing Roof and Wall Leaks Using Alternating Electric Fields and Vapor Detection," *Water in Exterior Building Walls: Problems and Solutions, ASTM STP 1107*, Schwartz, T. A., Ed., ASTM International, West Conshohocken, PA, 1991.

[28] McKim, H. L., Walsh, J. E., and Arion, P. N., "Review of Techniques for Measuring Soil Moisture in Situ," U.S. Army Cold Regions Research and Engineering Lab, Hanover, NH, Special Report 80-31, 1980.

[29] Selig, E. T. and Wobschall, D. C., "Capacitance Sensor for Soil Moisture Measurement," *Transp. Res. Rec.*, Vol. 532, 1975, pp. 64–76.

[30] Smith, P. C., Johnson, A. I., Fisher, C. P., and Womack, L. M., in *The Use of Nuclear Meters in Soil Investigations: A Summary of Worldwide Practice, ASTM STP 412*, ASTM International, West Conshohocken, PA, 1967.

[31] *3400 B Series Surface Moisture-Density Gages Instruction Manual*, Troxler Electronic Laboratories, Inc., Research Triangle Park, NC, 1980.

[32] Jenkins, D. R., Mathey, R. G., and Knab, L. I., "Moisture Detection in Roofing by Non-destructive Means—A State of the Art Survey," NBS Tech Note 1146, National Bureau of Standards, Washington, DC, 1981.

[33] Hedlin, C. P., "The Use of Nuclear Moisture Density Meters to Measure Moisture in Flat Roofing Insulations," Proceedings, Second International CIB/RILEM Symposium on Moisture Problems in Buildings, Rotterdam, September 1974.

[34] Van Der Held, E. F. M. and Van Drunen, F. G., "A Method of Measuring the Thermal Conductivity of Liquids," *Physica* (*Amsterdam*). Vol. 15, 1949, pp. 865–881.

[35] Haupin, W. E., 1960, "Hot Wire Method for Rapid Determination of Thermal Conductivity," *Am. Ceram. Soc. Bull.*, Vol. 39, 1960, pp. 139–141.

[36] Lentz, A. E. and Monfore, G. E., "Thermal Conductivity of Concrete at Very Low Temperatures," *J. Portland Cement Assoc.*, Vol. 7, 1965.

[37] Lentz, C. P., "A Transient Heat Flow Method of Determining Thermal Conductivity: Application of Insulating Materials," *Can. J. Tech.*, Vol. 30, 1952.

[38] Vos, B. H., "Measuring Moisture Content and Distribution in Construction," *Build Int'l.*, 1972, pp. 51–54.

[39] Bloodworth, M. E. and Page, J. B., "Use of Thermisters for the Measurement of Soil Moisture and Temperature," *Proceedings, Soil Science Society of America*, Vol. 21, 1957, pp. 11–15.

[40] Mack, A. R. and Brach, E. J., "Soil Moisture Measurement with Ultrasonic Energy," *Proceedings, Soil Science Society of America*, Vol. 30, 1966, pp. 544–548.

[41] James, W. L., Boone, R. S., and Galligan, W. L., "Using Speed of Sound to Monitor Drying in a Kiln," *For. Prod. J.* Vol. 32, 1982.

[42] Lief, M. and Trechsel, H., *Moisture Migration in Buildings, ASTM STP 779*, ASTM International, West Conshohocken, PA, 1982.

[43] Trechsel, H. and Bomberg, M., *Water Vapor Transmission Through Building Materials and Systems, ASTM STP 1039*, ASTM International, West Conshohocken, PA, 1989.

[44] *Handbook of Fundamentals*, ASHRAE Atlanta, 2005, Chap. 25.

[45] Bomberg, M., "Testing Water Vapor Transmission: Unresolved Issues," *Water Vapor Transmission Through Building Materials and Systems, ASTM STP 1039*, Trechsel, H. and Bomberg, M., Eds., ASTM International, West Conshohocken, PA, 1989.

[46] Joy, F. A. and Wilson, A. G., "Standardization of the Disk Method for Measuring WVT," *Humidity and Moisture*, Wexler, A., Ed., Reinhold Publishing, New York, 1965, Vol. 4.

[47] Bomberg, M., "Testing Water Vapor Transmission: Unresolved Issues," *Water Vapor Transmission Through Building Materials and Systems, ASTM STP 1039*, Trechsel, H. and Bomberg, M., Eds., ASTM International, West Conshohocken, PA, 1989.

[48] Dunn, L. M., “Need for Research and Development of Test Methods for Windows,” *Testing Window Assemblies, ASTM STP 251*, ASTM International, West Conshohocken, PA, 1959.

[49] “Water Permeability of Masonry Walls,” NBS Report BMS7, National Bureau of Standards, Washington, DC, 1933.

[50] “Water Permeability of Walls Built of Masonry Units,” NBS Report BMS82, National Bureau of Standards, Washington, DC, 1942.

[51] “Standard Test Method for Water Penetration of Windows, Curtain Walls and Doors Using Dynamic Pressure,” *AAMA Standard 501.1-05*, Architectural Aluminum Manufacturers Association, Schaumburg, IL.

[52] “Quality Assurance and Diagnostic Water Leakage Field Check of Installed Storefronts, Curtain Walls, and Sloped Glazing Systems,” *AAMA Standard 501.2-03*, Architectural Aluminum Manufacturers Association, Schaumburg, IL.

[53] “Voluntary Performance Specifications for Windows, Skylights and Glass Doors—A North American Fenestration Standard,” *AAMA/WDMA Standard 101/I.S. 2/NAFS-02*.

[54] “Minimum Design Loads for Buildings and Other Structures,” *ASCE 7-98*, American Society of Civil Engineers, New York, 1998.

[55] Hutcheon, N. B., “Forty Years of Vapor Barriers,” *Water Vapor Transmission Through Building Materials and Systems: Mechanisms and Measurement, ASTM STP 1039*, Trechsel, H. R. and Bomberg, M., Eds., ASTM International, West Conshohocken, PA, 1989.

[56] Persily, A. K. and Grot, R. A., “Pressurization Testing of Federal Buildings,” *Measured Air Leakage of Buildings, ASTM STP 904*, Trechsel, H. R. and Lagus, P. L., Eds., ASTM International, West Conshohocken, PA, 1986.

[57] Lagus, P. L., “Air Leakage Measurements by the Tracer Gas Dilution Method—A Review,” *Building Air Change Rate and Infiltration Measurement, ASTM STP 719*, Hunt, C. M., King, J. C., and Trechsel, H. R., Eds., ASTM International, West Conshohocken, PA, 1980.

[58] Grot, R. A., “A Low Cost Method for Measuring Air Infiltration Rates in a Large Sample of Dwellings,” *Building Air Change Rate and Infiltration Measurement, ASTM STP 719*, Hunt, C. M., King, J. C., and Trechsel, H. R., Eds., ASTM International, West Conshohocken, PA, 1980.

[59] Harrje, D. T., Gadsby, K., and Linteris, G., “Sampling for Air Exchange: Rates in a Variety of Buildings,” *ASHRAE Trans.*, Vol. 88, Part 1, 1982.

[60] Harrje, D. T., Bohac, D. L., and Nagda, N. L., “Air Exchange Rates Based Upon Individual Room and Single Cell Measurements,” Proceedings, Sixth Air Infiltration Centre Conference, Netherlands, 1985.

[61] Collet, P. F., “Continuous Measurement of Air Infiltration in Occupied Dwellings,” Building Design for Minimum Air Infiltration, Proceedings of the Second Air Infiltration Centre Conference, Stockholm, 1981.

[62] Lagus, P. L. and Persily, A., “A Review of Tracer Gas Techniques for Measuring Airflows in Buildings,” *ASHRAE Trans.*, Vol. 91, Part 2, 1985.

[63] Potter, N., Dewsbury, J., and Jones, T., “The Measurement of Air Infiltration Rates in Large Enclosures and Buildings,” Air Infiltration Reduction in Existing Buildings, Proceedings of the Fourth Air Infiltration Centre Conference, Elm, Switzerland, 1983.

[64] Zuercher, C. H. and Feustal, H., “Air Infiltration in High Rise Buildings,” Air Infiltration Reduction in Existing Buildings, Proceedings of the Fourth Air Infiltration Centre Conference, Elm, Switzerland, 1983.

[65] Prior, J., Littler, J., and Adlard, M., “Development of Multi-Tracer Gas Techniques for Observing Air Movement in Buildings,” *Air Infiltration Rev.*, Vol. 4, No. 3, 1983.

[66] Bahnfleth, D. R., Mosely, T. T., and Harris, W. S., “Measurement of Infiltration in Two Residences,” *ASHRAE Trans.*, Vol. 63, Part 1, 1957.

[67] David, R. J., *Gas Chromatographic Detectors*, John Wiley, New York, 1974.

[68] Lagus, P. L., “Characterization of Building Infiltration by Tracer Dilution Methods,” *Energy*, Vol. 2, 1977.

[69] Perera, E. D., Walker, R. R., and Oglesby, V. D., “Ventilation Rates and Intercell Airflow Rates in a Naturally Ventilated Office Building,” Air Infiltration Reduction in Existing Buildings, proceedings of the Fourth Air Infiltration Centre Conference, Elm, Switzerland, 1983.

[70] Irwin, C., Edwards, R. E., and Howarth, A. T., “An Improved Multiple Tracer Gas Technique for the Calculation of Air Movement in Buildings,” *Air Infiltration Rev.*, Vol. 5, No. 2, 1984.

[71] I’Anson, E. I., Irwin, C., and Howarth, A. T., “Air Flow Measurement Using Three Tracer Gases,” *Build. Environ.*, Vol. 17, 1983.

[72] Harrje, D. T., Dietz, R. N., Sherman, M., Bohac, D. L., D’Ottavio, T. W., and Dickerhoff, D. J., “Tracer Gas Measurement Systems Compared in a Multifamily Building,” *Air Change Rate and Airtightness in Buildings, ASTM STP 1067*, Sherman, M., Ed., ASTM International, West Conshohocken, PA, 1990.

[73] Dietz, R. N., Goodrich, R. W., Cote, E. A., and Wieser, R. F., “Detailed Description and Performance of a Passive Perfluorocarbon Tracer System for Building Ventilation and Air Exchange Measurements,” *Measured Air Leakage Performance of Buildings, ASTM STP 904*, Trechsel, H. R. and Lagus, P. L., Eds., ASTM International, West Conshohocken, PA, 1986.

[74] Sherman, M. H., “Air Infiltration in Buildings,” REPT 10712, Lawrence Berkeley Laboratory, Berkeley, CA, 1982.

[75] Grot, R. A. and Persily, A. K., “Air Infiltration and Air Tightness Tests in Eight U. S. Office Buildings,” Proceedings, 3rd Air Infiltration Centre Conference, London, 1982.

[76] Modera, M. P., Brunsell, J. T., and Diamond, R. C., “Improving Diagnostics and Energy Analysis for Multifamily Buildings: A Case Study,” Proceedings, ASHRAE/DOE/BTECC Conference on Thermal Performance of the Exterior Envelopes of Buildings, Clearwater, FL, 1985.

[77] Lagus, P. L., Kluge, V., Woods, P., and Pearson, J., “Tracer Gas Testing within the Palo Verde Nuclear Generating Station,” Proceedings, 20th DOE/NRC Air Cleaning Conference, Boston, 1988.

[78] Trethowen, H. A., “Air, Earth, Water, The Sources of Moisture,” AIVC Technical Note 20, AIVC Coventry, England, 1987.

[79] Kolokotroni, M., Saiz, N., and Littler, J., “Airborne Moisture Movement in Occupied Dwellings. A Case Study Approach,” *Air Infiltration Rev.*, Vol. 14, No. 1, 1992.

[80] Cole, G. G. and Schwartz, T. A., “Establishing Appropriate Field Test Pressures for Investigation of Leakage through the Building Envelope,” *Water in Exterior Building Walls: Problems and Solutions, ASTM STP 1107*, Schwartz, T. A. Ed., ASTM International, West Conshohocken, PA, 1991.

12

Investigating Moisture Damage Caused by Building Envelope Problems

Heinz R. Trechsel[1] and Niklas W. Vigener[2]

Introduction

THE MAJORITY OF BUILDING PERFORMANCE problems are caused by water leakage through the building envelope and condensation of moisture in exterior wall and roof assemblies. Identifying the sources of water leakage is a critical first step to developing a regimen of effective building repairs. This chapter reviews common building envelope leakage problems and discusses investigative techniques to identify the sources of leakage.

To the layperson, 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 investigating moisture damage caused by building envelope problems 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, or the diagnosis of 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 11 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 practical to provide a detailed, specific standard method or guide on how to identify causes and determine effective remedial actions for every case. It is, however, possible to give broad suggested concepts and approaches for such identifications and determinations. ASTM developed several standards on investigating the condition and performance of exterior building walls; see the references at the end of the chapter. ASTM E2128 in particular offers expert guidance on the investigation of water leakage through exterior building walls [1].

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. For purposes of the investigation, it is helpful to differentiate between exterior and interior sources of moisture:

Exterior sources include rainwater (most common and pervasive cause of envelope leakage), melting snow, surface run-off, groundwater (in below-grade structures), and water vapor from moist humid air.

Interior sources include occupant generated moisture (e.g., steam generated by cooking, bathing, etc.), and high humidity levels generated by special building uses (e.g., pools, archival storage conditions in museums, etc.), as well as plumbing leaks. A special type of interior sourses are construction moisture, specifically from sitecast concrete built into the structure at the outset.

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

[1] *Retired, Arlington, VA.*
[2] *Senior Principal, Simpson Gumpertz & Heger Inc., Rockville, MD.*

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, warm, humid air infiltrating into an air-conditioned building increases indoor humidity. 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 inter-related. 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 unprotected, they can become saturated with moisture. 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 or during a water test. 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. Where access is difficult, and leakage volumes are small and therefore difficult to observe, a 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.

General Investigative Approach

Generally, all building investigations should follow the same general approach:

1. Observe the problem in the field.
2. Perform background review and research on the building.
3. Develop an initial hypothesis based on the initial observations, research, and the investigator's personal experience.
4. Develop a test protocol that mimicks the actual conditions the building is subjected to in service.
5. Obtain safe exterior and interior access. Perform testing to replicate the problem. Make sample openings in the building envelope to verify building construction.
6. Develop and implement sample repairs. Test sample repairs.

The following sections outline investigation techniques for several common moisture problems. See the outline protocol near the end of this chapter for additional guidance.

Rain Leaks

Determining leak locations by water testing is the most critical part of the investigation because it lays the groundwork for the investigator's repair recommendations. Note that sometimes water tests are also useful to confirm that exterior leaks are NOT the problem (e.g., to help confirm condensation problems in roof assemblies, water testing is helpful to exclude exterior leak as cause of the damage).

Before performing any testing, first conduct an interior survey to identify existing leak locations. Map out damage locations on building drawings and correlate with exterior features of the building. Note typical problem spots that should be reviewed and tested during the investigation. Remove interior finishes to allow observations of the water leakage paths. Test representative leak locations with a calibrated spray rack in accordance with relevant ASTM standards.

Steep Roofs: Problem spots include gutters, chimneys, ridges, rakes, gables, dormers—in short, all roof perimeter conditions or locations where the roof changes direction or materials. Perform water testing and verify that the interior leakage during the tests matches the existing damage pattern and actual leakage observed during a rain. Perform partial disassembly to look for concealed causes of leakage and verify construction and configuration of the building materials. For all testing, generally start at the bottom and work upward to isolate leakage paths.

Low-slope Roofs: Problem spots include penetrations, drains, parapet terminations, and transitions to other roof areas; again generally material discontinuities and roof perimeter conditions. Begin water test at bottom-of-slope conditions and work upward. The test procedure is different for loose-laid membranes and adhered membranes. For loose laid membranes, a leak may originate far from the interior damage location and travel on the structural deck until it reaches a penetration (e.g., at an opening) where it can leak to the interior. When investigating these membranes, start the water test near the damaged area and work upslope, remove ballast, and carefully scrutinize the membrane for damage, such as holes or separated membrane seams. For membranes that are continuously adhered to the structural deck the approach is different. If the membrane is properly installed, the leak will always be in the vicinity of the interior damage because the leakage water cannot travel between the membrane and the deck. Some hybrid systems require special attention. For example, PVC roofing and waterproofing systems with an adhered grid-strip system compartmentalize the space under the membrane and are intended to confine the leakage to individual quadrants. For low-slope roofs, investigators frequently use flood tests to cover the entire membrane with water and look for leaks, but this technique does not address many vulnerable conditions that are above the membrane levels; e.g., perimeter flashings and wall terminations. Before conducting a flood test, the investigator must verify that the structural load capacity of the roof is sufficient to support the weight of the water.

Walls, Curtain Walls, and Windows: Typical problem spots include: window and door perimeters, transitions between exterior cladding materials, and wall components with horizontal projections. Begin the water test near the bottom of the assembly and work upward, systematically testing and eliminating suspect locations and conditions. Isolate test locations by covering a portion of the exterior wall with plastic sheeting, and expose and test individual components in turn. For example, when testing a window, perform individual tests of the glazing perimeter, window frame, window perimeter joint, and finally the entire assembly including the wall beyond.

Most significant leakage problems manifest themselves during water tests performed without applied differential pressure. Where merited, perform tests with applied differential pressure and in accordance with applicable ASTM test standards. The investigator must carefully select representative test pressures for the building's geographic location based on weather records, and apply this test pressure to all components of the assembly, including windows, window perimeter joints, and adjacent wall system components. Manufacturer's published "proof test" pressures for windows are often unrealistically high [2].

Test duration: The investigator must use judgment here. As a general rule, modern cavity wall and curtain wall construction does not absorb significant amounts of moisture within its component materials and leaks appear relatively quickly. Some interior building materials (e.g., batt insulation, interior gypsum sheathing) absorb significant amounts of water and may cause some delay between the time of the actual leak and its manifestation on the interior. It is helpful to remove these materials prior to testing. In older buildings, thick masonry walls can frequently absorb large amounts of water before leakage to the interior occurs. In some older buildings, leaks may not occur until days after rainfall or testing and may manifest themselves as damp spots, efflorescence, or blistering paint, rather than liquid water. In these buildings, seasonal variations may cause changes in the moisture content of the masonry that the investigator must take into account; e.g., a nearly saturated masonry wall following a week-long rain will allow a quicker leak than a relatively dry masonry wall following a summer dry-spell. For all testing, the investigator should generally wait for a "steady state" after the first leak occurs to ensure that all leak locations have been identified.

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![3]), 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 E1105 "Field Determination of Water Penetration of Installed Exterior Windows, Curtain Walls, and Doors by Uniform of Cyclic Static Air Pressure Difference" [3] prescribes the use of 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.

A Word on Building Access

Most investigations require that the building investigator be up-close and personal with the building. For large buildings, investigations that rely on visual observations from the ground frequently miss important details and are of limited use. The investigator should generally hire a competent contractor to provide building access for a hands-on review of envelope components, and to make and repair sample openings. See the suggested investigation protocol below.

Leaks from Interior Sources

These include leaks caused by steam pipes, water supply and return lines, interior roof downleaders, plumbing fixtures, and condensation within or near air conditioning units. Typical indications of water damage from an interior source include chronic leaks that appear to be unrelated to precipitation, interior leaks that appear far from the building envelope, and interior leaks with seasonal variations where chronic leakage stops abruptly (e.g., steam leaks related to heating season). The investigative approach for interior leaks requires consultation with a Mechanical Electrical and Plumbing (MEP) engineer to locate, review, and test mechanical and plumbing systems. Frequently water testing is useful to exclude leakage through the building envelope as the source of the damage.

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

[3] In practice, work from a scaffold or from a movable stage is more realistic. All equipment must, of course, meet OSHA standards for safety.

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 [4,5], 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 10 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. Infrequent or only short-term 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 5 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 and heating systems on the potential for moisture damage can be significant. However, a full treatment of this issue is outside the scope of this Manual. For an in-depth discussion the reader may want to review the many books and reports issued by the American Society of Heating, Refrigeration and Air Conditioning Engineers, Inc.

Condensation problems also frequently occur in high humidity buildings such as swimming pools, museums, and archival storage facilities. These buildings must have, but frequently do not, specially designed building envelopes to contain the humidified air without condensation. Moisture problems occur, for example, when warm and humid interior air exfiltrates through the building envelope. To prevent exfiltration, these buildings require continuous air barriers (to limit exfiltration) and vapor barriers (to prevent vapor diffusion). In practice, continuity of these membranes is difficult to achieve at structural framing penetrations, roof-to-wall transitions, window frame perimeters, mechanical penetrations, and other discontinuities in the building envelope.

Investigative techniques for condensation problems in high-humidity buildings require a careful review of the building construction and its relation to mechanical system performance. It is useful to schedule the investigation to fall into the season where the problem is most prevalent (e.g., during the winter to investigate condensation in the exterior wall system of a pool in the northern United States). In general, the following steps are required (see Chapter 11 "Measurement Techniques and Instrumentation," for more detailed guidance on measurement techniques):

- A review of the construction drawings to verify intended construction materials and detailing.
- Sample openings to verify the as-built construction, configuration, and condition of building materials at problem spots (see above). The bigger the sample opening, the more useful it is; very small openings for inserting borescopes do not give nearly as much information as large openings that allow the investigator to reach into the wall cavity.
- A review of the mechanical systems by an MEP engineer specializing in building systems to verify that systems are commissioned and working as intended, and to verify building pressure.
- Tests for air leakage through the building envelope. In these tests, the building, or a part of the building, is pressurized using a mechanical blower, and the air flow through the blower is measured to determine the airtightness of the building envelope.
- Humidity and surface temperature measurements generate required parameters for analytical methods (see below).

- Air movement tests by infrared thermography. This technique allows the detection of temperature differentials within a building envelope and is useful to track air leakage. Air leakage is often associated with mass transport of humidified air through building envelopes, which can cause condensation problems.

Analytical methods to determine condensation potential are also available. Several available software programs can model the thermal and moisture related behavior of building materials and wall constructions (e.g., THERM, WUFI, FRAME) and are useful to model the hygrothermal behavior of assemblies (e.g., frame, glazing, perimeter construction) under a set of interior conditions (relative humidity and temperature) to determine the heat and moisture movement and across assemblies, the condensation potential of an existing assembly, and to analyze and optimize the configuration of the repair design. See Chapter 10 and ASTM MNL40 [6] for references to these analysis tools.

Moisture from Occupancy

Chapter 7 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 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 [7].

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 realistically high internal moisture loads, and effords to educate the occupants about the effects of excessive water use should be part of a comprehensive moisture management program (and will conserve precious natural resourses. Investigative techniques for moisture from occupancy are similar to those discussed above for condensation. Accumulation of excessive moisture produced by occupants is frequently a ventilation problem and should be reviewed by a MEP specialist.

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 a wall or other cavities, humid basement and crawl space air can also gain access directly to the attic [8].

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 is 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, in cold climates, 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 [9]. 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 [10]. 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 damp-proofing 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* [11].

Construction Moisture

According to ASHRAE, construction moisture can be a source of moisture in buildings for the first years of a building's use [12]. 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. Construction moisture is typically a problem of construction sequencing and poor post-construction management of the HVAC system. Typical issues include porous materials that were installed before building is enclosed and subsequently got wet (most frequent problem), porous materials allowed to get wet before installation, and inadequate ventilation during and after construction. Investigation of damage caused by construction moisture requires a review of construction photos and logs to determine the construction sequence and correlate it with weather records, and a review of HVAC operation practices post-construction.

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 relative contribution to the problem. This process is critical because even small amounts of moisture can produce significant problems, and effective repairs must therefore address all individual contributions to the moisture damage. 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. When 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 at least several causes at once instead of disruptive drawn-out monitoring and construction activities. When 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, 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.

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.

When 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 cannot 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. See the guidance on test locations in the previous sections above.

Moisture Investigation Checklist

As discussed in this chapter and in other chapters of this manual, there are many possibilities of types of moisture problems and many different causes and remedial actions. However, there are a few causes and examinations that should always be considered. Ten of these most frequent sources of moisture problems are listed below. The investigator should always consider them.

1. Except in dry climates, always consider rain leaks first. Telltale signs: Problems appear during or shortly after heavy rains, but remember that the location of any leak may not be where it appears.
2. Condensation of humid indoor air likely if problem occurs in high-humidity areas, such as kitchens and bathrooms. Poorly ventilated bedrooms also can qualify as high-humidity areas during prolonged sleep times with doors and windows closed. This is most likely in cold climates, but can also be a source in air-conditioned houses in warm climates.
3. If condensation occurs on double-glazed windows dur-

ing cold weather, the indoor humidity is probably too high and condensation (and potential mold growths within the wall construction) is possible to likely. Remedial action may be increased ventilation. Opening windows will also help. If a humidifier is used, turn it off.

4. In air-conditioned buildings in warm and humid climates, if rainwater penetrates the exterior of the wall and accumulates within wall materials or cavities, moisture distress and mold may occur within or on the indoor surface of the wall depending on wall construction assembly.
5. Also in warm and humid climates, vapor resistant interior finishes; such as vinyl wallpaper will cause moisture problems and mold growth.
6. Moist basements and crawl spaces are often the result of poor drainage around the building. The ground should slope at least 6 in. for every 5 ft from the building face; better 1 ft for every 10 ft.
7. Downspouts not connected to storm sewers should end on splash blocks. Most available splash blocks are 2 ft long; if available, 3-ft blocks are more effective in carrying the water away from the building face.
8. Moist basement and crawl space floors will result in moisture problems in the spaces above. Covering the floor with a vapor retarder is required. If for some reason this is not practical, the vapor retarder can be attached to the underside of floors to reduce migration of moisture into upstairs occupied spaces. Seal all cracks and utility penetrations in floor.
9. Where a high groundwater table causes occasional or regular flooding of basements or crawlspaces, a system of drainage pipes and sumps with a pump may be the only viable solution.
10. Windows frequently leak and may be a significant source of moisture not only to the inside of the wall but also to spaces within the wall below the window.

These issues are covered in greater detail elsewhere in this manual, but should always be kept in mind when investigating moisture problems.

Examples of Moisture Investigations

While troubleshooting is in general a technical function (called forensic science in some quarters and in some industries), it must be understood that the investigator in most cases does not have unlimited time and resources, that the conditions at the time when problems occurred cannot always be duplicated, that some of the evidence may have been altered or entirely destroyed, and that the behavior of the occupants may have changed between the time when the problems occurred and the time the investigator arrives on the scene. It is for these reasons, as the beginning of this chapter mentioned, that troubleshooting is largely an art, not a science. Past experiences of the troubleshooter will play a major role in how he or she approaches his task and how he or she prioritizes the causal factors. Thus, two investigators may differ in their opinions about the major cause of moisture distress in a particular case and on the most urgent remedial actions. As building science develops, we will become more sure of the causes and remedies in the area of moisture control in buildings. Thus, in the following examples, some investigators will differ significantly with the conclusions of the authors.

The following presents six 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 midrise 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 multiyear 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* [13]. In contrast, to minimize disruption of the building's seasonal operation, the owner of the mid-rise building initially seriously limited diagnostic work. The next 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 last two case studies pertain to historic buildings that were performed as part of design for necessary restoration work after decades of service. The fifth study illustrates the effect of water leakage from interior sources, which are frequently mistaken for rain leaks. Careful analysis of the actual causes of the water leakage is required to avoid misguided repairs. The final case study deals with water leakage through thick masonry walls, a common problem with historic masonry buildings.

The examples presented are based on actual building studies and disputes in which the authors 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 authors, that could alter the authors' conclusions. Although based on actual and believed to be reliable data, the studies are presented here as illustrations of 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 [14,15].

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 forced 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

- Water infiltration tests indicated that gross leakage occurred at the window sill, and lesser but still significant amounts of water leaked into the concrete block cavities on walls without windows.
- 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. 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.
- Ground drainage tests indicated poor drainage, a finding consistent with observation of standing water during and for hours after brief but heavy rainfalls. 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.
- 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.
- 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 [15,16].

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 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 [17]. 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 in. by 4 in. (100 mm 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 window 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 E779 "Test Method for Determining Air Leakage Rate by Fan Pressurization" [18] and by tracer gas tests according to ASTM E741, "Determining Air Change in a Single Zone by Means of a Tracer Gas Dilution" [19].

Results

The initial water vapor transmission tests showed that the exterior building paper had a water vapor permeance in the range of 0.1 perm to 0.5 perms (6–29 ng/Pa·s·m^2). According to ASTM C755, "Selection of Vapor Retarders for Thermal Insulation" [20], 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 O.2 to O.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 inner face of the wall [21], and that the primary cause of the moisture distress was moisture condensation on the incorrectly installed vapor retarding membrane on the winter 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: Multifamily 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°C):	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 [22]. 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-in. by 6-in. (50-mm 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 ot observed moisture distress and the conduct of E 96 "Test Methods for Water Vapor Transmission of Materials" [23], 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 1/4-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, and above the head of windows. It was also found that the wall siding, instead of the specified 1-in. overlap, averaged less than 0.24-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 weather barrier 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.

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%

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.

Gypsum 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 (7,470 ng/(Pa·s·m^2)

Gypsum Sheathing: 45 perms (2,585 ng/(Pa·s·m^2)

Plywood Sheathing: 10 perms (575 ng/(Pa·s·m^2)

The 6-mil polyethylene 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 [2,875 ng/(Pa·s·m^2)], respectively, were considered sufficiently well documented in the literature [24].

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[4] of the two walls were as shown in Table 1 at start of test, after six days, and after nine days.

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.

Example 5: Interior Steam Leak in Historic Masonry Building

Location and Topography

The building is a monumental masonry building in an urban area in the northeastern United States. The building was completed around 1900.

Climate

Heating degree days:	6888	
Cooling degree days:	574	
Winter design temp:	99%	−6°F (−21°C)
	97.5%	−1°F (−18°C)
Summer design temp:	1%	91°F (33°C) DB, 73°F (23°C) WB
	2.5%	88°F (31°C) DB, 72°F (22°C) WB
	5%	85°F (29°C) DB, 70°F (21°C) WB
Summer dry bulb:	93°F (34°C) and over:	16 h
	80 to 93°F (27 to 34°C):	417 h
Summer wet bulb:	73°F (23°C) and over:	132 h
	67 to 73°F (19 to 23°C):	775 h
Prevailing winds:	Summer: South Winter: West Northwest	

Based on this climate data, the buildings are located in a climate defined as Climate Zone III.

Design and Construction

The building has thick masonry wall with up to 2 ft. deep granite facing stones and brick back-up masonry. Interior partition walls are brick masonry with furred-out cement plaster finishes. Floors in this area of the building are cast-in-place reinforced concrete and support a cement plaster drop ceiling. Supply lines for the steam radiators run within a trough in the concrete floors just inboard of the exterior walls.

[4] 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.

Problem Manifestation

The ornamental plaster ceiling in the legislative library housed on the west elevation of the building had been suffering chronic water leakage for several years. The damage, initially a small area of peeling paint, grew progressively worse until a plaster rosette fell from the ceiling and a portion of the room was closed as a safety precaution. The damaged area was located just inboard of the exterior building wall.

Diagnostic Work

Review of existing drawings and specifications: Very few existing building drawings were available, so the investigators had to rely on sample openings and field measurements to determine the as-built conditions. A review of limited as-built plumbing drawings showed that the downleaders for the roof drainage are not in the vicinity of the damaged area.

Initial Site Visit: During the initial site visit, the investigators spent several hours on site to determine access requirements and discuss them with a contractor. The contractor erected interior and exterior scaffolding to provide safe access to the damaged ceiling and the exterior facade near the damaged area.

Occupant Surveys: The investigators discussed the appearance of the damage with the library staff, who reported that leakage (water dripping from the damaged portion of the ceiling) occurred only during the spring and summer months. Beyond this, the staff had little information regarding the leakage.

Weather Data: No weather data was collected for this investigation.

Experimental Plan: The investigators developed an experimental plan that included access to the damaged area, selective demolition of building finishes to ascertain the existing construction, and water testing to determine leakage paths from the exterior.

Diagnostic Tests: During the first step of the field work, the investigators removed sufficient materials on the interior to allow measurements of the concealed building construction and draw accurate as-built sketches of the area. During this work, the investigators discovered a concealed plumbing chase within the floor slab above the leak. Because the chase was insulated with a material that appeared to be asbestos, the chase had to be abated by a specialty contractor prior to performing additional investigative work in this area, a process which required several weeks. While this work was in progress, the investigators performed systematic water tests of the exterior walls and windows above the leak. The tests had lasted several days to account for the thickness of the masonry walls and the likely required duration for a leak to occur. This testing produced no leaks. In the meantime, the asbestos removal had uncovered several steam lines in the plumbing chase that supply steam radiators in the offices below the library. Regular reviews of the steam lines showed periodic leakage from a deteriorated pipe joint. A MEP specialist who reviewed the condition of the steam heat system for the building determined the following.

The boilers for the system produce hot water for the building, as well as steam for the radiators. In the summer, when the heat is turned off, a small amount of steam escapes into the system, condenses in the steam pipes, and builds up a considerable water head within the pipes. This water leaked out of perforations and defective pipe joints and caused the damage in the library. In the winter, when the heat is turned on, the pipes contain only steam, which is at relatively low pressure compared to the water head caused by the condensation, and does not cause sufficient leakage to cause drips into the library.

Following the field investigation work, the building plumber replaced the steam lines, and following this work the building maintenance staff and the investigators monitored the area for several months, but saw no further leakage. Moisture measurements of the damaged plaster following the repair work to the pipe showed that the plaster had dried out. After this time, the investigators concluded that the steam lines had been the sole cause of the moisture damage, and the ornamental plaster in the library was restored.

Results

The water infiltration tests produced no leakage to the interior. The interior sample openings allowed observations of the chronic water leakage from the steam pipes. A review of the operating parameters of the building's steam heat system confirmed the source of the water that had damaged the plaster ceiling.

Conclusions

1. The case study demonstrates several common challenges associated with leakage investigations: Concealed hazardous materials complicated and delayed the work of the building investigator (common in older, say, pre-1980, buildings only).
2. Even though the water leakage came from an interior source, water tests of exterior building features were required to exclude rain leaks as a source of water.
3. Troubleshooting the interior leakage required the expertise of a MEP engineer.
4. Monitoring the performance of sample repairs (in this case the plumbing repairs) gave the investigators assurance that the problem had been resolved before designing permanent repairs.

Example 6: Rain Leak Through Exterior Walls in a Historic Masonry Building

Location and Topography

The building is an approximately 1930 reading room with large, ornamental windows. It is part of a university library in an urban area in the northeastern United States.

Climate

Heating degree days:	5793	
Cooling degree days:	573	
Winter design temp:	99%	3°F (−16°C)
	97.5%	7°F (−14°C)
Summer design temp:	1%	88°F (31°C) DB, 75°F (24°C) WB
	2.5%	84°F (29°C) DB, 73°F (23°C) WB
	5%	82°F (28°C) DB, 72°F (22°C) WB
Summer dry bulb:	93°F (34°C) and over:	3 h
	80 to 93°F (27 to 34°C):	245 h

Summer wet bulb:	73°F (23°C) and over:	237 h
	67 to 73°F (19 to 23°C):	1186 h
Prevailing winds:	Summer: Southwest Winter: North Northeast	

Based on this climate data, the buildings are located in a climate defined Climate Zone III.

Design and Construction

The building has approximately 18-in.-thick masonry walls consisting of 4- to 8-in.-thick granite facing stones and brick back-up masonry. The inboard side of the back-up masonry wall is covered with a bituminous coating. Painted cement plaster finishes are applied to a separate clay tile finish wall that is separated from the back-up wall by a 1/2 in. wide cavity (denoted "weep cavity" on the original drawings; see below). Windows consist of leaded glazing set into carved limestone window surrounds that span the full depth of the walls. A steep slate roof drains into a copper-lined built-in gutter around the building perimeter.

Problem Manifestation

The ornamental plaster above the windows, and along the window heads and jambs had been suffering chronic moisture damage for several decades. The damage quickly reappeared after it had been addressed with plaster repairs and repainting.

Diagnostic Work

Review of Existing Drawings and Specifications: Original construction drawings and specifications were available from the archives of the University's facilities office. The drawings confirmed the wall construction (see above) and showed that the windows were not protected with flashing. No plumbing lines, such as interior downleaders, are shown on the drawings near the damaged areas.

Initial Site Visit: During the initial site visit, the investigators selected a representative building location for testing, and discussed access with a restoration contractor. The contractor subsequently provided pipe scaffold to access both the exterior and interior of the wall in a damaged area.

Occupant Surveys: Building maintenance staff reported seeing no water leakage (i.e., free water running down on interior finishes) on the plaster, even during heavy downpours. Occasional leakage was reported on the limestone window tracery (ornamental carved limestone grapevining and mullions). Plaster damage typically appeared days after a significant rain. Damage frequently appeared following periods of prolonged wind-driven rains, but not after short but heavy downpours.

Weather Data: No weather data was collected for this investigation.

Experimental Plan: The investigators developed an experimental plan that included access to the damaged area, selective demolition of building finishes to ascertain the existing construction, and water testing to determine leakage paths from the exterior.

Diagnostic Tests: During the first step of the field work, the investigators and assisting contractors removed several large patches of interior plaster to allow measurements of the concealed building construction and draw accurate as-built sketches of the wall, and to observe leakage; see below. Using calibrated spray racks, the investigators then performed systematic water tests of the exterior walls and windows to determine the source of the water damage. Tests were performed as follows:

- Spray window glazing and tracery with water while window perimeter and adjacent masonry is covered with plastic.
  Test duration: several hours.
  Result: minor water leakage at window tracery joints below areas with damaged plaster.
- Spray limestone window surround with water while window glazing, window tracery, and adjacent masonry is covered with plastic.
  Test duration: several hours.
  Result: no visible leakage or damp plaster.
- Spray masonry above window surround with water while window glazing, window tracery, and window surround are covered with plastic. Test duration: one day.
  Result: After several hours of testing, the investigators noted water seeping out of holidays in the mastic coating on the inboard side of the back-up wall. The water ran downward within the cavity between the back-up wall and the clay tile finish wall until it collected on the limestone window head and soaked the plaster in previously damaged wall areas. The test also wetted previously damaged plaster finishes within the field of the wall where debris bridged the cavity.

Results

Water comes to the interior at holidays in the mastic coating over the back-up wall, and runs down within the "weep cavity" until it hits an obstruction, such as the window heads. This is consistent with the observations of the building maintenance staff who had reported plaster damage following prolonged rains, but not after brief but copious summer downpours. The investigators designed remedial work, consisting of masonry waterproofing and flashing repairs, and implemented them on one window. The repairs were then tested following the same regimen as during the diagnostic work. After the successful tests, the repairs were implemented on the entire building.

Conclusions

The case study demonstrates several common challenges associated with leakage investigations in older masonry buildings:

1. Mass barrier walls are vulnerable to prolonged wind-driven rain. The investigator must be patient and test long enough determine the actual leakage paths, but not subjecting the building to unrealistic conditions. The testing, which produced leakage through the wall only after hours of testing, indicates that short rainfalls do not produce sufficient leakage to damage interior finishes, but prolonged rains will eventually saturate the wall masonry and allow seepage to the interior.
2. Damaging leakage can be caused by small amounts of water that never manifest themselves as observable free water running down on interior finishes. The resulting elevated moisture levels will over time cause significant finish and masonry damage.
3. As in the previous case study, performing sample repairs

and testing their performance prior to performing remedial work is an important check on the field investigation work.

Comparison of the Six Examples

The 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: 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, 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. In the fifth example, the investigators used water testing to show that leakage through the exterior walls was not the cause of significant interior damage. They then used other investigative techniques, including sample openings, to find the actual source of the damage and consulted with other experts, namely MEP engineers and environmental engineers experienced with hazardous materials abatement, to repair the cause of the problem. In the final example, the investigators adjusted their water testing procedure to match the weather conditions (prolonged but not necessarily heavy wind-driven rain) during which building personnel had reported leakage, but also to the as-built conditions of the building (very thick masonry walls may require hours of testing before leakage occurs) to reproduce the observed leakage and avoid unrealistic test conditions.

Who Should Conduct the Tests?

All examples indicate the importance of having tests conducted only by well-qualified experts. Tests should follow ASTM guidelines where practical to ensure that test results are reproducible. However, the investigator must keep in mind that building envelope investigations are part science and part art. Although test standards can provide valuable guidance, the success of the investigation is largely determined by the experience and creativity of the investigator who applies these tests. 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 inter-related components, and the test methods, although providing useful data, provide only one set of data in this complex system [25]. 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 Cl6 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" [26].

During the work on the first example, the investigator 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 in conducting the specific tests required. 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 conduct 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 conduc 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?

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. The recently-developed ASTM E2128 "Standard Guide for Evaluating Water Leakage of Building Walls," provides guidance and consistency for building evaluations [1]. Other standards, such as ASTM E2270 [27] and ASTM E1825 [28], although not directly related to building envelope leakage, provide direction for building envelope investigations, as well as the assessment of building envelope materials and problems.

Such protocols represent a significant step toward establishing failure investigations, forensic engineering, and "troubleshooting" as a separate engineering discipline. The standards ensure consistency among building investigators, leading to reproducible results, which are a necessity in dispute resolution. 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-test 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 0.12 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. For existing buildings, drawings can frequently be obtained from the Department of Buildings for the jurisdiction. Drawings for historic buildings can sometimes be obtained from public libraries. Along with the drawings, construction photos often give useful hints on the building construction, and are sometimes available for landmark buildings. Copies of construction drawings are also useful to mark field observations, photo locations, and other information collected by the investigator.

Initial Site Visit

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. As part of the initial site visit, the investigator must review the building to determine access requirements to promising sample locations (see below), and determine required repair materials for the sample locations. For newer buildings, this visit should include a review of existing warranties (roofing systems are frequently covered by warranties). Such warranties can be voided by destructive testing unless special precautions are followed. The initial site visit can also include the occupant survey (see below).

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.

The investigator must keep in mind that occupant surveys are subjective. They are useful to determine the general extent of a problem, develop the agenda for the field testing, establish test locations, etc., but the investigator must not rely on hearsay when forming their opinions regarding the causes of the moisture problem.

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. The experimental plan must take into account the logistics of performing the testing, including building access. Exterior building access using scaffolding, hydraulic lifts, or other access equipment is best provided by specialty restoration contractors familiar with similar work. A knowledgeable contractor frequently contributes to the investigation by providing practical construction knowledge to the investigator, or making sample repairs for ad-hoc testing.

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:

- Water tests to track leakage paths into the building.
- Sample openings to determine configuration and condition of building materials.
- Collection of material samples for later review and laboratory analysis. Older buildings frequently contain hazardous building materials, including lead, asbestos, and

PCBs. Although the presence of these materials is typically unrelated to building leakage, the required abatement will typically cause a substantial increase in repair costs. If the building investigators suspect that hazardous materials are present, they must obtain help from a properly qualified professional, generally an engineer specializing in hazardous materials abatement, to avoid exposing themselves, building tenants, or the general public to health hazards during the investigation.
- Mechanical systems review (by MEP engineer). Such reviews are useful to determine if mechanical systems are contributing to moisture problems.
- 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.
- Air movement tests by infrared thermography.
- Sample repairs during the testing program give the building investigator important clues for a later repair design. Sample repairs are then retested to determine their response to the repair approach.

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.

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.

REFERENCES

[1] ASTM, Standard E2128, "Standard Guide for Evaluating Water Leakage of Building Walls," *Annual Book of ASTM Standards*, ASTM International, West Conshohocken, PA, 2001.

[2] Cole, G. G., and Schwartz, T. A., "Establishing Appropriate Test Pressures for Investigation of Leakage Through the Building Envelope," Thomas A. Schwartz, Ed., *Water in Exterior Building Walls: Problems and Solutions, STP 1107*, ASTM International, West Conshohocken, PA, 1991.

[3] ASTM, Standard E1105, "Field Determination of Water Penetration of Installed Exterior Windows, Curtain Walls, and Doors by Uniform Cycle Static Air Pressure Difference," *Annual Book of ASTM Standards*, ASTM International, West Conshohocken, PA, 2000.

[4] Wilson, A. G. and Garden, G. K., "Moisture Accumulation in Walls Due to Air Leakage," paper presented at RILEM/CIB Symposium on Moisture Problems in Buildings, Helsinki, Finland, NRCC 9131, 1965.

[5] Handegord, G., "The Need for Improved Air Tightness in Buildings," Building Research Note 151, National Research Council of Canada, Ottawa, 1979.

[6] ASTM, MNL40, *Moisture Analysis and Condensation Control in Building Envelopes*, ASTM International, West Conshohocken, PA, 2001.

[7] Trechsel, H. R., and Achenbach, P. R., "Measuring Air Change Rate in Individual Rooms," *Standardization News*, ASTM International, West Conshohocken, PA, 1987, pp. 52–53.

[8] Socolow, R. H., "The Twin Rivers Program on Energy Conservation in Housing: Highlights and Conclusions," NTIS, U.S. Department of Commerce, Springfield, 1978, pp. 32–34.

[9] Oliver, A. C., *Dampness in Buildings*, Nichols Publishing, New York, 1988, p. 145.

[10] Heiman, J. L., "An Evaluation of Methods of Treating Rising Damp," M. Lieff and H. R. Trechsel, Eds., *Moisture in Buildings, ASTM STP 779*, ASTM International, West Conshohocken, PA, 1982, pp. 121–137.

[11] Oliver, A. C., *Dampness in Buildings*, Nichols Publishing, New York, 1988, pp. 145–181.

[12] ASHRAE, *ASHRAE Handbook of Fundamentals*, American Society of Heating, Refrigerating, and Air Conditioning Engineers, Atlanta, GA, 1989, chap. 21, p. 21.1.

[13] Trechsel, H. R., Achenbach, P. R., and Conklin, S., "Field Study on Moisture Problems in Exterior Walls of Masonry Housing on the Coast of the Gulf of Mexico," F. J. Powell and S. L. Mathews, Eds., *Thermal Insulation: Materials and Systems, ASTM STP 922*, ASTM International, West Conshohocken, PA, 1987, pp. 371–393.

[14] Moore, J. R., Spielvogel, L. G., and Griffin, C. W., "Air Conditioned Buildings in Humid Climates; Guidelines for Design, Operation, and Maintenance," Southern Division, Naval Facilities Engineering Command, Charleston, SC, NTIS AD-A090145, 1980, p. 3.

[15] ASHRAE, *ASHRAE Handbook of Fundamentals*, American Society of Heating, Refrigerating, and Air Conditioning Engineers, Atlanta, GA, 1989, chap. 21, pp. 21.12–21.13.

[16] Moore, J. R., Spielvogel, L. G., and Griffin, C. W., "Air Conditioned Buildings in Humid Climates; Guidelines for Design, Operation, and Maintenance," Southern Division, Naval Facilities Engineering Command, Charleston, SC, NTIS AD-A090145, 1980, p. 4.

[17] ASHRAE, *ASHRAE Handbook of Fundamentals*, American Society of Heating, Refrigerating, and Air Conditioning Engineers, Atlanta, GA, 1989, chap. 21, p. 21.10.

[18] ASTM, Standard E779, "Test Method for Determining Leakage Rate by Fan Pressurization," *Annual Book of ASTM Standards*, ASTM International, West Conshohocken, PA, 2003.

[19] ASTM, Standard E741, "Determining Air Change in a Single Zone by Means of a Tracer Gas Dilution," *Annual Book of ASTM Standards*, ASTM International, West Conshohocken, PA, 2000.

[20] ASTM, Standard C755, "Selection of Vapor Retarders for Thermal Insulation," *Annual Book of ASTM Standards*, ASTM International, West Conshohocken, PA, 2003.

[21] "Minimum Property Standards," U.S. Department of Energy, 1963.

[22] ASHRAE, *ASHRAE Handbook of Fundamentals*, American Society of Heating, Refrigerating, and Air Conditioning Engineers, Atlanta, GA, 1989, chap. 22, p. 22.10.

[23] ASTM, Standard E96, "Standard Test Method for Water Vapor Transmission of Materials," *Annual Book of ASTM Standards*, ASTM International, West Conshohocken, PA, 2005.

[24] ASHRAE, *ASHRAE Handbook of Fundamentals*, American Society of Heating, Refrigerating, and Air Conditioning Engineers, Atlanta, GA, 1989, chap. 21, p. 22.14.

[25] Bomberg, M., "Testing Water Vapor Transmission: Unresolved Issues," H. R. Trechsel and M. Bomberg, Eds., *Water Vapor Transmission Through Building Materials and Systems: Mechanisms and Measurements, ASTM STP 1039*, ASTM International, West Conshohocken, PA, 1989, pp. 153–167.

[26] Toas, M., "Results of the 1985 Round Robin Test Series Using ASTM E96–80," *Water Vapor Transmission Through Building Materials and Systems: Mechanisms and Measurements, ASTM STP 1039*, H. R. Trechsel and M. Bomberg, Eds., ASTM International, West Conshohocken, PA, 1989, pp. 73–90.

[27] ASTM Standard E2270, "Practice for Periodic Inspection of Building Facades for Unsafe Conditions," *Annual Book of ASTM Standards*, ASTM International, West Conshohocken, PA.

[28] ASTM, Standard E1825, "Guide for Evolution of Exterior Building Wall Materials, Products, and Systems," *Annual Book of ASTM Standards*, ASTM International, West Conshohocken, PA, 1996.

MNL18-EB/Oct. 2009

13

Case Studies of Moisture Problems in Residences

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, except occasionally where related to field or laboratory studies. The chapter describes research and studies published in the open literature as well as unpublished studies conducted by the author and others. 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 in this chapter is on case studies of shell-dominated residential-type buildings. Most of the studies involve single family or multi-family low-rise wood-frame residences, although a few of them involve other types, including apartments. A few examples of moisture problems in office or other nonresidential buildings from the author's experience are also presented. However, a separate chapter in this manual describes case studies of commercial and institutional buildings in more detail. 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, where possible, between existing buildings that are usually older and newly constructed buildings. Some field and laboratory studies apply to both types of buildings; when that is the case, those studies are described in the section that seems most appropriate. 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. Almost all the relevant southern climate studies concern hot and humid climates; only one deals with a hot and dry climate. 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. In addition, there are very few studies available involving buildings in mixed 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, not including exterior walls, and (3) exterior wall excess moisture problems. 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. Damage can often be extensive and expensive because of them. 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 concern over indoor air quality related to mold growth, 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 such as walls and ceilings and around windows; growth of dust mites and other organisms; and basement dampness and leakage. In addition, interior gypsum wallboard or plaster can also be deteriorated as a result of water leaks, especially around windows and doors. Plumbing leaks can also cause serious mold and decay problems. They appear to be rather common in multi-family apartments.

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 air tightening that the incidence of moisture problems is dramatically increasing in homes weatherized without concern for moisture problems.

Mold and Mildew Problems

Of the indoor moisture problems, mold and mildew would now have to be considered one of the most serious. Years ago, it used to be considered just a nuisance, but now health concerns are widespread. For our purposes in this chapter, mold and mildew are essentially synonymous terms. 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].

That can occur in one of three ways. First of all, mold and mildew occurs on cold surfaces where the relative humidity is highest. Recall that, for a given amount of water vapor indoors, relative humidity increases as the temperature of the air next to the surface decreases. In cold climates that often occurs on the cold inside surfaces of exterior walls, such as those caused by missing insulation or thermal bridges (local areas that are poorly insulated) or in unheated spaces such as closets on exterior walls. It is typically noted on inside gypsum wallboard or plaster surfaces around window frames as well as exterior walls and ceilings, especially in high and low corners. If the indoor temperature is 70°F (21°C) and the indoor relative humidity is 50 %, then the surface relative humidity will be at or above 80 % when the temperature equals or drops below 57°F (14°C). That can easily occur around window frames and sills or other surfaces. In fact, localized mold growth around windows is probably the most prevalent type of mold growth in residences in northern climates, especially when drapes or shades are closed, which lowers the local surface temperatures around windows. It is seen surprisingly often in apartments or other homes where shades or drapes are left closed permanently, most likely for privacy reasons. Moreover, mold growth can occur on cold surfaces even when the indoor air relative humidities are relatively low, such as well below 50 %. In a study of 20 new, energy-efficient homes in Montana, 50 % had visible mold on surfaces even though the average measured living room relative humidity was only 40 %, with a maximum of 55 % and a low of 23 % [2]. What counts is the relative humidity at surfaces rather than in the air well away from the surfaces. The homes in Montana clearly had localized cold spots that increased the relative humidity enough to grow mold. Mold growth at localized cold spots is probably the most commonly occurring type.

In warm climates such as the southeastern United States, the relative humidity is often above 80 % at surfaces because the weather is so humid. That is especially true of cold surfaces in air-conditioned spaces, such as behind vinyl or other wallpaper which acts as a vapor retarder. Because moist air is often drawn in from the humid outdoors, it often will cause mold growth on surfaces hidden from view, such as in wall cavities behind gypsum wallboard that are cooled by air conditioning.

The second way that mold growth can occur is when the indoor air is excessively humid because of abnormally high moisture generation, possibly coupled with unheated or poorly heated spaces and inadequate moisture control, or both. That means the local indoor air must be fairly humid, with a relative humidity value generally greater than about 60–70 %. Those relative humidity values are somewhat lower than what is required for mold growth because the indoor air away from surfaces is usually warmer than at exterior surfaces. When the indoor humidity is excessively high, the mold growth is usually relatively widespread rather than localized. This type of mold growth is often seen where indoor spaces are not heated, coupled with very high occupancies and possibly with frequent boiling of liquids. This is typically not as common in northern climates as localized mold growth at cold spots. In southern climates this type of mold growth is much more common.

The final way that mold growth occurs is when surfaces get excessively wet. That can occur due to such things as flooding due to plumbing leaks or overflowing baths or toilets or regular wetting of gypsum wallboard around showers. It can also occur due to wetting during construction or because of water leaks into the building envelope caused by construction errors or improper design or inadequate maintenance. One particular example of such mold growth is around exterior wall floor molding with slab-on-grade construction. Wetting of the slab edges or bottom surfaces from rain wets the adjoining wall members and causes mold growth, in part because the floor surfaces are the coolest. Water vapor emitted into living spaces from drying of new concrete floor slabs during the first year or two after construction also is a potential source of moisture that often leads to mold growth. These types of mold problems can be particularly serious because they often cause hidden mold growth inside walls, floors, and other cavities. Because mold can grow in a matter of a few days under the right conditions, it is imperative that wetted materials be dried out within 24–48 hours of the initial wetting.

The incidence of mold and mildew and other problems related to excessively high indoor relative humidities is extremely important because it has been connected to biological contaminants that are now being recognized as causing significant health problems, although many of the alleged "toxic" mold problems may have no scientific basis [3,4]. 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 [5] 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 due to improper grading away from the house or 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 attic condensation, or both; frost and mold; ice dams; roof wood decay; and condensation, mold, and decay in crawl spaces. Roofing and attic moisture problems are typically caused either by leaks or because moist indoor air is migrating into the attic. Crawl space moisture problems are often caused by improper grading or drainage, or both, lack of a crawl space ground cover, or venting of outdoor air into crawl spaces in some humid climates, especially with air-conditioned interior spaces.

Exterior Wall Moisture Problems

Exterior wall excess moisture problems include high wood moisture contents in the various wall components (which by itself may not be a problem, especially if the components dry out in warm weather when decay fungi can grow), mold growth, and wood decay (sometimes called dry rot), and subsequent structural damage. Wood decay is caused by a fungal growth. The conditions required for the growth of decay fungi are warm temperatures [around 75 to 90°F (24 to 33°C) is optimum, and there is little growth below 50°F (10°C)], high wood moisture content (greater than about 30 %, with no growth below about 20 %), and exposure to air [6]. In northern climates wood normally will not decay in winter because the required conditions are not met—namely, the wood is not warm enough for the growth of decay fungi. In the summer in such climates, wood normally dries out except when leaks exist such as roof or siding leaks that wet the wood. In southern climates all the conditions for the growth of decay are fairly easily met if wood in a building gets wet by leaks due to construction errors or if wood is in contact with or too close to the ground. Scheffer at the U.S. Forest Products Laboratory developed a climate index for estimating the potential for decay in wood structures above ground [7] that shows that structures in the southeastern United States are most prone to wood decay because of the prevalence of rainy, warm weather conditions. Of course, if structures get excessively wet in any climate, decay can occur. That is why preventing water entry is so important.

Mold growth inside walls is also a moisture problem of concern. Mold will grow on wood- or paper-based wall members when equilibrium moisture contents are above about 19–20 %. That is wetter than most typical untreated wood members in walls. Thus, it takes wetting by some means such as construction defects allowing water intrusion to produce the elevated moisture contents (or the elevated surface relative humidity of 80 % or greater, as noted earlier). There are, of course, other possible causes, such as contact with wet concrete or members wetted by sprinklers or by rain splash back [8].

Another type of mold growth that falls within this last category of moisture problems within walls is mold on lumber. This typically involves either sap stain or so-called black mold on the lumber [9]. It recently has become an issue with the increased concern with mold in buildings. This type of mold is often present when green lumber is delivered to a job site. Some lumber is being returned to the lumber yard if it has mold on it. It can also occur if lumber that is mold-free at delivery is wetted on the job site after delivery. Such wetting can occur during construction (for example, during rainy weather) or even after construction is completed if conditions exist such that long-term wetting of the lumber continues, as, for example, if wood members are not sufficiently dry when walls are closed in.

Other types of wall moisture problems include: blistering and peeling cladding and trim paint; wood siding shrinkage, cupping, and cracking; siding buckling; siding swelling; and plywood siding delamination. 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 siding buckling is often caused by improper nailing.

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 [10]. 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 questions.

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 [4,792 degree days (DD)] were inspected and found to have an average indoor daytime relative humidity and temperature of 56 % and 68.5°F (20.3°C) [11]. 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 significantly air tightened, 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 (6,835 DD) were similarly inspected during the 1982–83 winter and found to have an average indoor daytime relative humidity and temperature of 47 % and 67°F (20°C) [12]. 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 [13]. 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 [14] 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 that 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. and Canadian dwelling units have indoor moisture damage, then *one million U.S. and Canadian 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 [15]. Between 1970 and 1982, more than 5,000 such homes were manufactured, 3,400 of which were built and installed in Wisconsin. After 1986, extensive plywood wall sheathing 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 fairly airtight and poorly ventilated (no exhaust fans), leading to somewhat high indoor relative humidities [15]. Mold and mildew inside the homes was common, but no more so than the older, less airtight homes inspected in the Portland and Spokane studies [11,12]. 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 [16]. That appeared 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.

While the sheathing decay was initially attributed to high levels of indoor moisture [15], results from a later field test and computer modeling study clearly indicated that the primary cause was the presence of an exterior vapor retarder (EVR) that trapped moisture within the wall cavity that was migrating from indoors by vapor diffusion [17,18]. Along with the decay, there was mold growth in the wall cavities and even on interior surfaces of the exterior walls. In this case wall materials that were wetted because of improper construction caused the mold growth.

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 [16].

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 [19]. 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 [20], 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 [21]. 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 that 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 signs 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.

The Wallaceburg (Ontario, Canada) Health and Housing Mold Studies

About 30 questionnaire studies around the world have shown a consistently strong correlation between occupant-reported respiratory disease symptoms and reported dampness or moisture and mold problems in houses. That includes a Canadian study that focused on 15,000 houses in 30 communities across Canada. That Health Canada questionnaire study was followed up with a field study to compare actual exposure with measured health outcomes to verify the validity of the strong correlation. Measurements were made of exposure to a number of indoor air pollutants, the health of early school age children, and the conditions and performances of the houses. A number of papers have been written about this research (see Ref. [22]).

Biological exposure concentrations were measured in 402 houses in Wallaceburg, Ontario, Canada. While samples were analyzed for viable mold spores and ergosterol (a component of mold), for cat and dust mite antigen, and for bacterial endotoxin, reported health problems correlated primarily with mold exposure. A wide variety of sampling and investigation protocols, along with survey forms, were used to assess the conditions and performance of the houses. Then the data was statistically analyzed. These studies debunked a number of preconceptions by demonstrating that: (1) air leaky houses did not have less mold than tight ones, (2) the group of houses with high contamination were leakier (and older) than the group of houses with low contamination, (3) tighter houses had lower air exchange rates but did not have higher relative humidities or higher levels of contamination, (4) high measured relative humidity did not correlate with biological contamination, (5) and problems with the house were more often the source of moisture rather than occupant moisture generation behavior.

The study also showed that mold growth from condensation on windows was common (it was noted in a majority of the houses); many of the observed moisture and mold growth problems were related to soil contact problems, and ventilation by itself will not prevent problems since source rate dominates the existence of problems because ventilation varies only slightly compared to the large variations in source rates. The study also presents a number of implications for the housing industry as well as codes and standards.

Field Evaluation of the Moisture Balance Technique to Characterize Indoor Wetness

As part of the HUD Healthy Homes Initiative, a study was initiated to monitor the temperature and humidity of 76 buildings in Providence, Rhode Island, with a goal of quantifying the "wetness" of buildings [23]. Hourly values of temperature and humidity were recorded for units in the buildings, typically in the family room and bedroom. Sensors also were placed in the basements and several buildings were equipped with outdoor sensors. Values reported are for one five-month wintertime period for 15 buildings (31 dwelling units). Eleven of the 15 buildings were multi-unit, whereas the other four were single-family.

The moisture balance was found to be higher at the upper stories in the multi-family buildings because moisture is carried from below due to the stack effect. The results also showed that basements in the multi-family buildings were quite dry (in the wintertime *only*).

Values of temperature and relative humidity were recorded for indoor and outdoor air. The values were used to compute the vapor pressure for both indoor and outdoor conditions. The difference between them is defined as the moisture balance. This analysis was predicated on the assumption that indoor vapor pressure in many living spaces closely tracks the outdoor vapor pressure, with a slight increment of indoor vapor pressure over outdoor. The increment is one characterization of indoor "wetness." This method is applicable to moisture damage situations involving widespread elevated relative humidity rather than damage caused by localized water entry or accumulation, such as from leaks, or locally elevated relative humidity, such as around window cold spots. Analysis of the results also suggested that a shorter monitoring period, such as monthly, might be possible to isolate the source of the higher moisture within a building. Because of the small sample size, no conclusion could be reached regarding the addition of ventilation exhaust fans on the moisture balances.

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. In another case, extensive mold on interior gypsum wallboard was found to be caused by water infiltrating into the wall cavity from a leak at a deck to wall intersection. While it is often difficult to recognize and diagnose, sometimes indoor moisture problems are caused by leaks and other external water sources. Incidentally, in the Portland Study [11] about 12 % of the 103 older existing 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 or under, or both, 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. In addition, failure to properly slope the ground away from basement and crawl space foundations can cause similar wetting of the foundation [building codes typically require 6 in. (15 cm) of slope away from the house in the first 10 ft (3.5 m)]. Excess moisture caused by these problems can produce mold on interior surfaces, especially near the floor.

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 (93 m^3) of normal soil to be about 100 lb (45 kg) per day, whereas the rate increases to about 400 lb (181 kg) per day if there is standing water covering the crawl space ground. These results are in agreement with other estimates [24]. 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 that then lead to problems. If left uncorrected, it also can result in decay of floor wood members. The crawl space evaporation moisture source can be substantially reduced by the addition of a ground cover. In many locations it is wisely required by code. It probably should be required in all crawl spaces.

Mold often will grow in closets, especially if they are on exterior walls. In one case of a residence in a newly finished basement where a new slab floor had been poured, mold was found on the wood molding in a closet at the base of an exterior wall. The lack of heat in the closet with its door closed, in combination with excessive water vapor evaporation from the drying slab (based on concrete vapor emission tests the author conducted), caused elevated relative humidities in the closet and the resultant mold growth. A dehumidifier was installed in the basement, and that coupled with installing a louvered door to help better heat the closet area, resolved the problem. Oftentimes, just installing a louvered door will suffice when a large source of moisture does not exist in the closet and the problem is mainly due to the existence of cold surfaces with elevated relative humidities.

In another case involving a large apartment complex in Portland, Oregon, mold was observed in many of the first floor units on gypsum wallboard walls and wood moldings near the slab-on-grade concrete floors soon after construction was completed. No mold was found in any of the second story apartments. In that case the concrete floor slab had the code-required vapor barrier below it, so all the construction moisture in the slab that needed to dry out entered into the wall and living spaces above it. It appeared that lack of slab edge sealing also exacerbated the situation by the rain-soaked soil wetting the slab edge; the porous concrete was then wetted by capillary action. The sill plates inside the walls were then wetted by contact with the slab, and that then elevated the relative humidity inside the walls and wet the wall materials sufficiently to cause considerable mold growth. Since this was a common problem in the development company's apartment house construction, it was decided to install hard-wired and plumbed portable electric dehumidifiers in each of the apartments' laundry rooms, both in the development mentioned as well as all their new ones. Many hundreds have been installed. Their operation has largely eliminated the mold growth problem at a modest initial cost. Furthermore, because the apartments are electrically heated, and because the dehumidifiers are efficient heat sources that displace the need for the normal electric heat, there is no additional operational cost involved with using the dehumidifiers.

It should be noted that in a number of similar cases involving both single-family residences and apartments in many states, wet slabs have caused vinyl flooring to mold underneath such that the vinyl has visually unappealing dark stains. There are a variety of possible causes that allow water entry into the slab, both from above by leaks, such as around toilets or shower stalls, or from below. That includes the construction moisture that must dry out of the concrete slab into the indoor spaces. More attention has to be paid to keeping the slabs dry, especially at the slab edges, and making sure the slab is sufficiently dried out before the dwellings are closed in. The construction practice of installing a layer of sand between the bottom of the concrete slab and the polyethylene moisture barrier is one example of how slab wetting can occur that causes moisture problems. Fortunately, it is a practice that is not necessary. Lstiburek [25] has written a nice explanation of why it is important *not* to install sand layers between poly and slabs.

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. (25 mm) 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 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 gypsum wallboard 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.

Some older low income apartments in Portland, Oregon, had severe mold on the gypsum wallboard of exterior walls in bedrooms. It was found that a large number of occupants were sleeping in the bedrooms, which significantly increased the moisture generation load over what would normally be expected. In addition, the bedrooms were closed off and unheated because the occupants could not afford to heat them, nor did they see a need. Those two factors resulted in generally elevated relative humidities in the bedrooms with resultant widespread mold growth. In another similar low income housing situation with a large number of occupants, long term boiling of liquids, and insufficient heating, there was a musty smell indoors, and the walls were quite moldy behind furniture and generally moldy throughout on wall and ceiling surfaces. Because the humid indoor air leaked into the attics as a result of the stack effect, the roof framing and sheathing also was almost completely covered with black mold. Those were two cases where neither the owners nor the occupants understood the moisture ramifications of high occupancy and low indoor air temperatures.

In a mold case involving some apartments near Seattle, Washington, there was mold on the lower gypsum wallboard portions of some of the exterior walls, including the molding. The rooms with mold had mid-height concrete walls behind the sheetrock on the exterior walls, with soil coming to just below the window level outdoors. Upon investigation it was determined that the drain pipe around the perimeter of the building was buried only about six inches below the top surface of the soil surrounding the building on two sides. Furthermore, the bitumen waterproofing applied to the concrete foundation did not extend above the drain pipe location. So rain wetted the soil, which wetted the concrete wall surfaces both above and below the drain pipe, as well as the concrete slab exterior surfaces, such that liquid water readily wicked into the concrete. The air in the wall cavity behind the fiberglass wall insulation and gypsum wallboard thus became quite humid, which caused mold to grow on the gypsum wallboard. This was a problem caused by poor drainage that resulted from improper installation. Had the walls been properly waterproofed and the drain pipe installed at the base of the foundation footing, the mold growth likely would not have occurred.

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 80 to 85°F (27 to 29°C), the dew point temperature of the indoor air was just a little less than about 70°F (21°C). 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 70°F (21°C) 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 70°F (21°C) almost every day of the year, and so condensation occurred almost 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.

In another case involving a large residential indoor pool in its own separate pool building, within the first year water was found dripping down off of and badly staining large wooden roof support beams and plaster walls. Upon inspection, it was found that the roof's plywood structural sheathing/decking also was wetted and stained. Once again it was a roof condensation problem, but the cause was somewhat different. In this case the architect decided to install an interior vapor retarder that was penetrated by numerous unsealed can lights and could not be satisfactorily sealed at its edges against the support beams. So water vapor easily penetrated behind the vapor retarder and into the roof's fiberglass insulation space. It passed right through the porous insulation and condensed on the cold plywood roof decking lower surface below the roofing tiles when the decking was at a temperature below the dew point temperature of the indoor air (72°F [21°C]). In addition, the ceiling's ventilation was flawed in that there was insufficient vent area by a wide margin in the first place, and the high and low vents were placed a few feet down from the roof peak and up a few feet from the roof eaves. So there was considerable space where no ventilation at all existed. That was especially problematic at the peak. It seems clear that the architect did not understand what was going on from a moisture point of view and did not get professional assistance from someone who did. Moreover, numerous other design professionals did not understand what was causing the problem. The fix in this case was to remove the tile roof and install structural insulated panels (SIPs) that utilize rigid insulation above the roof decking with a fully sealed vapor retarder membrane between the plywood and the SIPs. That way there was no chance the humid air could get beyond the vapor retarder, and there was no need for roof ventilation.

It is frustrating to realize that mechanical engineering and architecture design professionals would make such basic design errors in pool buildings 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, including architects. 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

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 eave 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 soffit 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, along with adding bathroom exhaust fans, 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 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 [26].

Typically, about 10 % of the homes visited for weatherization already are too tight and below tightness guidelines [27] 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 (7 L/s) per person or 0.35 ACH, whichever is greater, set out originally 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 future. While low-income housing weatherization agencies have recognized that airtightening to save energy definitely can lead to moisture problems and consequent health effects, many utilities that are expanding their weatherization programs are not fully 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 significantly tightened, the more moisture and health problems we will see.

Moreover, much of our experience with interior moisture problems is with single-family detached housing. Yet it would appear that the situation with multi-family housing might be much worse. It simply has not been well 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* (albeit older) 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 [28].

With such heaters, gas log fireplaces, and residential ovens, 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 (8,800 W) unvented heater produces about 8 gal (30 L) of water per day, which is more than twice that generated by a typical family of three or four (about 3 to 4 gal [11 to 15 L] 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 has been 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.

Incidentally, 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. [29] 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 10–15 years, the ductwork of hundreds if not thousands 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 walls 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-19°F·ft^2·h/Btu (R-3.3 m^2·K/W) in walls] and relatively airtight with an air-vapor retarder causes indoor moisture problems or damage [2,30]. 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 [31], 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 or sills, or both, 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 new homes (recirculating kitchen fans that do not exhaust to the outdoors were used), and no bathroom ventilation in about half of the new 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 Whole House Mechanical Ventilation on Indoor Relative Humidity Levels

Many 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 (10 to 11 L) of water vapor per day [about 3 gal (11 L)], the majority of which is due to respiration and perspiration. 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 dehumidification, or both. 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.

The effect of continuous whole house mechanical ventilation on indoor relative humidity is shown in Fig. 1. The plot is based on the results of MOIST simulations for a typical new airtight home with somewhat high, but not unrealistic, indoor moisture generation [32]. The high moisture generation rate was assumed in order to produce elevated indoor relative humidities that might be considered too high and in need of reduction. The 50 cfm (23.6 L/s) ventilation exhaust flow rate assumed for the simulation is an actual (i.e., measured) value rather than a rated value. Measured or actual flow rates are about one half the rated values [2,30]. The flow rate assumed in the simulation is believed to be a reasonable upper limit to the amount of flow considered for indoor whole house ventilation.

As can be seen in Fig. 1, the indoor RH does not drop very much when continuous mechanical ventilation is used

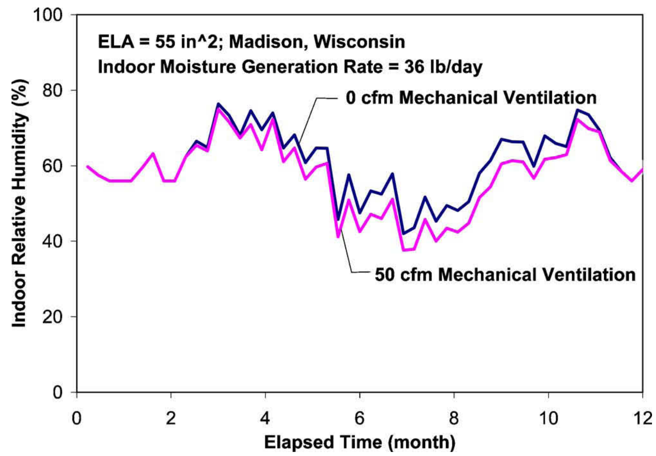


Fig. 1—The effect of whole house ventilation on indoor relative humidity.

in the Madison, Wisconsin, climate. While the indoor RH drops by as much as 6–7 % RH during the winter months, the reduction during the mild fall and spring months when indoor RH values are the highest is quite small and of little overall consequence. With or without continuous mechanical ventilation during the fall and spring months, the indoor air RH values are well above 70 %. Thus, while mechanical ventilation may be of assistance for improving overall indoor air quality, it provides only minimal moisture control. Clearly, if there is a moisture problem associated with high indoor relative humidities, whole house mechanical ventilation is not the answer, as is often assumed. In such a case, dehumidification would probably be the best alternative to maintain satisfactorily low indoor moisture levels. Of course, spot bathroom and kitchen exhaust ventilation, when it works properly and is used properly, is always helpful in removing moisture generated at its source before it mixes with the rest of the air in the dwelling so as to help reduce indoor relative humidities.

Indoor Moisture Control Using Mechanical 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 sub par 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 sometimes being augmented with additional central ventilation using air-to-air heat exchangers (AAHX) and whole house exhaust-only ventilation systems. Yet, as noted above [2,30], 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 [2,30]. Thus, a 50 ft^3/min (24 L/s) fan system has a measured flow rate of about 25 ft^3/min (12 L/s).

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 (12 L/s) airflow is measured through a nominal 50 ft^3/min (24 L/s) bathroom exhaust fan, the real additional ventilation of the house is only about 12 ft^3/min (6 L/s). 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 [33].

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 five or ten minutes (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. Dehumidistat 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, one bathroom exhaust fan was controlled with a dehumidistat. After a shower, the fan typically ran about one hour before automatically turning off [the measured flow rate was 40 ft^3/min (19 L/s)]. In addition, there is a new breed of bathroom exhaust fans that automatically turn on when there is a rapid increase in the air's relative humidity. They, along with exhaust fans that are turned by occupancy sensors, have a preset timer that will allow them to run as long as one hour and then turn them off automatically. In the author's own home two remodeled bathroom exhaust fans that automatically turn on and off (after one hour) have worked well.

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 electric dehumidifier. Dehumidification is probably the most effective strategy for houses with indoor moisture problems when source control will not or cannot work, especially in mild and humid conditions since during such times ventilation may not be particularly effective. One U.S. field study by the author [34], 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 [35,36]. There are high-capacity residential dehumidifiers that can maintain an indoor relative humidity of about 40 to 45 % while costing less to operate than a conventional residential dehumidifier; unfortunately, they have a much higher first cost.

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. Most of the larger capacity dehumidifiers sold in home improvement stores now have automatic defrost control. Since even some 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 65 to 70 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 June 2002 *Consumer Reports* magazine for assistance in selecting an appropriate model (about $200); a new 70 pints per day model that operates at low indoor temperatures is recommended. 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 high cost to do so.

In most cases, annual operating costs should be less than $50 at 12 cents/kWh. 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 [34], 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 an energy resource. In short, while there is a modest first cost to purchase the unit, in electrically heated residences, such as apartments, there is no cost for operation. In fact, if a dehumidifier is used, then the overall cost of heating the residence will actually be reduced a bit.

Newly Constructed Homes in Southern Climates

Indoor Moisture Control Using Dehumidification and Ventilation in Hot-Humid Climates

As residential cooling systems get more efficient and the cooling loads of residences are reduced, the cooling system typically does not run long enough to provide sufficient dehumidification in hot-humid climates. Thus, 20 homes were tested and monitored in Houston, Texas, to evaluate humidity control performance and operating cost of six different integrated dehumidification and ventilation systems that could be applied by production builders [37]. Fourteen houses had one of the six integrated dehumidification and ventilation systems and also met a high standard of energy efficiency criteria. Six houses were reference houses—three having the same high standard of energy efficiency measures and controlled mechanical ventilation, while three met code minimums for energy efficiency and did not have mechanical ventilation. Temperature and relative humidity were monitored at four living space locations and in the attic where the space conditioning equipment and air distribution ducts were located. Equipment operational time was monitored for heating, cooling, dehumidification, and ventilation. Results showed that energy efficiency measures, combined with controlled mechanical ventilation, change the sensible and latent cooling load fractions such that dehumidification separate from the cooling system is required to maintain indoor relative humidity below 60 % throughout the year. The system providing the best overall value, including humidity control, first cost, and operating cost, involved a standard dehumidifier located in a hall closet with a louvered door and central-fan-integrated supply ventilation with fan cycling. However, it is not clear if the cooling cost to remove the waste heat and the "free heat" [34] from the dehumidifier was taken into account in determining operating costs.

Field Studies of Exterior Moisture Problems: Crawl Spaces

There is considerable interest in the potential for moisture problems in residential crawl spaces. This is especially true in the Pacific Northwest and the southeastern United States where crawl space construction is very common. Moisture-related problems include such things as high relative humidity levels that might elevate indoor moisture levels and cause indoor health problems, mold and mildew that might cause indoor health problems, as well as high moisture levels in the crawl space wood members that could lead to wood decay and subsequent structural damage. There are concerns and limited contradictory evidence over whether the present code levels of crawl space ventilation and ground cover requirements are sufficient to prevent such problems. There are also those who believe that no ventilation is actually best, especially if a ground cover is in place to substantially reduce evaporation from the soil. At present there is a surprising lack of well-documented field evidence from the Pacific Northwest over this issue, but there are new comprehensive field results for the southeastern United States that will be discussed.

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 U.S. 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 [38]. However, it is generally believed that some ventilation is still necessary even if a ground cover is in place. The 2006 International Building Code does allow unvented crawl spaces provided either mechanical ventilation exists or conditioned air is supplied to the space, along with perimeter insulation.

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 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

Efforts to save energy in homes in heat climates 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 40°F (4°C)]. 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 [39] 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 mild but humid 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 [39]. In particular, Duff conducted two separate investigations in the Southeast in a test home built over a well-drained soil [40,41]. 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. [42] 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 [43].

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 [44]. Six of the crawl spaces had their masonry block walls insulated with 1-in. (25 mm) 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 [45]. 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.

Crawl Space Conditions in New and Existing Pacific Northwest Homes

As a part of three major field moisture studies undertaken in the Pacific Northwest [46], the crawl spaces of 121 homes were inspected during the winter for moisture problems, including mold and mildew, elevated moisture contents in wood members such as floor joists and subflooring, and wood decay. The presence of a ground cover or standing water was noted, and a check for the existence of moisture problems inside the homes also was made. The sample of homes inspected includes 29 older homes in Portland, Oregon, 37 older homes in Spokane, Washington, and 55 relatively new and energy efficient homes in the metropolitan area of Seattle to Olympia (38), the Washington coast (13), and Montana (4). Some of the older homes did not have a ground cover in their crawl space, whereas all the new ones did (as required by code), and standing water was noted in some of the crawl spaces with and without a ground cover. Both open and closed vents were observed, although open vents were the most common.

Mold and mildew in the form of very minor surface staining were only very occasionally observed in the crawl spaces, and generally speaking, there were no noticeable musty odors. In addition, the moisture content of randomly selected wood members was almost always observed to be below 20 %. While a few spot measurements of wintertime relative humidity taken in crawl spaces with ground covers in place were in the range of 50–65 %, relative humidities in the crawl spaces generally were not measured. So the impact of the crawl space conditions on the conditions inside the homes is not known. However, the homes had what is considered to be fairly high indoor relative humidities and numerous indoor moisture problems—probably due mostly to lack of adequate indoor moisture control. Finally, in all those cases, there was never a single case of elevated moisture contents near or above the fiber saturation point of about 30 % [6]. Moreover, there never was any wood decay observed, except in a very few isolated cases where plumbing leaks existed or where wood members were improperly in direct contact with the earth. Generally speaking, the crawl spaces were almost completely devoid of moisture-related problems.

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. Furthermore, in the Northwest summer rain is quite infrequent, keeping the soil relatively 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.

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 [47]. 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 0.42 lb/ft^2 (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 [48]. 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.

Monitoring of Four Conditioned Crawl Spaces in Ohio (3) and New Mexico (1)

As background for this Building Science Corporation (BSC) research, its author makes the following assertions: "conditioned crawl spaces perform better than vented crawl spaces in terms of safety, health, comfort, durability and energy consumption; in addition, conditioned crawl spaces also do not cost more to construct than vented crawl spaces; moreover, existing vented crawl spaces are experiencing serious moisture and mold problems and are costing builders and homeowners significant resources to repair." There are likely some areas in the U.S. where some of these assertions are true. It should, however, be noted that in some locations, such as the Pacific Northwest, where vented, unconditioned crawl spaces with under floor insulation are widely used, moisture problems are few and far between [46]. Thus, simply closing the vents in the wintertime to save energy may be a prudent and cost effective approach. Moreover, the allegation of reduced energy consumption does not appear to have been proven with scientific data. For example, in Oregon the building codes agency had a study undertaken to compare the heating costs of utilizing perimeter insulation with closed vents versus underfloor insulation with open vents; the use of underfloor insulation was found to be most cost effective from a life cycle cost basis.

Furthermore, the author of the BSC study asserts "that despite the obvious problems with existing vented crawl spaces and the obvious benefits of conditioned crawl spaces there is not a significant trend towards the construction of conditioned crawl spaces. One of the reasons typically cited by builders and designers is "the code does not allow me to build unvented crawl spaces." This is both generally correct and misleading. The model codes do not allow the construction of "unvented" crawl spaces—except in very limited circumstances, but they do allow the construction of "conditioned" crawl spaces. The distinction is important and necessary.

To examine the characteristics of conditioned crawl spaces, four of them were constructed and monitored over a 12-month period in Ohio and New Mexico [49]. Three of the crawl spaces were "actively" conditioned, with a supply duct providing conditioned air to them, along with transfer grilles to provide a return path to the indoor space. One of the homes in Ohio was "passively" conditioned, in that the crawl space was connected to the interior with transfer grilles only (no supply duct was provided to the crawl space). Indoor, outdoor, and crawl space temperatures and relative humidities were measured for all four homes. However, no nonconditioned, vented crawl spaces were monitored for comparison purposes. Moreover, crawl space wood member moisture contents were not measured in this study.

It was concluded that the active conditioning, as expected, did a much better job of controlling conditions in the crawl spaces. That was fortuitous since building codes allow active conditioning as an alternative to passive, natural ventilation (see the 2006 International Building Code, Section 1203.3). It is noted in the report that "there will always be situations where "active" conditioning is unnecessary—such as dry climates and where small crawl spaces are well connected to conditioned basement spaces." New Mexico is such a dry climate, and so it is not clear if active or any crawl space conditioning is necessary there to avoid moisture problems. It would seem that a conventional vented crawl space would work quite well, especially with a ground cover in place. It would likely perform just as well from a moisture point of view if the vents were closed, and that would save energy. Unfortunately, as noted earlier, no vented (or unvented), nonconditioned crawl space was studied in that climate to allow a proper comparison of their performance from a moisture point of view.

There are even wet climates such as the Pacific Northwest where a conditioned crawl space is not necessary if the purpose of conditioning is only to avoid moisture problems. They are typically not a problem there, largely because crawl spaces there are dry in the winter and the nonhumid summer weather largely without rain does not cause moisture problems with vented crawl spaces like it does in climates that are humid in the summer and where it regularly rains. In the BSC report code issues regarding conditioned crawl spaces are dealt with at length, and the data are used to support the current code requirements for the construction of conditioned crawl spaces.

North Carolina Crawl Space Venting Versus Nonventing Moisture Study

The most extensive research on vented versus nonvented crawl spaces to date has been done by the Buildings Group at the Advanced Energy organization in North Carolina. Their latest study [50] compared the performance of closed crawl spaces, which had sealed foundation wall vents, a sealed polyethylene film liner, and 1.0 ft^3/min (0.5 L/s) of air supplied by a heating, ventilating, and air conditioning (HVAC) system for each 30 ft^2 (2.8 m^2) of crawl space ground surface, to traditional vented crawl spaces with wall vents and polyethylene film covering 100 % of the ground surface. The study was conducted at 12 owner-occupied, all electric, single-family detached houses with the same floor plan and located on one cul-de-sac in the southeastern United States. Using the matched pairs approach, the houses were divided into three study groups of four houses each. Comparative moisture measurements for these crawl spaces and submetered heat pump kWh use were recorded. Findings supported that, for the humid conditions of the southeastern United States, properly closed crawl spaces were a robust measure that produced substantially drier crawl spaces and significantly reduced occupied space conditioning energy use on an annual basis. One of the significant findings of this research was that some type of supplemental drying mechanism, in addition to closed vents, was required in crawl spaces in the southeastern United States. Just closing the vents was not sufficient to avoid moisture problems in the southeastern United States. For homes with HVAC systems with ducts in the crawl spaces, adding supply air into the crawl space worked well. Alternatively, for homes without ducts, dehumidification in the crawl space is another strategy that should work.

ASHRAE Recommended Practices for Controlling Moisture in Crawl Spaces

It would be remiss not to mention the full collection of papers from a 1994 ASHRAE meeting symposium that address a variety of issues regarding crawl spaces [51]. A number of the papers describing field studies have already been discussed in this crawl space section. However, some of the various symposium papers provide valuable input regarding a variety of other issues related to moisture control in crawl spaces. One of the papers includes laboratory test results of air flow through crawl space vents; those results are at odds with conventional wisdom regarding code vent area requirements. In addition, for those concerned with controlling moisture in crawl spaces, the *ASHRAE Journal* article titled "Crawl Space Myths" is recommended reading [52].

Field Studies of Exterior Moisture Conditions: Basements

Underground Space Center Basement Foam Insulation Study

The thermal performance of both exterior and interior full wall R-10 ft2·h·°F/Btu (R-1.8 $m^2 \cdot K/W$) 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 [53,54]. Both poured masonry and concrete block walls were examined with the basement temperature maintained at 68°F (20°C). 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 module 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 (13.6 and 25.0 L). In comparison, the block module insulated on the exterior yielded only between 2.5 and 5.7 gal per week (9.5 and 21.6 L 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 might 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 Exterior Moisture Problems: 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 [55] 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. Salient 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. [56] 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 was also 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. [57] 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-facing 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 [58–60]. 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 vapor 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 Field 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 [2,30]. 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 [61]. 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 soffit 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. Of course, reducing indoor relative humidities will also help reduce attic moisture problems, and there are a wide variety of ways of doing that.

Field Studies of Exterior Moisture Problems: Roofing

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 [62]. The roofs were wood-framed with plywood inner and outer deck surfaces, R-11 $ft^2 \cdot h \cdot °F/Btu$ (R-1.9 $m^2 \cdot K/W$) 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 was also 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 is not. This is obviously not a unique case, but rather is one of many that happen to be documented in the literature.

Structural Insulated Panel (SIP) Roof Problems in Alaska

In about 20 multi-family dwellings built prior to 1996 in Juneau, Alaska, moisture damage to SIP (structural insulated panels) roofs was observed. The moisture damage occurred at the top OSB skin of the panels that were constructed with rigid insulation sandwiched between two OSB skins. An independent panel of experts was convened by the Structural Insulated Panel Association to investigate the problem [63].

The pattern of damage in the SIP roofs investigated was concentrated at the panel seams towards the ridges of roof assemblies. Warm moisture-laden air exfiltrated at gaps in the SIP joints and migrated upwards within the joints toward the roof ridges, depositing moisture at the upper cooler exterior surfaces along the way. That resulted in wetting of the upper surfaces of the panel joints, OSB panel edges, and the underside of the roofing paper. That resulted in structural degradation.

After their assessment, the team of experts concluded that the cause of the damage fell into three categories: the lack of closure at the joints due to lack of sealant, or the lack of a continuous sealant, or the failure of sealant at the joints. In the first category, virtually no effort was made to obtain an airtight joint. No sealant of any kind was installed. So these assemblies clearly failed due to improper workmanship. In the second category, sealant was applied, but the applied sealant was clearly installed in a haphazard manner. In those assemblies the failure again was due to poor workmanship. Poor detailing at the ridges was common. Air sealing was ineffectual due to lack of effort. In the third failure mode, it appeared that the sealants themselves failed in adhesion. The panel opined that the application of sealants in the appropriate location under typical weather conditions in Juneau, Alaska, was a major issue. They also found that, where joints were sealed, particularly at lower interior surfaces, there was no damage. They felt that, had the joints been sealed at panel perimeters at the lower interior surfaces, failures would not have occurred. In addition, they noted that the absence of damage away from panel edges or within the plane of the panels discounted vapor diffusion or the lack of a vapor barrier as a causal factor.

A Comprehensive Hygrothermal Investigation of an Unvented Energy-Efficient Roof Assembly in the Pacific Northwest

A study of the hygrothermal properties of a vented flat roof assembly in a wood-framed multistory apartment building in the Pacific Northwest was undertaken to investigate the consistent premature failures [64]. Moisture and temperature sensors were installed in four locations in the roof assembly; sensors were in place one year in the old assembly and one year after a new assembly was installed. In the new assembly rigid insulation was placed on the exterior side of the sheathing, directly under the roof membrane, and the passive attic ventilation was sealed. Hygrothermal computer simulation software, MOISTURE-EXPERT V1.2, was utilized to investigate the existing roof assembly and the alternate assembly. The computer simulation demonstrated the extreme sensitivity to interior air leakage to the existing roof assembly and the robust design of the unvented insulated roof assembly. Field data revealed the original roof assembly experienced moisture contents on the underside of the roof sheathing greater than 30 % for several months of the year, with a net yearly accumulation of moisture. The authors concluded this roof assembly should not be used in the Pacific Northwest. The new unvented roof assembly did not experience moisture contents in the roof sheathing over 18 %. The addition of the insulation above the sheathing kept it warm and free of condensation. This assembly rendered passive attic ventilation irrelevant.

Laboratory Studies of Exterior Moisture Problems: Roofing

Building Research Association of New Zealand Study

Solar Driven Moisture Transport 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 [65]. 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 follow-up 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.

Laboratory Study of Exterior Moisture Problems: Siding

Buckling of Shiplap Hardboard Siding[2]

Widespread waviness and buckling of 0.5 in. (12 mm) thick shiplap hardboard siding was observed at a single-family housing development near Fresno, California. The vast majority of the buckling was caused by improper lack of restraint of the siding due to nail spacing being greater than 16 in. (0.41 m) o.c. Such nail spacing on hardboard siding was a building code violation at the time of the construction and was considered a construction error. Sometimes the studs themselves were spaced more than 16 in. (0.41 m) o.c., and sometimes nails missed a middle stud or there were no nails into some studs such that the nail spacing was 32 in. (0.82 m). Sometimes a very large nail spacing existed because nails were not installed in a number of adjacent studs. Stud spacings of about 18–24 in. (0.46–0.61 m) were common on numerous homes, while spacings as large as 48 in. (1.2 m) were measured.

Calculations of the amount of buckling as a function of the nailing/stud spacing were completed using an equation by Spalt and Sutton [66]. The results showed a significant impact of nail spacings greater than 16 in. (0.41 m) o.c. on the amount of buckling. The greater the spacing, the greater the amount of buckling. That calculation result was generally noted in the field.

Generally speaking, siding properly nailed on 16 in. (0.41 m) centers did not buckle, as the calculations predicted. In about 8–12 cases, however, siding properly installed on 16 in. (0.41 m) centers did indeed buckle, even after the initially buckled siding was replaced. It was alleged that buckling of siding nailed on 16 in. (0.41 m) centers would occur simply due to its exposure to the humid winter outdoor air. Computer modeling of the moisture performance of the siding using the MOIST software [67] showed that lack of an interior warm side vapor retarder in the walls resulted in a substantial increase in the siding moisture content and very likely caused the buckling of siding nailed on 16 in. (0.41 m) centers. The model predicted that the summer low siding moisture content was about 5 %. It also predicted that the maximum winter moisture content of the siding with a vapor retarder in place was about 7 %, whereas without it (almost all the homes did *not* have one) the peak moisture content was about 17 %. That is a significant difference. Thus the lack of a vapor retarder in and of itself very likely caused the buckling in those walls with siding nailed to studs on 16 in. (0.41 m) centers and contributed to the buckling that occurred with stud spacing greater than 16 in. (0.41 m) o.c.

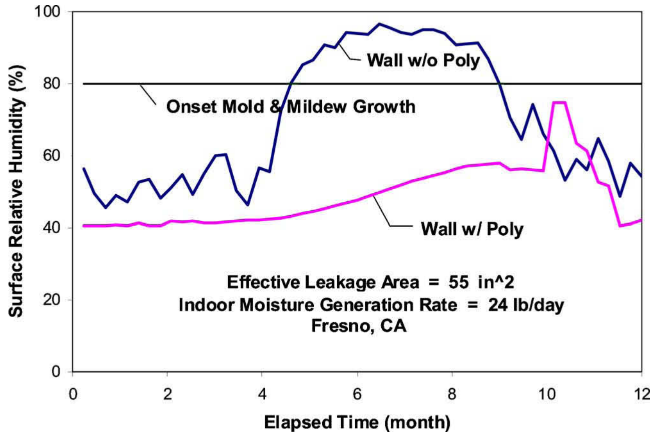


Fig. 2—The effect of the presence of a polyethylene interior vapor retarder on the surface relative humidity at the building paper.

The modeling also showed that the lack of an interior vapor retarder led to surface relative humidities at the building paper of greater than 80 % for more than a month, the critical threshold for the growth of mold and mildew [1] (see Fig. 2). In fact, there was widespread growth of mold and mildew on the grade D building paper, and that is highly unusual in that climate for walls with hardboard siding with a continuous vapor retarder installed as required by all hardboard siding manufacturers. Incidentally, there was no mold on the building paper right behind the studs, again indicating that the moisture source for the mold growth was vapor diffusion from indoors.

Laboratory testing at the U.S. Forest Products Laboratory by McNatt [68] and unpublished testing for a law suit at Portland State University (PSU) by the author of this chapter clearly showed that hardboard shiplap siding does not buckle when nailed to studs spaced 16 in. (0.41 m) o.c. The PSU tests involved spraying large amounts of water on test walls continuously for eight weeks. The test results also showed that siding waviness did occur with nail/stud spacings of 24 in. (0.61 m) and 32 in. (0.81 m). Yet the siding in those tests did not buckle according to the American Hardboard Association definition of buckling being deformation greater than one-quarter inch out of plane between studs. The only source of any siding moisture gain in those spray tests was the outside painted surface of the siding, which was maintained at a surface relative humidity of close to 100 % for the eight week test period. Surprisingly, the siding's moisture content only increased by about 5 % during the eight week test. There simply was not enough moisture gain into the siding to cause it to "buckle," even with large nail spacings. That is most likely due to the lack of sufficient moisture gain into the siding in those PSU tests due to the lack of moisture migration from moisture laden *indoor* air

[2] Includes a companion computer simulation study of the moisture performance of the siding.

into the backside of the siding. In the actual homes, which were fairly airtight (0.30 ach) and relatively humid, there was no vapor retarder in the walls and clear evidence that enough moisture got to the back of the siding for mold to grow on the building paper. For buckling to occur either there has to be no vapor retarder in the wall such that backside wetting occurs because of vapor diffusion, or else the backside has to get wet from leaks from construction errors. Buckling caused by leaking behind the siding did not appear to be at all widespread in the housing development.

This case study involving site inspection with siding removal, laboratory buckling testing, and computer modeling has provided important new insights about the causes of buckling, the clear need for an interior vapor retarder even in a mild mixed climate like that of Fresno, California (2,500 heating degree-days), and the relevancy of techniques involving only one side exterior wetting used by the American Plywood Association for laboratory buckle testing of different siding products [69].

Buckling of Plywood and Hardboard Panel Siding

A comprehensive study of buckling of panel-type siding products (not lap siding) was undertaken by the American Plywood Association [69]. One of the objectives was to assess the stability performance of wood-based siding panels under severe moisture conditions that may exist during service life. Unfortunately, the study did not include the investigation of panel wetting on its back side, such as might occur without an interior warm side vapor retarder in place, or wetting caused by leaks on the back side of the panels. Both effects are likely at least as important to the overall buckling behavior of panel siding as the methods tested. The study included a comprehensive review of moisture exposure cycles developed by other researchers.

Large scale wall testing involved a three week interval of continuous wetting on the unfinished exposed surface of the panels to simulate severe in-service conditions. Contour data indicating the wall contours were measured and evaluated. There was a wide variation in buckle performance for the broad range of products tested. The baseline physical and mechanical properties of the various siding products also was evaluated using a variety of test techniques, including oven-dry/vacuum-pressure-soak moisture cycles to evaluate dimensional changes, wet-one-side moisture cycles to simulate rain exposure, 50–90 % relative humidity exposure cycles to evaluate linear expansion changes that can occur with humidity variations, and an edge wick test to evaluate edge swell after wetting, freezing, and drying. In addition, edge checking was visually evaluated on siding products that were exposed to three-and-one-half years of exterior weathering at the APA exposure fence in Tacoma, Washington. The bending stiffness and compressive stiffness of the siding panels were evaluated. A variety of small-scale tests also were undertaken to determine if simpler alternatives to the large scale tests could be developed. While most were not particularly successful, a stability coefficient based on panel properties was most accurately able to predict the buckling performance demonstrated on the large scale wall.

Field Studies of Exterior Wall Moisture Problems

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 [70] 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 [71] 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 of this chapter) that are discussed next.

The Portland and Spokane Studies

In Portland, Oregon (4,732 DD) and Spokane, Washington (6,835 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 [11,12]. 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 70s.

From the wall-opening measurements in the two studies, no high wood moisture contents above 20% were noted out of 5,234 wall cavity wood member readings, except where leaks, or wood members in contact with soil, or "splashback" was found. 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 dries 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 is 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.

Cases of Wood Decay Associated with an Exterior Vapor Retarder

Background on a Potentially Serious Moisture Problem

Residences in the Pacific Northwest and in other northern heating climates are conventionally built with wood-framed walls. Older existing site-built homes typically do not have a dedicated vapor retarder anywhere in the walls, whereas newly constructed homes in those climates most commonly have a vapor retarder on the inside of the wall cavity, usually right behind the gypsum wallboard. Typically it takes the form of polyethylene sheet or asphalt-impregnated kraft paper backing on fiberglass insulation batts. Sometimes code agencies (such as in the state of Washington) allow the use of vapor barrier paints with a perm rating equal to or less than one as an alternative to the two aforementioned approaches. Typically, pva sealers or primers are used rather than paints rated as a vapor barrier with a perm rating of one or less. However, the in-place perm ratings of the primers and sealers that are labeled as vapor barriers are typically greater than one perm, and so they are not an appropriate vapor retarder. Most new manufactured homes, as well as many older mobile homes, also have vapor retarders on the interior side of exterior walls (and ceilings).

The purpose of installing a vapor retarder on the warm side of the wall cavity in northern heating climates is to minimize the diffusion of water vapor into the wall cavity from the indoor spaces during the heating season [18]. That helps prevent or reduce the incidence of wall moisture problems such as elevated moisture contents in the wall components or attendant mold or decay, as well as other potential problems, including cladding buckling, cupping, and splitting, or reduced service life of the cladding's paint.

In some cases, a vapor barrier exists on the outside, rather than on the inside, of the wall cavity in northern heating climates. That, unfortunately, acts to trap moisture within the wall cavity that would otherwise migrate out, which can result in serious moisture buildup with its resultant problems.

As an example, many older mobile homes, especially those built before the 1980s, were manufactured with a vapor retarder on the outside of the wall cavity—typically right behind the metal (or sometimes wood) siding. Vapor retarder materials applied continuously included polyethylene sheet, thin foam with kraft paper coatings on each side of the foam, and asphalt-impregnated kraft paper. The purpose apparently was to keep moisture that condensed on the backside of the metal (or wood) siding from wetting the insulation.

Unfortunately, the exterior vapor retarder (EVR) traps moisture migrating as a vapor through the wall cavity from the inside to the outside during the heating season. In the case of the older mobile homes, the vapor condenses during cold weather on the inside surface of the vapor retarder, runs down it, and collects on the bottom plate or rim joist or elsewhere. Sufficient moisture builds up within wood members to lead to wood decay.

A number of U.S. Department of Energy research projects undertaken in the Pacific Northwest [2,11,12,30] have conclusively shown that in conventionally-constructed walls without an EVR located in northern heating climates there is no evidence of wood decay occurring, except when caused by leaks or wood members directly in contact with earth. Thus decay in walls is not expected to occur under normal conditions, especially in older homes. In fact, there is almost no field evidence of decay occurring in conventionally constructed walls without leaks, whether they are site built or manufactured. However, the presence of an EVR can cause mold growth and wood decay with its resultant structural damage. There are four cases of wood decay associated with an EVR to be discussed in the following sections.

Tri State Homes

As noted in an earlier section, the first known cases of extensive decay in the plywood sheathing and wall framing members of hundreds, if not thousands, of manufactured homes involved the Tri State Homes built in Wisconsin, Minnesota, and Michigan between 1972 and 1982 (the company has since gone bankrupt). After 1986, extensive wall wood decay was reported. The decay was initially attributed to high levels of indoor moisture [15], but based on later field studies and computer simulation results, the primary cause was determined to be the presence of an EVR that trapped moisture within the wall cavity [17]. The low permeability retarder was the building paper improperly located on the outside of the plywood sheathing behind hardboard lap siding; its permeability was measured and found on average to be 0.65 perms [38 ng/(s-m^2-Pa)]. The EVR trapped water vapor migrating from indoors by vapor diffusion in the plywood sheathing. There was no interior vapor retarder to retard vapor diffusion [18]. Thus, the presence of the EVR and the lack of an interior vapor retarder caused the plywood to get much wetter than normal during the winter and spring, and it reduced the rate of drying of the plywood. Because of that, the wood was still quite wet in the early summer when temperatures were high enough to promote the growth of decay fungi. The result was severe and extensive rotting of the plywood sheathing that occurred over a span of many years. But the decay progressed slowly each late spring and early summer before the sheathing finally dried out, such that it was only first noticed about 14 years after the first homes were built. Moreover, the wet wall conditions led to the growth of substantial mold that seriously impacted the health of many of the occupants [16].

Early site visits and a home inspection program revealed decay in fewer than half the homes. Nonetheless, the number of homes with decay was substantial [15]. 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 and essentially none to the hardboard siding. There was significant deterioration of the building paper in many locations.

According to Merrill and TenWolde [15], a survey of homeowners and air tightness 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 were tight (about 0.3 ACH from blower door tests using the LBL methodology [31]), they were not extremely so, and many others in that region were 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 from a later field study and computer modeling for 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 [17]. 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 EVR that trapped moisture within the wall cavities. While the wetting potential of the walls was relatively high, the drying potential was rather poor. Infrared thermography results as part of the later field study ruled out the possibility of air leakage playing a significant role in the moisture migration.

During the later field study mentioned earlier [17], an inspection of 17 Tri State homes in Wisconsin that had siding removed (completely in 11 of the cases) revealed that 15 had plywood decay and 12 of the 15 cases were severe enough that the plywood could be torn apart by hand. Nine of the 11 homes with siding completely removed had decay present. Many of the walls were unusually wet during winter and early spring, while plywood moisture contents well above 60 % (the meter limit) were measured during late June and early July when the plywood in a conventionally constructed wall is considerably drier. The plywood moisture contents measured in the Tri State homes during that early summer, as well as during the previous winter and early spring, were higher than the highest values measured in any of the three Pacific Northwest wall moisture studies [2,11,12,30]. It is conjectured that most, if not all, of the Tri State homes either already have experienced or eventually will experience severe plywood decay with its associated structural deterioration. Plywood delamination also was observed in eight of ten of the cases.

While it has long been noted that the outside layers of a wall should be less permeable than the inside layers [18], these results dramatically emphasize the catastrophic results that can occur when the rule is not followed.

A comparison of sheathing and siding moisture levels for walls with and without an EVR also was undertaken using the MOIST computer model developed at NIST [66]. The modeling results further reinforced the field inspection finding that the EVR was the cause of the structural damage. The results clearly showed that the sheathing stayed wet much longer into warm weather when decay fungi can readily grow with an EVR than without one.

The one major factor that is different about these homes is the unusual wall construction. Had no cold EVR 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.

RCDP Mobile Home Weatherization Project

As part of a Pacific Northwest field study initiated by the Bonneville Power Administration (BPA) RCDP program to study the impact of weatherization on moisture conditions in existing mobile homes, the exterior siding (mostly metal) of walls of twelve older mobile homes in Butte, Montana; Shelley, Idaho (near Idaho Falls); Shelton, Washington (near Olympia); and Redmond, Oregon (near Bend) was temporarily removed to install moisture monitoring sensors (wood member moisture content, relative humidity, and temperature). Siding was typically removed in two small sections of the wall. It was noted that some of the homes had an EVR in place just inside the siding [72].

In several cases where an EVR was present, extensive condensed moisture was noted on the inside surface of the retarders, which most typically was clear polyethylene sheet. Often the bottom sole plate was relatively wet from the condensed water dripping down onto it. Measured maximum wall cavity wood member moisture contents were 33, 44, and 52 % for three of those homes. Most importantly, decay was present in structural wood members of four homes with an exterior vapor retarder (three in Washington and one in Oregon). Decay was mainly noted in the sole plate and the rim joist (header); some of it was isolated and relatively minor, but some was major. In one case a whole corner was rotted and lacked structural integrity. The decay could be even more extensive if all the siding was removed and the rest of the wall areas were inspected. Notably, there was no decay found in any of the homes that did not have an exterior vapor retarder. Moreover, for those homes the maximum wall cavity wood member moisture content was less than 16 %, which is considerably drier than the maximums noted above for walls with an EVR.

The structural wood moisture content later continuously measured in the wall of one of the Shelton, Washington, houses with an EVR exceeded 40 % (excessively wet), and then the sensor signal went off scale. Upon subsequent inspection of the wall cavity, water was noted pooling on the bottom plate leading to the elevated moisture content and eventual shorting of the moisture content monitoring pins in the plate.

These findings suggest that the presence of an exterior vapor retarder in the walls of older mobile homes contributes to elevated wall moisture levels and structural deterioration. Clearly it would not be prudent to perform any weatherization that would air tighten such homes, such as interior or exterior sealing or insulating (especially dense pack cellulose) or replacing windows. That could lead to higher indoor air moisture levels and, thus, to more condensed water in the walls and a greater chance of even more extensive wood decay. The lifetimes of the affected mobile homes could be jeopardized. Previous BPA research [2] has shown that wall wood member moisture contents increase when indoor relative humidity levels increase. In addition, there could be serious health repercussions associated with air tightening homes with an EVR. Utility and low income housing agencies need to be made aware of these findings.

Clearly, further research is needed to provide a solution to this problem. Computer modeling to predict and compare moisture accumulation conditions in walls with and without exterior vapor retarders in a wide variety of climates needs to be undertaken. It may turn out that some locations are less susceptible to this moisture problem. In addition, more extensive field surveys of a large sample of older mobile homes should be initiated to determine the extent of the problem. This probably should be done to older mobile homes located in both mild and colder climates since the conditions are so very different.

Finally, possible remedial actions should be explored. That might include removing the entire exterior vapor barrier, or removing it and replacing it with a vapor permeable barrier such as a housewrap, or simply cutting the retarder open at the bottom of the wall cavity. It might be possible to add small vents through the siding and the adjacent vapor retarder, although that is not advisable at present. All these possible solutions need to be explored and compared, probably with side-by-side field testing.

The presence of the exterior vapor retarder may actually act as an air barrier that impedes natural drying but also makes the house tighter. That would then increase indoor relative humidities that would lead to elevated moisture levels in the wall cavities. That too needs to be explored. Indoor moisture control using dehumidification may be necessary.

However, until this issue is fully resolved, it is recommended that if any weatherization that would air tighten an older mobile home is planned, the walls need to be opened to check for the presence of an EVR. That is fairly quick and easy. If one is present, weatherization on that type home needs to be temporarily delayed until satisfactory remedial actions are available in the future. If agencies proceed with weatherization of these type mobile homes, then they may make a bad situation worse. The large numbers of older mobile homes that are inspected and found to not have an EVR can be weatherized as planned.

Vinyl-Sided Multi-Family Housing in the Pacific Northwest

A large three-story wood-framed apartment complex near Portland, Oregon, was found to have indoor mold problems soon after construction was completed. It was felt that windows were leaking, and that was contributing to the mold growth. As a result, vinyl siding was removed to check for window leakage. Problems with improper application of window flashing and wall housewrap were noted, and all the siding was removed to fix those problems. In addition, it was noted that wet construction materials were not allowed to dry out sufficiently. Once some of the housewrap was removed, it was then discovered that there were water stain marks all over the outside surfaces of the gypsum sheathing that was right behind the housewrap. It looked like water was draining down the gypsum sheathing, not only around windows, but everywhere. Upon removal of all the housewrap and the gypsum sheathing, it was found that the OSB structural sheathing and some of the framing members were decayed in many areas—often badly.

Initially, it was felt that the decay was due to window leakage, as some of the decay was clearly around windows. However, decay was noted in many locations well away from windows, and especially high on the third story walls just below a roughly four foot wide overhang. It was clear that the water staining on the gypsum sheathing and the decay on the OSB in that area was not due to rain water leaks.

It was concluded that the cause of the staining and the decay was condensation of water vapor within the outer layers of the wall cavity. The vinyl siding was acting as an exterior vapor retarder, trapping the moisture migrating by both diffusion and air convection from the inside of the apartments toward the outdoors. Some of the moisture was clearly condensing in the OSB, resulting in elevated moisture contents and eventual decay. Some of the water vapor also migrated through the gypsum sheathing, as it is fairly permeable. Finally, some of the water vapor migrated all the way to the housewrap, the coldest surface inside the vinyl siding, where it condensed and drained down it and the adjacent outside surface of the gypsum sheathing—thus leaving it badly stained.

It is widely believed that vinyl siding is quite breathable and not an EVR. For example, it is often stated that it has multiple weep holes on its drip edges that would allow it to drain and breath. Sometimes it is stated that the siding is loose and that should allow it to breath. Clearly the vinyl siding material itself is not at all permeable, so the only way it can breath is through the weep holes or if the siding is loosely held in place. It did not appear to be loosely held in place in the case of this development. However, in this case there were only a few very widely-spaced, very small weep holes in some of the drip edges. Interestingly, the weep holes are actually blocked because of the way adjoining pieces interlock. Thus, those few vent holes simply did not allow it to breath or drain well enough.

It should be noted that some of the mold originally observed after construction was caused by wetting of the concrete slab-on-grade floors. The slab edges were not protected from wetting by the moist adjacent soil during the rainy non-summer season. Thus, the indoor environment was somewhat more humid than what is typically found with multi-family residences—especially those with crawl spaces rather than slab-on-grade construction. That may have been a contributing factor to the condensation and subsequent wall damage.

Another two-story wood-framed apartment building in Portland was found to have severe structural damage to the rim joist between floors and nearby wood components, including the gypsum and structural plywood sheathing. The gypsum sheathing was often heavily water stained in other areas in a pattern that could only be caused by condensation on the back side of the vinyl siding. All of the damage was clearly a result of the presence of vinyl siding acting as an EVR. The severe damage between floors was evidence of air leakage in that area as a contributing factor. As will be noted shortly, damage between floors is not uncommon with vinyl-sided buildings, although that by no means is the only location of damage.

I also have observed wall damage in Seattle, Washington, area apartment houses and townhouses with vinyl siding. In those cases I have observed the back side of vinyl siding that is dripping wet with condensation during cold winter weather. Oftentimes, water collects in the siding ridges on the back side and drips down the outside of the wall when the siding is opened up from its bottom edges. The weather resistant barrier (sometimes building paper and sometimes housewrap) is wetted, any gypsum sheathing (both paper-faced and fiberglass-faced) is wetted and stained and even deteriorated, and in many cases the structural sheathing such as OSB is wet, moldy, and sometimes even decayed. While condensation is observed on all wall orientations, it is typically worst on the north-facing walls. Water was observed leaking from the base of walls and ponding on breezeway walkways.

In another low income multi-family apartment complex in eastern Washington, where it is colder than in Portland or Seattle, I also have observed water actually dripping out from behind the vinyl siding in mild spring weather. When the siding was opened up, water dripped out, the back side of the siding was dripping wet, and the paper-faced gypsum sheathing was water stained and deteriorated. In addition, I observed truss-joist rim joists between floors were decayed on the north-facing wall. At that complex during colder winter weather others observed water that had leaked from vinyl siding joints that was frozen and also accumulated in breezeway walkways where it froze.

To my knowledge there is not a lot of experience with scientific investigations aimed at inspecting for moisture damage behind vinyl siding. However, in speaking with a number of remodeling and siding contractors in various parts of the country where the winter climate is cold, it seems clear that damage behind vinyl siding such as was noted in the Pacific Northwest is not unique. It remains to be seen if this problem is widespread or not. The fact that the siding itself does not decay or show evidence of any problems behind it may be hiding a serious problem in the wall cavities behind the siding. Only time will tell.

Decay in SIP Walls with Vinyl Siding in Alaska

Decay has been observed in multi-family housing walls constructed with vinyl siding over woven housewrap over SIPs (structural insulated panels) [73]. The SIPs are constructed with oriented strand board (OSB) faces on each side of rigid foam insulation. When the vinyl siding was removed, along with the housewrap behind it, "it rained on us from behind the housewrap." OSB decay was discovered on both sides of some of the insulated panels. When interior finishes were removed, sometimes hidden decay on the interior OSB was observed. Oftentimes the decay was extremely severe such that the OSB had no structural integrity.

Members of the construction company repairing the walls felt that the source of the moisture rotting the wall panels was mostly interior moisture, not rain penetration. This would appear to be another example of condensation occurring because of the existence of vinyl siding acting as an EVR trapping water vapor migrating from the indoors.

These last two examples suggest that there may be a huge deterioration problem with vinyl sided walls. Typically such siding does not exhibit damage on the outside that would make one want to open up the walls. So they usually do not get opened. Thus, any damage, such as that noted above, goes unnoticed. It may be worthwhile to undertake a field study to open up and examine vinyl-sided walls in cold climates to see if there really is a problem or not. It would be important in such a study to determine if weep holes really work or not as a means of getting moisture out of the wall cavities. At present we do not know if the above examples of damage in vinyl-sided walls are isolated anomalies or if they are just the tip of the iceberg.

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 [74]. 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 [11,12] 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 [2,30], 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 [2,30] 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.

Canadian (CMHC) Field Studies of the Water Penetration Performance of Windows

A number of field survey studies of water leakage into building envelopes have been undertaken over the years in Canada, with many undertaken in British Columbia. As a result of those studies, it has been found that windows are one of the main water leakage entry points into building envelopes and especially into wall cavities of multi-unit residential buildings. The results of those field surveys were assessed by the Canada Mortgage and Housing Corporation (CMHC) and the British Columbia provincial Homeowner Protection Office (HPO) to examine window performance [75]. It was reported that most, if not all, windows are prone to significant water leakage. Manufacturing, building design, installation, and maintenance were all contributing factors. More than half of new windows let water get past the operable glazing in factory testing. In on-site quality-control inspections using a different test method, 35 to 48 % of newly installed windows were found to leak through the window unit itself, through joints between the window and the rough opening, or both.

They found that the passage of time does not make the problem go away. After several years in service, the incidence of leaks rose because of deterioration and wear and tear. Windows in homes performed worse than commercial windows: 100 % of installed residential windows examined after years of service were found to leak either through the window unit itself or at points of attachment to the building.

While the report draws data from only a few hundred windows, all made in Canada and without brand identification, it was felt that the observations in the report apply to any company's windows in the United States or Canada. Moreover, all types of windows have a high risk of water penetration due to causal factors related to the window-to-wall interface. Even the best made windows could be damaged during shipping or installation. So they felt that designers today should take the approach that any window may allow water through at some time, and you should design the wall to handle that water.

The dominant leakage path found based on frequency of occurrence was identified as through the window-to-wall assembly interface to the adjacent wall assembly. That includes head, sill, and jambs, as well as leakage at coupler mullions or corner posts between two adjacent window assemblies. A high risk of consequential damage also was found to exist for leaks through the window itself to the adjacent wall assembly. A key factor in addressing the dominant leakage paths and improving window performance is the provision of sub sill drainage capability. The focus should be on getting water that leaks in out of the wall. A companion project to the study addressed water penetration issues associated with windows in the context of codes, standards, and certification processes [76].

Newly Constructed Homes in Northern Climates

National Bureau of Standards Insulating Sheathing Tests

Burch et al. [77] 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 [78,79]. 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 1,200 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 [80] 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 [81] 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 [82,83]. 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 [2,30].

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 professionals, building scientists, 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 [81] in the wood studs of seven occupied homes that had a low permeance foam sheathing, with or without a non-insulating 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 [2,30]. 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 under these conditions 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 [17]. In those homes, severe wall structural damage occurred due to wood decay, but the homes were about 14 years old before the damage was discovered. Incidentally, 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 [2,30].

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 a housewrap 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 leads 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 [84]. Burch et al. [77] 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 this 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 [2,30]; 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 [2,30] 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 [85]. 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 [61]. 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 that 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 flow meter.

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 in [11].

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 cellulose 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 [86]. 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 pre-installation 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 [47]. 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 [2,30] 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 0.42 lb/ft^2 (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.

Pacific Northwest Natural Exposure Test (NET) Facility Wall Study [3]

Concerns have arisen after extensive excess moisture-related wall damage has been found in residences in the Pacific Northwest of the United States and Canada. Thus, a comprehensive study [87] was undertaken by Washington State University (WSU) and Oak Ridge National Laboratory (ORNL) to help design wood-frame walls that are both energy efficient and moisture tolerant in the climate of the Pacific Northwest. The goals of the study were to test wall assemblies in the context of actual interior and exterior environmental loads, to test the hygrothermal response of specific building materials, and to undertake advanced hygrothermal modeling with specific emphasis on model verification. As part of that overall study, a fully instrumented natural exposure test facility or test hut was built to test twelve different full-scale 4 by 9 ft (1.2 by 2.7 m) wall sections. Instrumentation includes temperature, humidity, and moisture sensors, along with a limited number of heat flux transducers and outdoor weather parameters. One aim of the study was to examine the potential for mold growth in the various selected wall sections.

To date, tests have been run for more than one full year on stucco walls with and without ventilation. Vapor barriers have been found to be important in the Northwest climate. Moreover, fully ventilated cladding outperforms vented cladding, and significantly outperforms cladding without ventilation. Further tests will provide information comparing cladding types, structural sheathing board types, and insulation methods.

[3] This study includes computer modeling of the moisture performance of selected walls and laboratory tests to determine hygrothermal properties of selected wall component construction materials.

Airflows and Moisture Conditions in Residential Walls

Unintentional airflow in exterior framed walls frequently causes diminished thermal performance. Furthermore, even very small infiltrative or exfiltrative airflows with little or no effect on the thermal performance are capable of voiding the moisture protection provided by a vapor retarder. Combined with high indoor or outdoor humidity, such walls may accumulate excessive amounts of moisture. However, more data were needed on airflows in and through wall assemblies and the effect of airflows on moisture conditions in walls. Therefore, 20 wood-frame walls of ten different designs, characteristic of walls of manufactured homes, were constructed and installed in a test building near Madison, Wisconsin. In-place pressurization and depressurization tests were performed to separately determine the airtightness of the interior and exterior membranes of the wall. Air pressure differences across these walls were monitored during an entire winter season, along with temperatures and moisture conditions in the walls [88].

The measurements showed that providing wall cavity ventilation may cause pressurization of the wall cavity and can lead to a significant increase in air leakage and heat loss without reliably providing the intended protection from moisture accumulation in the cavity. Although several of the walls experienced condensation and mold growth, the moisture conditions in the walls showed no clear correlation with airtightness or with the amount of air flowing through the wall. Indoor humidity correlated strongly with wall cavity moisture conditions, suggesting that indoor humidity control is the most effective strategy to prevent excessive moisture accumulation in the exterior building envelope during the winter.

Field Studies of Ventilation Drying of Wood-Framed Walls [4]

Many enclosure assemblies in many different climates have traditionally been ventilated with exterior air. Brick-faced walls with a drainage plane right behind the brick are one prime example. The nature and magnitude of the benefits of

[4] The field study was complemented by laboratory testing and computer simulation.

providing a ventilated wall system have been debated, but little quantitative research has been conducted. Thus, full-scale field test house studies were undertaken to investigate the role of ventilation and sheathing membranes in the drying of wood-framed walls [89]. Several companion papers describe the technical background and the results of computer modeling and laboratory testing.

The studies involved five different 4 ft (1.2 m) wide by 8 ft (2.4 m) high wood-framed wall systems—three clad with brick and two with vinyl siding. No wood-based siding was tested. Moreover, only highly permeable fiberboard sheathing was used in these tests to reduce the impact of the sheathing properties on the drying; OSB and plywood sheathing were not used in the study. A total of over 20 moisture, RH, and temperature sensors were installed within each wall system. Air velocity within the ventilation space of the brick veneer was also measured directly. A unique intra-wall wetting system was developed to uniformly and repeatedly wet the wall sheathing three times at different times of the first year. The response was then monitored. The size of the ventilation space was changed in all the walls and a second year of monitoring commenced with three more wetting cycles.

The test results indicated that all walls allowed a very significant amount of drying, and some of the walls exhibited no moisture damage at all at the end of the experiment. It was found that drying rates varied significantly during different weather conditions. Moreover, ventilation was shown to increase the drying potential of some walls, and the nature of the sheathing membrane (housewrap or building felt) influenced the drying rate. The results also indicated that solar-driven vapor diffusion acts to redistribute vapor from within the wall to the interior (where it did cause some damage) and that ventilation reduces the magnitude of this flow. That reduction of inward drives due to ventilation had a larger effect for the absorptive brick cladding tested. The location of brick vents—both top and bottom—was clearly shown to be beneficial to drying. The vinyl siding profile tested allowed significant ventilation-induced drying, whether applied with or without furring. Whether the vinyl siding was loosely applied or did or did not have weep holes that are typically blocked by interlocking laps of siding was not specified.

Vancouver, British Columbia, Leaky Condo Investigations

Over the last 20 years or so significant numbers of low-rise multi-unit wood-frame buildings in coastal British Columbia have been plagued with envelope moisture problems. The types of problems include: water penetration, damage to cladding systems, and decay of wood components. Particularly hard hit were multi-unit condominiums in Vancouver, B.C. As a result of concerns about this problem, a number of studies have been initiated. One particular one that has been completed involved an extensive survey of building envelope failures in the B.C. coastal climate area [90]. Both buildings with moisture problems and control buildings without significant moisture problems were surveyed. The problem buildings had moisture problems within the walls, decks, or exterior framing that required $10,000 or more to repair. The actual sample included 37 problem buildings with 193 problems reported and nine control buildings. Cladding types included stucco, wood, and vinyl. The wall components included various combinations of building paper, housewrap, OSB, and plywood. Of the problem buildings, almost 50% were built between 1988 and 1990; another 16 % were built in 1994. These were considered construction boom times.

The results of the study indicated that the primary source of moisture leading to the performance problems was water entering the building from the exterior, rather than interior sources or construction moisture. About 90 % of the problems were thought to be related to interface details between wall components or at penetrations. The problems were thought to be related to poor design and construction rather than operations and maintenance or material defects. A number of key differences between problem and control buildings were identified. Almost all of the problems were associated with details such as at windows, decks, walkways, balconies, and penetrations on walls. All cladding types experienced performance problems, although the number of problems reported on stucco walls was greater. The study concluded that greater attention needs to be paid to water management principles. Finally, several recommendations were made to the construction industry as well as others. A resulting best practice guide was developed [91], as well as a building envelope rehabilitation consultant guide and owner/property manager guide [92]. It should be mentioned that somewhat similar problems were noted in Seattle, Washington, as well. The WSU/ORNL testing noted earlier [87] is examining many of those Seattle problems.

Study of High-Rise Envelope Moisture Performance in the Coastal Climate of British Columbia

Moisture problems have been observed in high-rise residential buildings as well as those in low-rise buildings in the coastal climate of British Columbia [90]. As a result, a field survey study of high-rise buildings was undertaken [93]. The low-rise study strategies and methodologies used formed a foundation for the high-rise study. The high-rise study focused on identifying causal relationships that resulted in either building envelope failures or successes in noncombustible high-rise residential buildings. The study sample included 35 buildings that were five stories or more that were no more than 19-years-old with one exception. The exception was a building constructed in 1974 that used a drained cavity design in its major assembly walls and that had experienced good performance. There were four problem-free buildings as controls. There were 16 different combinations of wall and window/door assembly types. The materials used in high-rise buildings were different than those used in low-rise buildings. The primary structure was concrete with steel stud framing, rather than wood. Wind and exposure was generally more severe, along with stack effect. Finally, mechanical systems played a role in pressurizing the buildings, and mechanical ventilation existed to manage interior moisture sources.

It was found that virtually all the assembly interfaces and details analyzed in the project had failures and problems. So the complexity of the exterior facades was not a significant causal factor in the occurrence of failures or problems. Moreover, the mechanical ventilation systems did not adequately control interior moisture conditions for a variety of reasons. Exterior moisture penetration at details within wall assemblies was a significant contributor to moisture problems, especially at wall-to-wall assembly interfaces and at wall-to-window assembly interfaces. Window assemblies were significant contributors to problems. Corrosion of concealed metal components in wall assemblies represented the majority of moisture damage necessitating the need for repairs. Exterior gypsum board (sheathing) also was severely damaged. Glass fiber-faced gypsum board was less damaged. Most of the face sealed assemblies, other than mass concrete wall assemblies, were found to be damaged. Most of the wall assemblies incorporating an exterior drainage cavity were not damaged, and none of them had experienced any problems.

Overall, the study confirmed that the nature of the problems experienced in the high-rise buildings were similar in many ways to those identified for low-rise buildings [90]. The predominant moisture source (exterior), path (details), and sensitive assemblies (face seal) were common in both types of buildings. However, performance problems in high-rise buildings manifested themselves quite differently than in wood-frame low-rise buildings.

In high-rise buildings, the key damage issues are damage to interior finishes; deterioration of exterior gypsum board due to softening of the core and mold growth on the paper facing; and corrosion of metal components of the cladding attachment system, including steel studs, clips, metal reinforcing, and fasteners. Finally, the study identified opportunities for improvement of the design and construction process that will impact positively on high-rise envelope performance and provided a number of recommendations on how those improvements could be achieved.

U.S. Forest Products Laboratory Moisture Performance Study of a Contemporary Wood-Frame House Operated at Design Indoor Humidity Levels

A case study involving moisture performance of a contemporary wood-frame house over a series of heating seasons in Madison, Wisconsin, was undertaken by the U.S. Forest Products Laboratory [94]. Over most of the heating seasons, the building was humidified to levels as calculated by methodology outlined in Section 4.3.2 of Proposed ASHRAE Standard 160, Design Criteria for Moisture Control in Buildings. Over the first two heating seasons following construction, indoor humidity levels moderately lower than design conditions were attained, even though the house was neither occupied nor humidified. According to the authors, the moisture source was evidently wet soil around the building foundation, a condition probably associated with roof runoff deposited near the foundation during construction. Alternatively, the source of indoor moisture could have been related to drying of the concrete. Over the third, fourth, and fifth heating seasons the house was brought to design indoor humidity values with less than anticipated moisture release by humidifiers. Throughout the study, the indoor humidity levels resulted in some window condensation in cold weather, but the condensation was restricted to glass panes. Attic spaces remained dry. Painted wood-based sidings showed no staining, buckling, warping, or finish failure. Stucco cladding showed cracking that, although minor, would be consistent with seasonal moisture accumulation in the sheathing. Substantial seasonal moisture accumulation was measured in the sheathing of exterior walls that did not incorporate an interior vapor retarder. Vapor retarding interior wall paint mitigated moisture accumulation, but nonetheless permitted seasonal peak sheathing moisture contents to exceed 16 %. Seasonal moisture accumulation was greater in walls clad with plywood panel siding or stucco than it was in walls clad with strandboard lap siding or brick veneer. With lap siding, an air gap between siding and sheathing, even though not intentionally ventilated, reduced seasonal moisture accumulation and aided in springtime dissipation of moisture.

Older Existing Homes in Southern Climates

Gulf Coast Masonry Wall Field Study

Trechsel et al. [29] 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 gypsum 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 wallboard 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 [95] 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 $(3\frac{1}{2}\text{-in.})$ 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 EVR 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 [78]. 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.

U.S. Forest Products Laboratory Back-Primed and Factory-Finished Hardboard Lap Siding Field Study

Because of durability performance problems with hardboard siding in southern Florida, the U.S. Department of Housing and Urban Development (HUD) proposed a local standard requiring prefinishing of siding and priming of all siding surfaces, including the back. However, the effectiveness of these practices was questioned. To determine if back-priming or factory finishing improved durability and performance of hardboard siding, factory-finished and factory-primed siding was installed on two test buildings in southern Florida [96]. The buildings were identical except that one had gutters and no overhangs and the other had overhangs and no gutters. Half the siding was back-primed and half was not. Moisture content, temperature and air pressure difference across the siding were continuously monitored for two years. The condition and thickness of siding boards were recorded every three months. After removal from the buildings, the siding was inspected and final moisture contents were determined. The siding was in excellent condition after about $2\frac{1}{2}$ years of outside exposure. In-place thickness swell of the siding was less than 2 % during the entire exposure, and back-priming did not decrease thickness swell. Moreover, there was no evidence that back-priming the siding reduced its in-service moisture content. If anything, back-priming was counter-productive in that it caused a slight increase in the moisture content of the siding. Whether the siding was from the overhang building or the guttered building did not seem to make a difference, but inspection of the windows and final moisture contents of the trim strongly suggested that overhangs provided additional protection of the gable ends (gutters were only present on the sidewalls).

Field Study of Rainwater Management Performance in Newly Constructed Stucco-Clad Walls

After three hurricanes in central Florida during August and September of 2004, serious water management problems were noted in newly constructed homes with stucco cladding. As a result, a field study [97] was undertaken to determine the causes and recommend ways to prevent such damage in future housing with that type cladding. Two types of stucco claddings were reviewed: “traditional three coat hard coat stucco” and “cementitious decorative finishes.” The first method is used with wood-frame wall assemblies and the traditional weather-resistive barrier (WRB) is “building paper.” The second method is used with masonry block construction. Both methods are common in the central Florida (Orlando) area. The first method is typically limited to the second floor and gable roof assemblies. The second method is the standard first floor wall construction of the majority of homes constructed in the region. The first floor mass assemblies were overwhelmed due to the extraordinary weather events. The mass assemblies were not able to store the quantity of penetrating water and not able to dry rapidly enough between wetting events and in many situations water entered past the interior lining. The second floor frame assemblies provided mixed performance. In many cases the second floor assemblies were also overwhelmed—principally for two reasons: drainage was poor due to the failure of plastic housewraps and other WRB systems to provide drainage and water holdout, and drained rainwater was not expelled to the exterior at the base of the second floor frame assemblies.

A number of construction and water management issues were reviewed, including stucco cracks, WRBs, and penetrations and openings in stucco claddings (particularly window and door openings, and service penetrations). Window and penetration problems were assessed by field testing. Test findings included the presence of window and penetration leakage, even in the absence of wind pressures. Mulled double windows were found to be of particular concern. The use of paint as a water management technique for stucco renderings applied to mass assemblies, as well as roof membrane problems, also were examined.

A number of recommendations were made, including those involving construction, code interpretation, code requirements, window testing, water-managed window and door installation requirements, and the development of water-managed details for dryer vents, electrical panel boxes, electrical boxes, and vent fan hoods.

South Carolina Natural Exposure Test (NET) Facility Wall Study

Concerns have arisen over excess-moisture related wall damage, especially in walls constructed using barrier-type EIFS, in southeastern U.S. coastal environments. Thus, a comprehensive study [98] was undertaken by the EIFS Industry Membership Association (EIMA) and Oak Ridge National Laboratory (ORNL) to help design walls that are moisture-tolerant in the southeastern U.S. climate. A fully instrumented natural exposure test facility or test hut was built on the coast near Charleston, South Carolina, to test 15 different full-scale wall sections—similar to the Pacific Northwest facility described in Ref. [87]. The project involved testing the moisture intrusion, drying potential, and energy performance of various configurations of exterior cladding systems (EIFS, brick, stucco, concrete block, and cementitious fiber board siding). In addition, the impact of innovative EIFS features, specifically liquid applied moisture control membranes, smart vapor retarder systems, and exterior cladding venting, on the performance of EIFS was evaluated. In addition, the effect of purposefully induced defects on the performance of EIFS walls was evaluated. Another purpose was to develop and calibrate a hygrothermal (moisture and temperature) computer model with the unique features of EIFS that will validate the computer model for all climatic regions. Preliminary results of the first year of testing are available in an executive summary at the EIMA website.

Laboratory Studies of Moisture Problems Inside Exterior Walls

Older Existing Homes in Northern Climates

Field Observations and Laboratory Tests of Water Migration in Walls with Shiplap Siding

In a number of legal cases across the country it has been alleged that hardboard siding performs poorly from a moisture point of view and, thus, is not a satisfactory siding material. In one particular case [99] involving an apartment complex of about 400 units in the San Francisco Bay area, decay of hardboard siding and wood trim as well as other wood members was noted. It was clearly found that the decay was primarily caused by substantial amounts of liquid rain water leaking behind the siding and other wood members. However, other decay or deterioration (e.g., swelling) of the siding was noted in areas where liquid water intrusion was not directly observed. It was speculated that liquid water might move laterally behind the siding from leak sites in the building envelope, and that might explain the existence of siding swelling observed at locations some distance horizontally from otherwise obvious leak sites. Deterioration of the hardboard siding also was found to be caused by a number of other installation problems such as allowing the bottom edge of the siding to be in direct contact with concrete. Swelling of some bottom courses of the siding also was noted, and it was speculated that standing water on concrete paving might be wicking up the gypsum board behind the siding. It also was alleged that rain water was wicking up between the siding laps and causing swelling and cracking of the siding. In addition, it was suggested that hardboard absorbs water “like a sponge” when compared to other widely used siding materials and contributes to deterioration of wall materials, including gypsum and OSB sheathings.

To test the validity of these hypotheses, a series of laboratory tests of water migration in mockup walls with hardboard siding were undertaken. Every effort was made to duplicate the construction and weather conditions at the apartments. One series of tests run on walls with both hardboard siding and redwood siding involved examining the lateral migration of water introduced between the siding and the 15# building paper. A second set of tests involved spraying water on two test walls to check for the existence of wicking between the laps. Another series of tests involved determining the vertical height and effect of capillary wicking in gypsum sheathing, gypsum board, and hardboard siding whose bottom edges were submerged in water to simulate wetting of their bottom edges. A fourth set of tests involved introducing water between the siding and building paper in four walls with different types of siding and comparing the impact on the OSB sheathing and the siding materials. A fifth set of tests even involved submersing hardboard siding and other materials in water to determine their relative water absorption characteristics.

Tests run on three walls with hardboard siding, and also redwood siding, conclusively showed that water introduced at a point leak source between the siding and the 15# building paper could readily migrate horizontally behind the siding for long distances. For one test wall with hardboard siding, the water flowed laterally at an angle of as little as 14° from horizontal over a horizontal distance of about 9 ft (2.7 m). The conclusion is that swollen siding horizontally well removed from a point leak source could readily be caused by the lateral migration of the water behind the siding. That is a new finding that correlates well with the field observations.

Another important finding from these laboratory tests is that the existence of relatively large amounts of water behind the siding for just a few weeks duration resulted in micro-cracking or checking of the paint on the bottom edges of lap joints along with swelling of the siding around nail heads. That swelling was accompanied by bowing of the siding between nail heads. What is interesting is that deteriorated siding in the field exhibited just those same characteristics. Moreover, after a month of wetting in these lateral migration tests the OSB behind the gypsum sheathing was decayed. It has been suggested by some experts that all hardboard siding readily absorbs water (either in vapor or liquid form), then expands slightly, and then micro-cracks, which leads to a worsening of the situation and to ultimate failure of the siding. It appears from these tests that the swelling and micro-cracking is not a characteristic of properly installed hardboard siding. Rather, it is a characteristic indication that way too much water has gotten behind the siding as a result of some type of leak. The tests also indicate that it takes more than just small amounts of water to cause these problems. Further tests undertaken for this study indicate that when similarly large amounts of water get behind T1–11 plywood or OSB siding, the same characteristics and deterioration occur to those siding materials, only the damage is much more severe and it occurs much more quickly.

Thus, the allegations suggesting that all hardboard siding performs poorly from a moisture point of view and will ultimately fail also appear to be false. For one thing, there is a great deal of hardboard siding in the field that is performing very well. That certainly is this author’s collective experience based on 22 years of inspecting hardboard siding in legal cases. Furthermore, this author has seen hardboard siding on a large number of homes that was 20–25 years old and was in excellent condition, along with one home with 41-year old hardboard siding in exceptional condition, while another one of the authors of this study (DPG) has seen hardboard that is 33 years old in excellent condition on thirteen fourplexes.

A second test involved spraying water on two test walls to check for the existence of rain water wicking up between the siding laps. The amount of water sprayed was considered a worst case amount of rain water to fall on a wall. There was absolutely no evidence of wicking occurring in these tests. That finding is in complete agreement with other laboratory tests described in the paper as well as field observations from hundreds of dwellings where siding has been removed and inspected for signs of wicking between laps. While water staining on the backside of hardboard siding might suggest that wicking does occur, these tests show that wicking does not occur; and the lateral migration tests provide an explanation for the existence of the very small amount of staining observed in the field. Almost all of the siding observed when removed in the field in dozens of legal cases has no staining on its backside. To the authors' knowledge there is no scientifically verified evidence that wicking ever occurs between the laps of hardboard siding and causes damage. Allegations of wicking happening with consequent damage occurring appear to be mere speculation that lack a factual basis.

A third set of tests involved determining the rate and vertical extent of, as well as the effect of, capillary wicking up either gypsum sheathing or gypsum board whose bottom edge was submerged in water, as occurred in the field due to ponding of water on concrete paving combined with improper flashing to protect the gypsum materials. It was found that both materials readily and quickly wicked up water from their bottom edges. They both wicked up more than 10 in. (25 cm) in 24 hours. In fact, water wicked up as much as about 4 ft (1.2 m) in the gypsum materials, with the gypsum board wicking faster than the more water-resistant gypsum sheathing. That led to the wetting of the OSB sheathing and hardboard siding in the test walls. The OSB sheathing in direct contact with the wetted gypsum materials was above its fiber saturation level of 25 % moisture content, and so would be prone to decay if it stayed wet. Furthermore, at the end of the tests we actually noted swelling and slight bowing of the hardboard siding that mimicked conditions noted in the field. So these results clearly explain the cause of the swelling of hardboard and the deterioration of OSB sheathing noted in the field where ponding was known to exist or where the gypsum sheathing was exposed to rain splashback. By comparison, hardboard was found to wick extremely slowly; it took four weeks to vertically wick up only 2.5 in. (6.4 cm).

The fourth set of tests involved introducing water between the siding and building paper in four walls with different types of siding and comparing the impact on the OSB sheathing and the siding materials during a four-month test period. It was found that the OSB sheathing was adversely impacted the most in the walls with T1–11 plywood and OSB panel siding (the sheathing was quite wet and moldy in both walls), whereas there was essentially no impact on the sheathing in walls with either shiplap hardboard or cellulose-reinforced cement lap siding. It is believed that the large amount of wax and resin in the hardboard kept it from absorbing as much water as the plywood and OSB siding. That allowed the hardboard to more readily drain and keep the wall the driest. Furthermore, at the end of the test the T1–11 plywood and OSB panel siding were swollen and deteriorated, whereas the hardboard and cement siding were not. Thus, these tests showed that, if water does get into a wall, then the best siding to have on the wall of those tested is either the hardboard or the cement siding. The hardboard certainly did not absorb water "like a sponge" as alleged; it remained quite dry. These tests also verified that it takes abnormally large amounts of water leaking into a wall cavity to result in swollen or deteriorated hardboard siding.

A final set of tests was undertaken to compare the relative water absorption of hardboard siding with that of other building materials, including cement siding, redwood siding, pine trim, and Douglas-fir stud framing material. All these materials were soaked in a water bath for a two week period to determine their percentage weight gain per unit surface area. The results of these tests showed that hardboard siding was the least absorptive of the materials tested. So it clearly does not soak up like a sponge in comparison to other commonly used wall materials.

In summary, a number of laboratory tests were completed to test a number of allegations of poor moisture performance of hardboard siding. In every case the allegations were shown to be incorrect and without basis. The tests also clearly point out that the deterioration of hardboard siding has to do with faulty installation rather than some inherent defect in the hardboard material itself. Thus, these tests strongly suggest that hardboard siding will perform satisfactorily as long as it is properly installed and maintained. That is in complete agreement with the collective experience of the authors of the research in dealing with many legal cases over the past 22 years where the performance of hardboard siding has been in question.

Newly Constructed Homes in Northern Climates

National Research Council Canada Moisture Management of Exterior Wall Systems (MEWS)

To address concerns over widespread moisture problems involving serious structural degradation in the exterior envelopes of low-rise wood-frame residential buildings in Canada and also the United States, a consortium called MEWS or Moisture Management of Exterior Wall Systems was established in 1998. It involves a partnership between the NRCC's Institute of Research in Construction (IRC), industry groups, and other stakeholders. The objective of MEWS has been to determine the minimum characteristics and levels of performance of various wall elements needed to satisfactorily handle rainwater ingress depending on the surface environment of the wall assembly. The main effort has been to develop an advanced hygrothermal model called "hygIRC" that could be used to predict the performance of various wall designs or assemblies in different Canadian and U.S. climates so as to contribute to effective moisture control in building envelopes. Experimental laboratory testing has been conducted as part of the MEWS effort to provide realistic inputs and validate the results of the hygrothermal model. Additional laboratory tests also have been undertaken to determine the hygrothermal properties of various wall component materials for use in the model. For the purposes of this case studies chapter, the focus is on the former laboratory studies. Further information regarding the laboratory studies aimed at developing hygrothermal model material properties is available on the IRC website. [5]

Laboratory evaluations of wall systems exposed to simulated wind-driven rain have been undertaken [100]. Performance tests were conducted to qualify the degree to which wall assemblies were able to maintain their watertight integrity when being subjected to static or dynamic pressure differentials concurrent with water spray using the so-called dynamic wall test facility (DWTF) at IRC. The tests were set up to assess the likelihood of water penetration under extreme simulated climatic conditions. Water entry assessments were used to determine the quantities and rates of water that might enter deficiencies of known type, size, and location on the cladding when subjected to simulated cli-

[5] http://irc.nrc-cnrc.gc.ca/ircpubs

matic extremes. These were the water entry loads to be input into the hygrothermal model.

From late 1999 to early 2001, 17 large-scale wall specimens were built for water entry investigation. The specimens included walls with the following claddings: five stucco, five Exterior Insulation and Finish System (EIFS), four masonry, and three siding (two hardboard and one vinyl). All specimens included a window, a duct, and an electrical outlet receptacle with built-in deficiencies that allowed wetting of the wall cavities. The construction of the wall specimens is described in Ref. [101].

The test results showed that all of the wall assemblies exhibited some water entry when subjected to the spray rates and pressure differentials used in the tests. The points of penetration were primarily at wall penetrations. Assemblies having a drainage cavity showed the least evidence of water penetration in all test sequences. In the case of the brick walls, no water was observed to penetrate to the stud cavity. The bottom line is that significant amounts of water entered many of the deficiencies; rates as high as 0.56 L/min (8.9 gph) were observed. All of the water ingress activity at the various points of entry are indicative of the significant amounts of water that can collect in a short period of time under unfavorable climate conditions (i.e., high and prolonged intensity of wind-driven rain).

Saskatchewan Research Council (SRC) Investigation of Window Installation Techniques to Minimize Rain Entry in Wood-frame Construction

A condominium complex recently built by a contractor in Saskatoon, Canada, had experienced widespread rain entry into the stucco-clad condominiums around the windows. The contractor wished to avoid such problems in future units. So a series of laboratory tests were undertaken at the SRC to help develop window installation techniques that would minimize the entry of rain, and also not appreciably add to the cost of the construction [102]. A test apparatus was built that could duplicate a wind-driven rain situation on the building wall. A fan was used on the apparatus to create a negative pressure equal to either 36 or 79 lb/ft^2 (137 or 300 Pa) across the wall test section. The artificial rain was provided by a series of spray nozzles that produced a flow equivalent to 8 in./h (203 mm/h) of horizontal rain. Some tests were run for 15 minutes, while others were run for four cycles of 5 minutes with the water spray on and the negative pressure applied and then one minute with the air pressure off and water spray on. A series of window installation tests were devised to test a number of different installation techniques ranging from good to bad. One of the interesting results was that when staples were used to affix the building paper, water would readily leak through the holes and enter the walls. Peel and stick membrane installed around the windows was particularly effective at sealing around the windows. However, concerns regarding it acting like an EVR and trapping moisture behind it were expressed.

I have observed wetted and moldy plywood sheathing behind such membranes around windows in the Pacific Northwest. In colder climates similar damage might occur, possibly in a more widespread fashion.

A Laboratory Test of Residential Wall Cavity Leak Water Drainage and Damage with Different Building Papers and Housewraps

Building papers and housewraps are installed in residential walls with siding to provide a secondary moisture barrier for water that might inadvertently get behind the siding. However, sometimes so much liquid water gets behind siding that the wall does not properly drain and remains wet for extended periods. That can lead to serious mold or rot problems. An approach that has long been suggested to improve drainage is to install vertical furring strips between the back of the siding and the building paper or housewrap. However, that approach involves additional effort and cost and is just now starting to be used, at least in the United States. Clearly what is needed is a moisture barrier-like material that both acts as a moisture barrier (building paper or housewrap) and provides a drainage space. It is possible that housewrap with a vertical groove-textured surface is such a material. One such housewrap was developed to provide drainage in EIFS and has been used with regular stucco.

Thus, it was decided to undertake a laboratory test [103] to determine the drainage characteristics of this groove-textured housewrap in a residential wood-frame wall with siding and to compare its performance with that of other conventional building paper or housewrap materials as well as the use of furring strips and also no building paper or housewrap. The materials or approaches tested, or both, included: vertical groove-textured housewrap, conventional housewrap, No. 15 felt, Grade D building paper, conventional housewrap with furring strips, and no building paper or housewrap. The basic laboratory test approach was to construct six 4 ft (1.2 m) high by 4 ft (1.2 m) wide two-by-four wood-frame walls that were identical except for the materials listed above. Then, to simulate a significant leak behind the siding, such as might occur due to a construction error or defect, the same amount of water was dripped into the center top portion of each of the walls between the back of the siding and the building paper/housewrap or the OSB sheathing in the case with no paper or wrap. Wall construction materials included: 5/16 in. (7.9 mm) fiber-cement panel siding, building paper/housewrap, possibly furring strips, 1/2 in. (12.7 mm) OSB sheathing, two-by-four framing filled with R-11 (RSI-1.9) batt insulation, and a 6 mil (0.15 mm) polyethylene vapor retarder. The test was run for about four months with water dripping slowly on and off daily into each of the walls with varying amounts as the test proceeded. The moisture content of the siding, sheathing, and framing in each of the walls was monitored regularly and compared. Attempts also were made to measure the amount of water entering each of the walls and the amount that drained out. At the conclusion of the tests, the walls were disassembled and any deterioration of the wall component materials was assessed and compared. Additionally, the water drainage characteristics of the six approaches were compared.

While, as expected, the most effective drainage and moisture performance was provided by the use of furring strips with housewrap, the groove-textured housewrap performed the best of the other walls and would provide cost-effective drainage. Surprisingly, the wall with No. 15 felt performed the worst by far, while the wall with the Grade D building paper did not perform much better. Both the felt and the building paper spread the leak water that entered from a point source across the test walls and so resulted in the most extensive and serious damage (elevated moisture contents, extensive mold growth, and even OSB decay in the case of the No. 15 felt). The housewraps limited the spread of the leak water and, hence, the damage, whereas the use of furring strips resulted in no observable water spread or damage within the wall cavity.

While the pros and cons of building papers or felts versus housewrap have been widely debated, the results of this study strongly suggest that, if limiting moisture damage in walls with significant water leakage is of primary concern, then using furring strips or housewraps is much more preferable to the use of building paper or felt. They provide the best insurance against damage in walls with construction defects that allow water intrusion. Several housewrap manufacturers have introduced "drainable" housewraps for use with any cladding materials. Incidentally, if furring strips are to be used to provide a drainage cavity, then the use of vented plastic battens rather than wood battens appears to be a better alternative from a cost, versatility, and moisture damage point of view.

It is often assumed that moisture barriers such as building papers and housewraps allow water leakage into the wall cavity to drain out such that damage does not occur. While building papers and housewraps may provide sufficient drainage to avoid damage with small amounts of incidental water, they do not provide protection with large amounts of water penetration into wall cavities. A small fraction of the entry water is absorbed by the wall components, and that is what causes the damage. The results of these tests also show that if water is present in sufficient amounts in walls without some type of drainage capability, then that water will pass right through any of the moisture barriers and into the sheathing and framing. That same result was found in another laboratory leak test of a wall with No. 15 felt [99]; water was found to have gone right through the felt building paper when the wall was opened up one day after the leak flow started. Thus, conventional moisture barriers do not, in fact, prevent water that gets or leaks behind siding from passing through them and causing moisture damage to wall components behind them.

Finally, these tests demonstrate that to get decay to occur in wall components such as siding, sheathing, or framing members, unexpectedly large amounts of water must have entered the wall cavity (i.e., gallons not drops). As a rule of thumb, based on these test results, a conservative estimate is that at least ten times as much water must enter a wall cavity when decay has occurred as the amount of water required to raise the moisture content of the affected area sufficiently to allow decay fungi to grow. In these tests about 96 gal (363 L) entered each wall over the four-month test period [slightly less than 1 gal (3.8 L) per day on average], and that resulted in OSB decay in a small area in one of the walls. That result suggests that when decay is observed in wall cavity components in the field, then at least about 96 gal (363 L) of water must have entered the wall cavity over some extended period of time. Incidentally, for a 4 ft (1.2 m) by 4 ft (1.2 m) by 0.5 in. (12 mm) thick piece of wood siding or sheathing, the amount of water that must be absorbed just to raise the moisture content of the material from a dry state of say 10 % moisture content to the minimum required for decay of about 30 % is one gallon! Clearly, if water leaks into a wall assembly, then other components such as the building paper and framing will absorb some the water. Moreover, the one gallon is the requirement to just get decay to start, but oftentimes much higher moisture contents exist that lead to decay. So many gallons of water entering a wall cavity are required to cause decay in a wood component of the size assumed in this example. An ancillary laboratory test of the water flow rate through a small hole in a horizontal surface showed that gallons of water can flow through a small hole in just one hour. Thus, small leaks can provide sufficient rain or irrigation water penetration into wall cavities over time to result in considerable damage.

It also seems clear from these tests that if gallons of water do in fact get into wall cavities, then neither natural drying nor even ventilated wall cavities will keep damage from occurring. The drying potential of those approaches is far outweighed by the wetting potential. Thus, the most important aspect of providing an air space behind siding is that it provides a drainage capability rather than just improves drying by ventilation.

Finally, it is sometimes stated that having a polyethylene interior vapor retarder in a wall in a heating climate is not a good idea because it will inhibit drying of a wet wall. But if the wall is getting wet enough such that decay is occurring, then this study shows that many gallons of water must be entering the wall cavity. In such wetting cases, whether there is any kind of interior vapor retarder in place will make little or no difference to the amount of degradation.

Older Existing Homes in Southern Climates

Laboratory Water Penetration Tests of Window and Shed Roof Flashing in Walls with Shiplap Hardboard Siding

The durability and suitability of many composite siding materials from a moisture point of view has been a contentious issue in the courts for a number of years. In a subdivision of about 400 single-family detached homes in West Palm Beach, Florida, decay of the hardboard siding and the adjacent wood trim, along with wood framing members, was observed in many situations. In many of the homes water entered the wall cavities and living spaces and caused damage to the walls and floors. It was alleged by plaintiffs' experts in a legal case brought by the developer against the siding manufacturer that the hardboard siding was a defective product and was the cause of the water entry and resultant damage. Specifically, they felt that rain water was wicked up between the siding laps by capillary action and wetted the siding and other wall components. That wetting then led to deterioration of the siding and other wall components. However, it was believed by the defense, as well as HUD investigators, that the real cause of much of the damage was bulk rain water leakage through improperly flashed aluminum windows and shed roofs over box windows.

Thus a series of laboratory tests were undertaken [104]: (1) to evaluate the water shedding performance of hardboard-sided walls with windows and shed roofs properly installed according to the siding manufacturer's installation instructions and good construction practices, and (2) to determine the mechanisms that caused water entry into the siding and wall cavities of the homes as actually improperly constructed. The tests involved slightly modified ASTM E331 type water penetration tests of a variety of mock-up walls, as well as new aquarium tests of capillary wicking between the laps of the hardboard siding. The ASTM E331 tests were aimed at examining the water leakage characteristics of windows installed in walls under heavy, wind-driven rain conditions. In one of the water penetration tests, water was sprayed on a plain wall without any penetrations to see if any water wicked up in between the siding laps. Additional spray tests were undertaken on walls with properly and improperly installed (very poorly flashed and sealed) windows as well as shed roofs with box windows to determine if leakage into the wall cavities occurred as a result of improper construction. In the aquarium tests two pieces of lap siding were immersed in dyed water such that the water just contacted the bottom drip edge of the top course of siding to check for capillary wicking between the laps.

The tests showed that water does not wick up between siding laps, in agreement with other test findings [99], that improperly flashed and sealed windows or shed roofs can allow surprisingly large amounts of water to enter into and even through walls, and that properly installing windows and shed roofs essentially eliminates water entry around them into wall cavities. In the test of an improperly flashed and sealed window, the total water penetration amounted to about 44 gal (170 L) in the three hour test. The amounts of water that got into the walls during these tests certainly are sufficient to cause the decay and deterioration that occurred on site. Even with less severe wind-driven rain conditions, it is clear that the improper flashing would lead to water entry. Poorly designed components such as leaky windows, or construction errors such as lack of sealants or flashing or improper flashing, do occur and can allow huge amounts of water to get behind siding (gallons rather than just drops).

Barrier EIFS Clad Walls in Wilmington, North Carolina

Serious, widespread failures of walls with barrier type EIFS cladding were first observed in residences in the hot and humid and rainy climate of Wilmington, North Carolina (actually a mixed climate). EIFS systems are also known as "synthetic stucco." Water intrusion into the wall cavities led to extensive decay of wood-frame wall components. The barrier-type EIFS clad walls were designed as face-sealed systems with the intent that water would be prevented from entering the wall assembly. No design provisions were made for the drainage or management of water that might penetrate into the wall. A field investigation was undertaken in 1995, followed by laboratory experiments and computer simulation [105]. The objective was to determine the cause of the problem and gain a better understanding of water penetration and moisture transport in such systems.

Several observations were made during the site visits and field investigations. Water was found to be intruding into the exterior walls near window assemblies, doorways, hose bibs, and roof rakes. There was little evidence that water was penetrating through the field of the EIFS cladding. In particular, vinyl combination windows (two or more units field joined by a vinyl mullion) were found to be problematic. Furthermore, flashing and sealing specifications recommended by the EIFS manufacturers were not followed.

The laboratory study results indicated that barrier EIFS clad walls are prone to leak in areas around penetrations and allow water to enter into the wall cavity. A drainage cavity wall also was tested and was observed to perform well, managing water around penetrations and preventing leakage into the wall cavity. The computer simulation results indicated that barrier EIFS clad walls in Wilmington have low moisture tolerance due to slow drying rates.

In conclusion, barrier-type EIFS clad walls were found to not provide effective management of rain penetration. As such, in-service performance is unpredictable and unreliable. In contrast to barrier-type EIFS clad walls, walls using a drained cavity approach were shown to provide good control of rain penetration. Additional laboratory testing of different drainage approaches incorporated into the design and construction for EIFS clad walls followed this study [106]. Long-term field testing of a vented EIFS wall assembly also was undertaken [107]. The EIFS in question used high density mineral fiber insulation placed in a support frame; however, it allowed air entry behind the insulation and the measured thermal performance was much lower than expected.

Conclusions

Indoor Excess Moisture Problems

It should be stressed that indoor moisture problems have not been particularly well documented in many parts of the United States and Canada, in part because until recently they were often considered more of an aesthetic nuisance than exterior or wall cavity moisture problems that might involve structural damage, which is clearly more severe. Based on the Iowa survey experience [10], it is 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. The industry probably has not done a good enough job of asking the right questions and so likely has 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. However, some of the alleged adverse impacts of so-called "toxic molds" may have been overstated, as the evidence connecting them to serious health problems does not exist [4], at least as yet. At any rate, nowadays indoor moisture "problems" are taken much more seriously than they were 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, until recently 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 even in newly constructed homes. At the other extreme, wall moisture problems are relatively rare, although there have been a few cases where the occurrence of severe structural damage has been widespread in particular climatic locations or because of the use of certain building products.

Some 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. Unfortunately, many homes still do not have adequate spot ventilation or appropriate controls and, in spite of the successes with use of dehumidification, its use is still not widespread.

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 building codes, programs involving weatherization of existing homes, and in the design, construction, inspection, and ongoing operation of new homes. Existing codes in some states still do not require a bathroom exhaust fan if an operable window exists, and the minimum flow capacity of fans (50 cfm rated) is way too low to be effective with nonautomatic controls. In addition, some existing codes allow recirculating kitchen fans that do not exhaust outdoors. Those codes need to be changed to help reduce the incidence of indoor moisture problems. Without increased emphasis on substantially improving indoor moisture control in all homes, the large number of moisture problems will not be reduced, leading to continued durability problems in many of the homes and 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 when a suitable ground cover is in place and, in fact, may even cause severe moisture problems in warm, humid climates, especially in air-conditioned homes. While the 2006 International Residential Code (IRC) does allow unvented crawl spaces when a ground cover is in place, continuously operated exhaust ventilation or conditioned air supplied to the crawl space is required, along with the installation of perimeter insulation. Earlier codes did not allow unvented crawl spaces, but the vents could be operable and, hence, closed. The 2006 IRC is an improvement, but there still are problems with it. For example, in Oregon, crawl space perimeter insulation is not allowed because life cycle costs were found to be lower with underfloor rather than perimeter insulation). So in Oregon unvented crawl spaces can not be built. Furthermore, the 2006 IRC now requires ventilation of 1 ft^2 (0.0929 m^2) for each 150 ft^2 (14 m^2) of underfloor area for homes built in Oregon, which is ten times more ventilation than has been used in the past. In addition, a ground cover is not required under the 2006 IRC for such cases. That seems unreasonable even with the increased ventilation, as during many parts of the year ventilation is ineffective. In addition, there clearly are regions like the Pacific Northwest where crawl spaces with sealed vents and a ground cover have worked quite well without any mechanical ventilation or conditioned air supplied to the crawl space, which is now required by the 2006 IRC. This needs to be changed, especially when it is realized that eliminating ventilation will save energy and probably reduce construction costs. Of course, in some situations, ventilation may be desirable, such as to help mitigate radon.

Attic moisture problems in ventilated attics 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. Reducing indoor relative humidities will go a long way to help solve attic moisture problems in such cases. In addition, sealing the ceiling bypasses and penetrations should greatly help reduce attic moisture problems. As with crawl spaces, there have been code changes (see the 2006 IRC) that allow unvented conditioned attics in addition to ventilated attics. That occurred at least in part because ventilating an attic is not always a good idea in all climates, and especially in hot and humid U.S. climates. All these code changes will hopefully reduce the incidence of attic moisture problems in housing.

It also is important to again stress that, as a rule, 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 suggests that the health effects of moisture-related biological contaminants are serious and need more research. For example, there has been limited research on the effects of dehumidification on the incidence of dust mites and mold growth, and that would seem to be worthwhile. In addition, there would appear to be a need to determine if mold growth hidden inside wall cavities contributes to elevated mold levels indoors to such an extent that they result in adverse health impacts for the occupants. That seems to be a potential problem that needs further research to clarify the situation.

Excess Moisture Problems and Damage Inside Exterior Walls

The past decade or two has seen a number of major wall moisture problems rear their ugly heads, as noted in earlier sections. Names like barrier-type EIFS (or synthetic stucco) come to mind, along with cities such as Wilmington, North Carolina, or Vancouver, B.C. Some have arisen in part because of a rush to meet heightened demand during boom production times with a consequent reduction in construction quality. In some cases engineered products have come to market without sufficient building science design forethought or field testing to assure that they will perform as intended, and that has led to serious moisture problems and related structural damage. OSB siding failures appear to be a prime example. In some cases widespread damage has resulted because of improper implementation of wall assemblies, such as with Tri State Homes. The CMHC findings that there are two kinds of windows: those that leak and those that will leak, is also disturbing. Recent observations of wall damage associated with vinyl siding are also troubling, especially because of the possibility that they are much more widespread than has been recognized to date.

These problems have led to a considerable effort to better understand water penetration into walls and other moisture issues. That is fortunate, because many of these problems appear preventable with proper design, construction, and maintenance. It is safe to say that our awareness of potential exterior wall problems has been heightened, and that appears to be bearing fruit in terms of increased effort to better understand how to prevent such moisture problems. Notable examples include improvements in window design and installation, along with efforts to utilize rain screens in wall construction.

Based upon this author's 30 plus years of experience assessing and resolving building moisture problems, including inspecting more than 10,000 dwelling units and opening up more than 1,500 wall cavities, a summary of the various ways that water moves in walls is presented in Ref. [108]. Numerous examples are given, as well as the various ways that moisture damage occurs in wood-framed walls as a result of water intrusion. It is hoped that this summary will provide background information that will help readers better understand the various case studies discussed in this chapter.

There is one further major issue that remains unresolved, namely building envelope construction choices in mixed use climates. There is confusion by designers and contractors in choosing appropriate parameters for this climate. For example, whether a vapor retarder should be used in walls, and where it should be located if one is used, is a question that has created a great deal of confusion amongst practitioners. There is a clear need for further research aimed at providing better guidance in this area.

Exterior wall moisture problems have received considerable attention, and yet wood decay and resultant structural damage inside exterior walls is relatively rare in comparison to the vast majority of homes that are performing satisfactorily. Nonetheless, wall moisture problems are often quite expensive when they 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). Of course, improving the durability of houses will reduce the incidence of mold-related problems that occur because of leaks. 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.

Appendix

RESIDENTIAL MOISTURE & MOLD PROBLEM INSPECTION CHECKLIST

Occupant name:____ Date:__/__/__
Address:____
Home phone #:_________________ Work phone #:_________________ Cell phone #:_________________
Service #:_________________ Tech #:_________________ House ID#:____________

Excess Moisture Symptoms/Problems

Interior: Occupant/Auditor Comments

□ Mold/mildew/stains on surfaces (e.g. walls, ceiling, floors, carpets)
  Note room type and location:____________________________________
  □ In bedroom closets: □ Mold/mildew on clothing
  □ Behind furniture and/or mattresses directly up against walls (poor air circulation)
  □ Behind messy piles directly up against walls, especially in closets (poor air circulation)
□ Mold/mildew/staining on window frames and/or around windows
□ 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
□ Liquid water condensation on walls or ceilings (especially bathrooms)
□ Sill condensation damage (staining, rot): minor[ ], major[ ]
□ Persistent condensation of bathroom mirror
□ Wet carpets
□ Overflowing toilet, tub or shower
□ Sweaty pipes (note location and season)
□ Basement dampness and leakage
□ Efflorescence (white powdery substance), mold and/or dampness on concrete foundation walls
□ Photograph all mold and/or condensation sites (overview and closeup shots)
□ Keep a log of each photograph (including date, apt. #, room and location in room)
□ Other (describe)

Exterior:
□ Attic condensation and/or frost
□ Attic mold
□ 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)
□ Other (describe)

Basic House Characteristics

House age (yrs):____; # of occupants: day__, night__; # of smokers:__
Heated living area (sq ft): _________; ceiling height (__ft, __inches); # stories:__
Window glazing: single[ ], double[ ], triple[ ], dbl low-e[ ]
Window frames: wood[ ], metal[ ], TIM (thermally-improved metal)[ ], vinyl[ ]
Wall insulation: Y__, N__; ceiling insulation: Y__, N__; floor insulation: Y__, N__
Floor type: full basement[ ](heated:__%, unheated:__), partial basement[ ](heated:__%, unheated:__), crawl[ ], slab-on-grade[ ], mixed[ ]
Foundation wall type: concrete[ ], conc. block[ ], stone/brick[ ]
Space heating type: electric resistance[ ], fan-forced wall heaters[ ], heat pump with ducts[ ], forced air furnace with ducts[ ]; gas wall heaters[ ]; hot water radiators[ ]; steam heat[ ]; room oil heater[ ]
No heat source in bedrooms: Y__, N__
Laundry room within apartment: Y__, N__
Other (describe):____

Monitoring and Occupant Interview Results

CFM50: pre-weatherization________, post-weatherization________
Thermostat settings: heating___°F or off___; cooling___°For off___
Measured temperatures: living room____°F, master bedroom____°F, heated basement____°F, unheated basement___°F
Measured RH: living room___%, master bedroom___%, heated basement___%, unheated basement___%, other (location:_____________)___%
[Be sure to keep exterior doors closed so indoor conditions don't change upon entering apartment]
Shades or blinds kept closed: 24/7: Y__, N__ (note locations:_______________________________________)
Kitchen exhaust fan: none[ ], recirculating, nonvented type[ ], vented type[ ]
Kitchen exhaust fan used: seldom[ ], whenever needed to clear windows or odors[ ], almost always when cooking[ ]; occupants limit use because fan is too noisy: Y__,N__
Primary bathing/showering bathroom exhaust fan: Y__, N__; rated cfm_____; # showers per day:___
Other bathroom exhaust fan: Y__, N__; rated cfm_____
Exhaust fans work (toilet paper test): primary bathroom Y__, N__; other bath Y__, N__; kitchen Y__, N__
Kitchen exhaust fan used: seldom[ ], whenever needed to clear windows or odors[ ], almost always when cooking[ ]; occupants limit use because fan is too noisy: Y__,N__
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 fan control: none[ ]; light switch[ ]; separate switch[ ]; timer[ ]; controller[ ]; dehumidistat[ ]
Bathroom and kitchen exhaust fans ducted/vented: to attic[ ], to outdoors[ ]
Measured exhaust fan cfm: master bathroom__, other bath__
Dehumidifier: none[ ]; # in basement[ ], used summer/spring/fall[ ], used winter[ ];
in other locations[ ], used summer/spring/fall[ ], used winter[ ] (locations:_____________)
Manually drained: Y__, N__
If Y, roughly how much water drained per day:______________gallons
Brands, capacity and model #s:____________________________
Forced air heating system return duct leak test with smoke generator: leaking[ ], well sealed[ ]
Reported health concerns:____
Other (describe):____

Potential Moisture Sources

Occupant/Auditor Comments

- ☐ 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:___
- ☐ Clothes dryer vent duct disconnected indoors
- ☐ Clothes dryer vent clogged
- ☐ Clothes dried indoors
- ☐ Firewood stored indoors, including basement
- ☐ Crawl space without ground cover
- ☐ Crawl space with partial ground cover (less than 80-90% coverage)
- ☐ Water pooling/ponding on crawl space ground cover
- ☐ Basement flooding
- ☐ 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
- ☐ 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
- ☐ Other (describe)

Recommended Moisture Control Strategies

□ Give occupants EPA "A Brief Guide to Mold and Moisture in Your Home" to read
□ Install inexpensive relative humidity/temperature meter (so-called hygrometer) in master bedroom
□ Ask occupants to regularly clean/scrub mold with soap and water
□ Educate occupants regarding need to increase use of bathroom & kitchen exhaust ventilation systems
□ Install bathroom fan automatic control: timer[ ], fan/light controller[ ], or dehumidistat[ ]
□ Install dehumidifier (65 pint per day minimum)(use existing model only if it has automatic defrost control)
□ Install new bathroom exhaust fan: quiet (2 sone maximum), 80 cfm minimum rated capacity
    □ With automatic fan control, □ Without automatic fan control
□ Keep the heat above 60 degrees Fahrenheit at all times, as low temperatures cause mold growth
□ Do not turn off the heat in any rooms (especially bedrooms)
□ Indoor moisture source control
    □ Vent clothes dryer outside
    □ Dry clothes outside
    □ Store firewood outside
    □ Cover aquariums
    □ Discontinue use of humidifier or vaporizer, especially in spring, summer, and fall when not needed
    □ Discontinue use of unvented space heater, including oven for space heating (major source of indoor air pollutants)
□ Raise shades or blinds as often as possible each day (extremely important!)
□ Allow at least two inches between furniture or other goods and exterior walls to warm wall surfaces
□ Immediately dry any water that spills or overflows from showers, tubs, toilets, sinks, etc., or onto carpets
□ Install crawl space ground cover
□ 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)
□ Recommend improved drainage (low cost option is to add 8-10 foot downspout extensions to move the gutter water flow away from the foundation)
□ Improve closet air circulation (leave doors open or install louvered doors) or heat closet (leave light on)
□ Other (describe)
□
□
□
□

Moisture Control Actions Already Undertaken by Occupants

Action Description With Approximate Date and Results of Action:
□
□
□
□
□
□
□

Additional Remarks

References

[1] International Energy Agency, *Annex XIV: Condensation and Energy, Volume 2: Guidelines and Practice*, Aug. 1990.

[2] Tsongas, G. A., "The Northwest Wall Moisture Study: A Field Study of Excess Moisture in Walls and Moisture Problems and Damage in New Northwest Homes," U.S. Dept. of Energy/Bonneville Power Administration, DOE/BP-91489-1, June 1990.

[3] duPont, P. and Morrill, J., *Residential Indoor Air Quality and Energy Efficiency*, American Council for an Energy-Efficient Economy, Washington, DC, 1989.

[4] Institute of Medicine, *Damp Indoor Spaces and Health*, The National Academies Press, Washington, DC, 2004.

[5] Sterling, E. M., et al., "Criteria for Human Exposure to Humidity in Occupied Buildings," *ASHRAE Transactions*, Vol. 91, Part 1b, 1985, pp. 611–622.

[6] *Wood Handbook: Wood as an Engineering Material*, Agriculture Handbook No. 72, USDA Forest Products Laboratory, 1974.

[7] Sheffer, T. C., "A Climate Index for Estimating Potential for Decay in Wood Structures Above Ground," *For. Prod. J.*, Vol. 21, No. 10, 1971, pp. 25–31.

[8] Tsongas, G., "Splashback—A Newly-Recognized Common Wall Wetting Mechanism Easily Controlled with the Use of Exterior Rigid Insulation," *Proceedings, Building Solutions, 1993 EEBA/NESEA Conference*, Boston, MA, March 3–6, 1993.

[9] Tsongas, G. and Quarles, S., "A Study of Issues Relating to Mold on Lumber," Final Report for the American Forest and Paper Association, April 2002.

[10] Prestemon, D. R., "Perceived Moisture Problems in Iowa Homes," Technical Note, *For. Prod. J.*, Vol. 41, No. 6, June 1991, pp. 47–48.

[11] Tsongas, G. A., "A Field Study of Moisture Damage in Walls Insulated Without a Vapor Barrier," ORNL/Sub-78/97726/1, Oak Ridge National Laboratory, Oak Ridge, TN, 1980; also *Proceedings, 1979 ASHRAE/DOE-ORNL Conference on the Thermal Performance of the Exterior Envelopes of Buildings*, ASHRAE SP 28, 1980, pp. 801–815.

[12] Tsongas, G. A., "The Spokane Wall Insulation Project: A Field Study of Moisture Damage in Walls Insulated Without a Vapor Barrier," U.S. DOE/Bonneville Power Administration DOE/BP-541, September 1985; also *Proceedings, 1985 ASHRAE/DOE/BTEEC Conference on Thermal Performance of the Exterior Envelopes of Buildings III*, ASHRAE SP 49, 1986, pp. 556–569.

[13] Tsongas, G. A., "Moisture Control in Lane County Housing Authority Selected Residences," final (unpublished) report for Lane County Housing Authority, December 1984.

[14] Moisture Induced Problems in NHA Housing," 3 Parts, Canada Mortgage and Housing Corporation, report prepared by Marshall, Macklin, Monaghan, Ltd., Cat. No. NH20-1/2-1983-1E, ISBN 0-662-12662-9, Ottawa, Ontario, Canada, June 1983.

[15] Merrill, J. L. and TenWolde, A., "Overview of Moisture-Related Damage in One Group of Wisconsin Manufactured Homes," *ASHRAE Transactions*, Vol. 95, Part 1, 1989, pp. 405–414.

[16] Olson, J., et al., "Tri State Homes: A Case Study of Liability for Defective Homes Which Created Unhealthy Environments Causing Personal Injuries," *Proceedings, International Conference on Building Design, Technology and Occupant Well-being in Temperate Climates*, Brussels, Belgium, Feb. 1993.

[17] Tsongas, G. and Olson, J., "Tri State Homes: A Case Study of Extensive Decay in the Walls of Wisconsin Manufactured Homes," *Proceedings, Thermal Performance of the Exterior Envelopes of Buildings VI Conference*, Clearwater Beach, FL, 1995.

[18] Anderson, R., "Condensation Problems: Their Prevention and Solution," U.S.D.A. Forest Service Research Paper, FPL 132, 1972.

[19] "Interior Moisture Project Phase 1 Final Report," File Number 06-88-0071-04.2, Nova Scotia Department of Mines and Energy, Residential Energy Programs, P.O. Box 1087, Halifax, N.S. B3J2X1, 10 April 1989 (contact George Foote).

[20] "Interior Moisture Project Phase 2 Final Report," File Number 06-90-0071-04.2, Nova Scotia Department of Mines and Energy, Residential Energy Programs, P.O. Box 1087, Halifax, N. S. B3J2X1, June 1990 (contact George Foote).

[21] Rose, W. B., "Case Study: Moisture Damage to Homes in Champaign County, IL," *Proceedings, Building Thermal Envelope Coordinating Council Symposium on Air Infiltration, Ventilation, and Moisture Transfer*, Dallas, TX, 1986.

[22] "Moldy Houses: Why They Are and Why We Care & Additional Analysis of Wallaceburg Data: the Wallaceburg Health and Housing Studies," Canada Mortgage and Housing Corporation Technical Series 02-103, 3/11/2003; http://www.cmhc-schl.gc.ca/publications/en/rh-pr/tech/02-103-e.html.

[23] Rose, W. and Francisco, P., "Field Evaluation of the Moisture Balance Technique to Characterize Indoor Wetness," *Proceedings, Performance of the Exterior Envelopes of Whole Buildings IX International Conference*, Clearwater Beach, FL, Dec. 2004.

[24] Trethowen, H., *Air, Earth, Water–the Sources of Moisture*, Air Infiltration and Ventilation Centre Moisture Workshop 1987, Building Research Association of New Zealand (BRANZ), Porirua, NZ, March 1987.

[25] Lstiburek, J., "Sand Layers Should Not Be Placed Between Polyethylene Vapor Barriers and Concrete Floor Slabs," Building Science Corporation, 2001, http://buildingscience.com/resources/foundations/sand_layer_under_slab.htm.

[26] Tsongas, G. A., "The Effect of Building Air Leakage and Ventilation on Indoor Relative Humidity," *Proceedings, Building Thermal Envelope Coordinating Council Symposium on Air Infiltration, Ventilation, and Moisture Transfer*, Dallas, TX, 2–4 Dec. 1986.

[27] Tsongas, G. A., "Building Tightness Guidelines: When Is a House Too Tight?" *Home Energy*, Vol. 10, No. 2, March/April 1993.

[28] Hecherling, P. S., et al., "Predictors of Occult Carbon Monoxide Poisoning in Patients with Headache and Dizziness," *Ann. Intern Med.*, Vol. 107, 1987, pp. 174–176.

[29] Trechsel, H. R., et al., "Field Study on Moisture Problems in Exterior Walls of a Masonry Housing Development on the Coast of the Gulf of Mexico," *Thermal Insulation: Materials and Systems, ASTM STP 922*, F. J. Powell and S. L. Mathews, Eds., ASTM International, West Conshohocken, PA, 1987, pp. 371–393.

[30] Tsongas, G. A., "A Field Study of Moisture Problems and Damage Inside New Pacific Northwest Homes," *Proceedings, ASHRAE/DOE/BTECC Conference on the Thermal Performance of the Exterior Envelopes of Buildings V*, Clearwater, FL, Dec. 1992.

[31] ASHRAE, *2001 Handbook of Fundamentals*, Ch. 26, "Ventilation and Infiltration," ASHRAE, Atlanta, GA.

[32] Burch, D. and Tsongas, G., "A Personal Computer Program for Predicting Heat and Moisture Transfer in Building Components," *Proceedings, Bugs, Mold, and Rot III Symposium*, Washington, DC, June 1999.

[33] Palmiter, L., private communication, Ecotope, Seattle, WA.

[34] Tsongas, G. A. and Wridge, R., "Field Monitoring of the Winter Performance of a Residential Dehumidifier," *ASHRAE Transactions*, Vol. 95, Pt. 1, 1989, pp. 284–294; also U.S. DOE/

Bonneville Power Administration, Report no. DOE/BP-981, Portland, OR, March 1988.

[35] Galbraith, C. H., "Portable Dehumidifiers for the Control of Condensation in Housing," *Building Services Engineering Research and Technology* (United Kingdom), Vol. 7, No. 1, 1986, pp. 1–10.

[36] Sanders, C., "Domestic Dehumidifiers," *Building Services Research Report* (Building Research Establishment, United Kingdom), Vol. 7, No. 9, September 1985, p. 93.

[37] Rudd, A., et al., "Residential Dehumidification and Ventilation Systems Research for Hot-Humid Climates," *Proceedings, 4th AIVC Conference*, Washington, DC, 2003; http://buildingscience.com/resources/presentations/Rudd_Residential_Dehumidification_and_Ventilation_Systems.pdf; Rudd, A., "Final Technical Paper: Advanced System Performance Dehumidification Project," U.S. Department of Energy Subcontract No. ADC-1-30469-00 Deliverable 11, 2002.

[38] 2006 International Building Code, Section 1203.3, International Code Council, Washington, DC; see also the 2006 International Residential Code, Section 408 (the companion code governing one- and two-family residential dwellings) which contains some differences in ventilation requirements and allows for unvented crawl spaces where a vapor retarder is installed and mechanical ventilation or conditioned air is provided.

[39] Quarles, S. L., "Factors Influencing the Moisture Conditions in Crawl Spaces," *For. Prod. J.*, Vol. 39, No. 10, 1989, pp. 71–75.

[40] Duff, J. E., "Moisture Content of Joist Over a Crawl Space," Research Paper SE-189, USDA Forest Service, Southeastern Forest Experimental Station, 1978.

[41] Duff, J. E., "Moisture Conditions of a Joist Floor Over an Insulated and Sealed Crawl Space," Research Paper SE-206, USDA Forest Service, Southeastern Forest Experimental Station, 1980.

[42] Moody, T. L., et al., "Heat Loss and Gain Through Floors Above Insulated Crawlspace Walls," *ASHRAE Transactions*, Vol. 91, Pt. 2, 1985.

[43] Choong, E. T. and Cassens, D. L., "Effect of Soil Cover on Wood Moisture Contents in Crawl Spaces of Houses," Note No. 36, Louisiana Agricultural Experimental Station, 1985.

[44] Harrje, D. T., et al., "Measurements of Moisture in Crawl Spaces Retrofitted for Energy Conservation," *Proceedings, Building Thermal Envelope Coordinating Council Symposium on Air Infiltration, Ventilation, and Moisture Transfer*, Dallas, TX, 1986.

[45] Jennings, C. W. and Moody, T. L., "Field Experiences Underscore the Importance of Moisture Control in Energy-Efficient Homes," *Proceedings, ASHRAE/DOE Conference on the Thermal Performance of the Exterior Envelopes of Buildings II*, ASHRAE SP 38, 1983, pp. 1063–1077.

[46] Tsongas, G., "Crawl Space Moisture Conditions in New and Existing Northwest Homes," *ASHRAE Transactions*, Vol. 100, Pt. 1, 1994.

[47] Dumont, R. S., "Wall Panel Moisture Tests, Outdoor Test Facility," interim report (unpublished), Prairie Regional Station, National Research Council, Saskatoon, Saskatchewan, Canada, May 1990.

[48] Moffatt, S., "Investigation of Crawl Space Ventilation and Moisture Control Strategies for British Columbia Houses," final report prepared for the Research Division, Canada Mortgage and Housing Corporation, by Sheltair Scientific, Ltd., Vancouver, BC, June 1991.

[49] Lstiburek, J., "Conditioned Crawlspace Construction, Performance and Codes," Building Science Corporation, November 2004, http://buildingscience.com/resources/foundations/conditioned_crawl.pdf.

[50] Davis, B. and Dastur, C., "Moisture Performance of Closed Crawl Spaces and Their Impact on Home Cooling and Heating Energy in the Southeastern United States," *Proceedings, Performance of the Exterior Envelopes of Whole Buildings IX International Conference*, Clearwater Beach, FL, Dec. 2004. See also "Closed Crawl Spaces: An Introduction to Design, Construction and Performance," www.advancedenergy.org.

[51] "Recommended Practices for Controlling Moisture in Crawl Spaces," *ASHRAE Technical Bulletin*, Vol. 10, No. 3, 1994.

[52] DeWitt, C., "Crawlspace Myths," *ASHRAE J.*, Vol. 45, No. 11, 2003, pp. 20–27.

[53] Goldberg, L., "The Thermal Performance of an Insulated Foundation," Minnesota Building Research Center, Underground Space Center, University of Minnesota, Minneapolis, MN, fact sheet number MNBRC-USC-FS06-1989, Oct. 1989, pp. 1–4.

[54] Goldberg, L., "The Thermal Performance of an Insulated Foundation, Second Year Results," Minnesota Building Research Center, Underground Space Center, University of Minnesota, Minneapolis, MN, fact sheet number MNBRC-USC-FS07-1990, Oct. 1990, pp. 1–2.

[55] Dutt, G. S., "Condensation in Attics: Are Vapor Barriers Really the Answer?, *Energy Build.*, Vol. 2, pp. 251–258.

[56] Burch, D. M., et al., "Experimental Validation of an Attic Condensation Model," *ASHRAE Transactions*, Vol. 90, Part 2A, 1984, p. 59.

[57] Harrje, D. T., et al., "Field Measurements of Seasonal Wood Moisture Variations in Residential Attics," *Proceedings, Thermal Performance of the Exterior Envelopes of Buildings III*, ASHRAE, 1986, pp. 620–633.

[58] Cleary, P., "Humidity in Attics—Sources and Control Methods," Lawrence Berkeley Laboratory Report No. LBL-17590, University of California, Berkeley, CA, July 1984.

[59] Cleary, P. and Sherman, M., "Seasonal Storage of Moisture in Roof Sheathing," *Proceedings, Moisture and Humidity 85 Conference*, 1985.

[60] Cleary, P. and Sonderegger, R., "A Method to Predict the Hour by Hour Humidity Ratio of Attic Air," Report No. LBL-17591, Lawrence Berkeley Laboratory, University of California, Berkeley, CA.

[61] Forest, T. W., et al., "Moisture Accumulation in a Building Envelope," final report, Mechanical Engineering Dept. Report No. 80, Department of Mechanical Engineers, University of Alberta, Edmonton, Alberta, Canada, T6G 2G8, April 1990.

[62] Tsongas, G. A. and Bolme, B., "A Case Study of the Cause of Roof Moisture Damage," *Proceedings, Building Thermal Envelope Coordinating Council Symposium on Air Infiltration, Ventilation, and Moisture Transfer*," Dallas, TX, 1986.

[63] Structural Insulated Panel Association, "SIPA Report on the Juneau, Alaska Roof Issue," Feb. 2002; http://www.sips.org/technical/juneau_report.html.

[64] Auer, D., et al., "A Comprehensive Hygrothermal Investigation of an Unvented Energy-Efficient Roof Assembly in the Pacific Northwest," *Proceedings, Thermal Performance of Exterior Envelopes of Whole Buildings X International Conference*, Clearwater Beach, FL, Dec. 2–7, 2007.

[65] Cunningham, M., Tsongas, G. A., and McQuade, D., "Solar Driven Moisture Transfer Through Absorbent Roofing Materials," *ASHRAE Transactions*, Vol. 96, Part 1, 1990.

[66] Spalt, H. A., and Sutton, R. F., "Buckling of Thin Surfacing Materials Due to Restrained Hygroexpansion," *For. Prod. J.*, Vol. 18 No. 4, 1968, p. 53.

[67] Burch, D., and Tsongas, G., "MOIST: A Numerical Method for Design," Chapter 8, *Moisture Analysis and Condensation Control in Building Envelopes, MNL40*, H. Trechsel, Ed., ASTM In-

ternational, West Conshohocken, PA, 2001.
[68] McNatt, J. D., "Buckling Due to Linear Expansion of Hardboard Siding," *For. Prod. J.*, Vol. 23, No. 1, 1973, p. 37.
[69] Zylkowski, S., "Dimensional Performance of Wood-Based Siding," Research Report 149, American Plywood Association, Technical Services Division.
[70] Weidt, J. L., "Minnesota Retrofit Insulations In Situ Test Program Extension and Review," ORNL/Sub-79/13660/1, Oak Ridge National Laboratory, Oak Ridge, TN, 1980.
[71] Weidt, J. L., et al., "Field Investigations of the Performance of Residential Retrofit Insulation," National Bureau of Standards Technical Note 1131, U.S. Dept. of Commerce, Washington, DC, 1980.
[72] Tsongas, G., "Wall Wood Decay and Weatherizing Older Mobile Homes," U.S. DOE/Bonneville Power Administration, RCDP Technical Update, DOE/BP-2545, 1995; also Tsongas, G., "Moisture and Mobile Home Weatherization," Home Energy Magazine, July/Aug. 1995.
[73] "Problems with Decay in Structural Insulated Panels (SIPs) More Severe than Originally Thought," The Forest Products Conservation & Recycling Review—Nov./Dec. 2003, p. 10; http://www.fpl.fs.fed.us/documnts.nltr112203.html.
[74] Lstiburek, J., "Insulation-Induced Paint and Siding Failures," *Proceedings, Energy Efficient Buildings Association Conference*, Minneapolis, MN, March 1987.
[75] "Water Penetration Resistance of Windows: Study of Manufacturing, Building Design, Installation and Maintenance Factors," Research Highlights, Technical Series 03-124, Canada Mortgage and Housing Corporation, Nov. 2003.
[76] "Water Penetration Resistance of Windows—Study of Codes, Standards, Testing, and Certification," Research Highlights, Technical Series 03-125, Canada Mortgage and Housing Corporation, Nov. 2003.
[77] Burch, D. M., et al., "The Use of Low-Permeability Insulation as an Exterior Retrofit System—A Condensation Study," *ASHRAE Transactions*, Vol. 85, Part 2, 1979, pp. 547–562.
[78] Sherwood, G., "Condensation Potential in Wood-Framed Walls," *Thermal Insulation: Materials and Systems, ASTM STP 922*, F. J. Powell and S. L. Mathews, Eds., ASTM International, West Conshohocken, PA, 1987, pp. 405–417.
[79] Sherwood, G. E., "Condensation Potential in High Thermal Performance Walls—Cold Winter Climate," Research Paper FPL 433, USDA Forest Products Laboratory, Madison, WI, 1983.
[80] Forest, T. W., "Moisture Transfer Through Walls," *Proceedings, ASHRAE/DOE/BTECC/CIBSE Conference on Thermal Performance of the Exterior Envelopes of Buildings IV*, ASHRAE, 1989, pp. 532–542.
[81] Kane, R., and Titley, G., "Case Histories of Moisture Monitoring in Residential Walls," *Thermal Insulation: Materials and Systems, ASTM STP 922*, F. J. Powell and S. L. Mathews, Eds., ASTM International, West Conshohocken, PA, 1987, pp. 615–629.
[82] White, J. H., "Moisture Transport in Walls—Canadian Experience," *Proceedings, ASTM Symposium on Mechanisms and Measurement of Water Vapor Transmission Through Materials and Systems*, Bal Harbour, FL, 6–10 Dec. 1987.
[83] "CMHC/CHBA Task Force on Moisture Problems in Atlantic Canada," Report No. NHA 6052, Canada Mortgage and Housing Corporation, Ottawa, Ontario, Canada, May 1988.
[84] Tsongas, G. A., "The Effect of Exterior Insulating Sheathing on Wall Moisture," *Proceedings, ASTM 2nd Symposium on Insulating Materials: Testing and Applications*, ASTM International, West Conshohocken, PA, 1991.
[85] Tsongas, G. A., and Nelson, G., "A Field Test for Correlation of Wall Air Leakage and Wall High Moisture Content Sites in Tightly Built Homes," *ASHRAE Transactions*, Vol. 97, Part 1, 1991.
[86] Vlooswyk, J. A., "Field Monitoring of Cellulose in Walls—Edmonton," Canada Mortgage and Housing Corporation, Ottawa, Ontario, Canada, final report, 8 Jan. 1990.
[87] Murray, C., et al., "Hygrothermal Performance of Wall Systems in a Test Facility in the U.S. Pacific Northwest: First Year Results," Interim Report to U.S. DOE, April 2005; see also: http://www.energy.wsu.edu/projects/building/moisture.cfm.
[88] TenWolde, A., et al., "Airflows and Moisture Conditions in Walls of Manufactured Homes," *Airflow Performance of Building Envelopes, Components, and Systems, ASTM STP 1255*, M. Modera and A. Persily, Eds., ASTM International, West Conshohocken, PA, 1995, pp. 137–155.
[89] Straube, J., et al., "Field Studies of Ventilation Drying," *Proceedings, Performance of the Exterior Envelopes of Whole Buildings IX International Conference*, Clearwater Beach, FL, Dec. 2004.
[90] "Survey of Building Envelope Failures in the Coastal Climate of British Columbia," Research Highlights, Technical Series 98-102, Canada Mortgage and Housing Corporation, 1998.
[91] "Best Practice Guide—Wood-frame Envelopes in the Coastal Climate of British Columbia," Canada Mortgage and Housing Corporation, 2000 (revised 2001); $89.
[92] "Building Envelope Rehabilitation Consultant Guide and Owner/Property Manager Guide," Research Highlights, Technical Series 2000-115, Canada Mortgage and Housing Corporation, 2000.
[93] "Study of Envelope Performance in the Coastal Climate of British Columbia," Research Highlights, Technical Series 02-120, Canada Mortgage and Housing Corporation, 2002.
[94] Carll, C., et al., "Moisture Performance of a Contemporary Wood-Frame House Operated at Design Indoor Humidity Levels," *Proceedings, Thermal Performance of the Exterior Envelopes of Whole Buildings X International Conference*, Clearwater Beach, FL, Dec. 7–11, 2007.
[95] TenWolde, A., and Mei, H. T., "Moisture Movement in Walls in a Warm Humid Climate," *Proceedings, ASHRAE/DOE/BTECC Conference on Thermal Performance of the Exterior Envelopes of Buildings III*, ASHRAE SP 49, 1986, pp. 570–582.
[96] Carll, C., et al., "Performance of Back-Primed and Factory-Finished Hardboard Lap Siding in Southern Florida," Research Paper FPL-RP-581, USDA Forest Products Laboratory, Madison, WI, 2000.
[97] Lstiburek, J., "Rainwater Management Performance of Newly Constructed Residential Building Enclosures During August and September 2004," Building Science Corporation report prepared for the Home Builders Association of Metro Orlando and the Florida Home Builders Association, January 2005; http://buildingscience.com/resources/walls/rainwater_management.pdf.
[98] EIFS Industry Members Association (EIMA) website: (http://www.eima.com/pdfs/EIMA_Executive_Summary_new.pdf.
[99] Tsongas, G., Govan, D., and McGillis, J., "Field Observations and Laboratory Tests of Water Migration in Shiplap Hardboard Siding," *Proceedings, Thermal Performance of the Exterior Envelopes of Buildings VII Conference*, Clearwater Beach, FL, Dec. 1998.
[100] Lacasse, M., et al., "Report from Task 6 of MEWS Project: Experimental Assessment of Water Penetration and Entry into Wood-Frame Wall Specimens—Final Report," Research Report IRC-RR-133, *Institute for Research in Construction, National Research Council Canada*, February 1, 2003; http://irc.nrc-cnrc.gc.ca/fulltext/rr133/.
[101] Bomberg, M., et al., "Report from Task 2 of MEWS Project: Description of 17 Large Scale Wall Specimens Built for Water Entry Investigation in IRC Dynamic Wall Testing Facility," Research Report IRC-RR-111, Institute for Research in Con-

struction, National Research Council Canada, Oct. 2002.

[102] Dumont, R. and Snodgrass, L., "Investigation of Window Installation Techniques to Minimize Rain Entry in Wood-frame Construction," Building Performance Section, Saskatchewan Research Council, Saskatoon, SK, unpublished report, Sept. 2000.

[103] Tsongas, G., Weston, T., and Helton, E., "A Laboratory Test of Residential Wall Cavity Water Drainage and Damage with Different Building Papers and Housewraps," to be published.

[104] Tsongas, G., et al., "Laboratory Water Penetration Tests of Shiplap (Dropside) Hardboard Siding," *Proceedings, Forest Products Society Conference on Wood-Frame Housing Durability and Disaster Issues*, Las Vegas, NV, 2004.

[105] Brown, W., et al., "Barrier EIFS Clad Walls: Results from a Moisture Engineering Study," *J. Thermal Insulation and Building Envelopes*, Vol. 20, Jan. 1997, pp. 206–226.

[106] Brown, W., et al., "Water Management in Exterior Wall Claddings," *J. Thermal Insulation and Building Envelopes*, Vol. 21, July 1997, pp. 23–43.

[107] Said, N., et al., "Long-Term Field Monitoring of an EIFS Clad Wall," *J. Thermal Insulation and Building Envelopes*, Vol. 20, April 1997, pp. 320–338.

[108] Tsongas, G., "Water Movement in Wood-Frame Walls," Session I: Durable Structures Don't Just Happen, *Proceedings, Wood Protection 2006 Conference*, Forest Products Society, New Orleans, LA, March 2006, pp. 23–39.

14

General Principles for Design of Building Enclosures with Consideration of Moisture Effects

Mark T. Bomberg,[1] Heinz R. Trechsel,[2] and Paul R. Achenbach[3]

Objectives

MODERN NORTH AMERICAN (NA) BUILDING ENCLO-sures are highly insulated and airtight. Most NA houses and buildings use mechanical ventilation. The use of air conditioning is becoming more and more prevalent. These and many other changes [1] have reduced the drying potential of walls and required that consideration of moisture in building enclosures (BE) becomes a more important component in the design process.

Therefore, the objectives of a designer or builder with respect to moisture control are:

1. To ensure the adequate performance during the service life.
2. To ensure good indoor environment by avoiding mold growth inside or on BE surfaces.
3. To ensure economic use of energy and materials.

A Systems Approach to Moisture Control

Background

An architect may distinguish between four subsystems that contribute to environmental control [2], namely:

1. The site subsystems (site design that includes shape and form of the building, landscape, roads and pathways, wind diversion, sun shading, etc.). These subsystems define the environment next to the building, the so-called mezzo-climate.
2. The building enclosure (the façade design that includes consideration of natural lighting and egress, e.g., doors, windows, balconies, terraces).
3. The subsystems that satisfy environmental and service demands.
4. The subsystems that facilitate the distribution of energy throughout the buildings which, together with (3), form a comprehensive environmental system.

Flynn and Segil [2] stated: "But rather than a simple correction of climatic deficiencies, the environmental control function of building must be oriented toward the more extensive sensory demands of various occupant activities and experiences. This occupant perceives light as the surface brightness and color; he absorbs heat from warmer surfaces and warmer air; and he himself emits heat to the cooler surfaces and cooler air. He responds physiologically to humidity, to air motion, to radiation and to air freshness. He also responds to sound. A major function of the building, then, is to provide for all the sensory responses concurrently—to establish and maintain order and harmony in the sensory environment."

Why is this goal not being regularly achieved in the real world? Today's design process involves construction and commissioning of buildings with a separation between the construction professionals and trades, where each has a circle of responsibility defined by their expertise. Architects—design the concept of the building; structural engineers—design the building shell and structure, mechanical engineers—design the HVAC and services; those who design fire, acoustic, and lighting are also thoroughly trained in their respective professions. Yet, architects and structural engineers in North America receive little or no formal training in building science. In effect, the team of specialized experts without the basic education in building science has no common ground on how… "to establish and maintain order and harmony in the sensory environment." The current design process does not provide the facility for predicting performance of a new system during the design stage. Nor does it usually provide the means for establishing a quality assurance program that starts during the design and continues through construction, and finally ending with the commissioning of the completed building. To provide such means one needs a set of measurable performance criteria.

The history of indoor air control (see later text in this chapter) highlights experience that led to the realization that moisture control is a systems problem; that is, the designer must find methods to prevent excessive air transport through the building enclosure, 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 minimizing construction costs. As a part of the design process, the building must be equipped with the means for disposing of construction moisture and mois-

[1] *Research Professor, Syracuse University, Syracuse, NY 13244, E-mail: mark.bomberg@gmail.com*
[2] *Consultant, 2111 Jefferson Davis Highway, Suite 804 North, Arlington, VA 22202.*
[3] *Deceased author of the first edition of this chapter.*

ture loads generated by the occupants and processes occurring in the building.

Since heat, air, and moisture transport processes through the building enclosure are not separable and must be dealt with simultaneously, we shall use the term environmental control to describe the functions encompassed in the four design subsystems noted above.

Priorities in Environmental Control

The larger the potential source of moisture the higher the priority should be assigned to dealing with it. The largest sources of moisture involving buildings are rain and groundwater. Since both areas of control appeared to be so well recognized, and there are several books related to these topics, the recent multi-million failures of building envelopes in the lower mainland of British Columbia [3] and North Carolina [4] came as a surprise to many building scientists. One source of moisture, almost as powerful as rain, is fog. Its effect on moisture pick-up by the adjacent enclosures has not been researched well to make any recommendations, yet one must be more careful when building in areas with frequent fog.

The second priority, in the order of significance, is the need to control air flows through building enclosures because this affects many aspects of building performance:

1. Indoor environment (IE) and indoor air quality (IAQ) as it relates to ventilation, air redistribution, humidity of air, and deposition of mold spores, dust particles and mites, and the release of volatile organic compounds (VOC) in building materials.
2. Durability of materials in the enclosure as it relates to moisture carried by the moist air.
3. Cost of heating or cooling of air leaking through the building enclosure (energy conservation).
4. Fire propagation as oxygen supply is critical for efficient combustion.
5. Smoke control as air movement during the fire causes smoke spread.
6. Efficiency of thermal insulation as it may be reduced by air movement (mixed convection).
7. Airborne noise as it relates to air transport and penetrations through the building enclosure.
8. Thermal comfort of the occupants as it relates to drafts.

The third aspect of environmental control is the amount of thermal insulation provided on the upstream part of the water vapor path to modify the location and the potential for water vapor condensation (insulation to the exterior of the condensing plane).

Last but not least, we need to examine the water vapor diffusion resistance to both faces of the wall. Vapor diffusion control must be considered not only for prevention of wetting of materials but also for drying of wetted materials to both the indoor and outdoor environments.

Approaches to Provide Environmental Control in Building Enclosures

Ultimately the provision of moisture control should follow the same pattern as is involved in structural design, i.e., it should be based on limit states design. The main steps in limit states design include identification of:

1. Exterior and interior loads.
2. Transfer mechanisms.
3. Quantifying hygrothermal stresses in the material/assembly.
4. Comparing hygrothermal stresses with allowable limits (criteria).

The following sources of moisture should be included as environmental loads:

- Construction (or built-in) moisture. This moisture is incorporated in materials such as concrete or stucco, absorbed in wood-based products or otherwise enclosed in the building assembly during construction.
- Driving rain. The rain that reaches vertical surfaces of the wall. The wind pattern around the building is highly nonuniform and therefore more driving rain reaches exposed top edges and corners of buildings than reaches the lower portions of the façade.
- Water vapor in the external or internal air is a source for moisture pick up depending on the temperature and moisture content of the materials facing air.
- Fog and dew, causing wetting as from a low intensity rain, but deposited broadly.

The following causes of air movement contribute to environmental loads:

- Wind pressures—as they vary depending on wind force, orientation and geometry of the building.
- Stack effects—internal pressures vary depending on height of the building and temperature differences between interior and exterior air.
- Unbalanced HVAC systems—local heating or cooling devices, local exhaust or air conditioning devices may cause pressure difference for shorter or longer periods of time.

Other environmental loads (effects) include thermal or hygric expansion or contraction of materials as well as moisture-originated shrinkage of materials.

Exterior and interior loads were discussed in Chapters 6 (climate) and 7 (moisture sources). These chapters identified and discussed the sources of moisture affecting a building, namely, climate, indoor moisture generation, groundwater, sprinkler water, and construction moisture.

Transfer mechanisms were discussed in Chapter 1 while material characteristics used in quantifying those transfers were discussed in Chapter 2. Chapters 3, 4, and 6 discussed the effects of moisture on reducing material performance and the potential for creating discomfort or health effects.

Finally, Chapter 27 gives an overview of the application of limits states to evaluation of freeze-thaw risk for clay-bricks. One may notice that since the first edition of Manual 18, unidirectional testing methods became more frequently used to valuate freeze-thaw risk for clay masonry, yet the one cycle test described in that chapter still remains in the future realm of acceptance.

One can speculate that this is caused by the slow pace of acceptance of heat, air, moisture (HAM) modeling as the means of performance evaluation. In contrast to structural engineering, where methods and values for material properties are in dispute, the test methods used for determination of hygrothermal properties are yet insufficiently developed. That, combined with generally poor characterization of tested specimens, makes comparisons between results measured at different laboratories difficult. While some progress

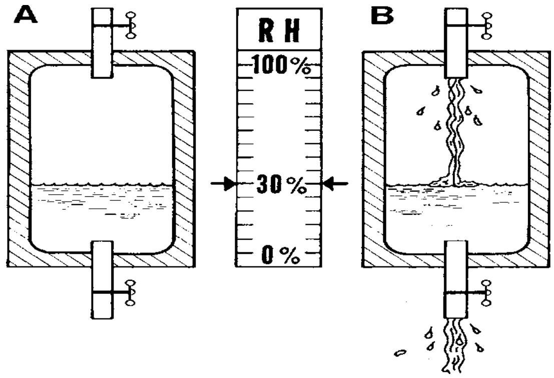


Fig. 1—Two approaches to moisture design: (A) design with barriers, (B) design based on moisture balance (flow-through) principles.

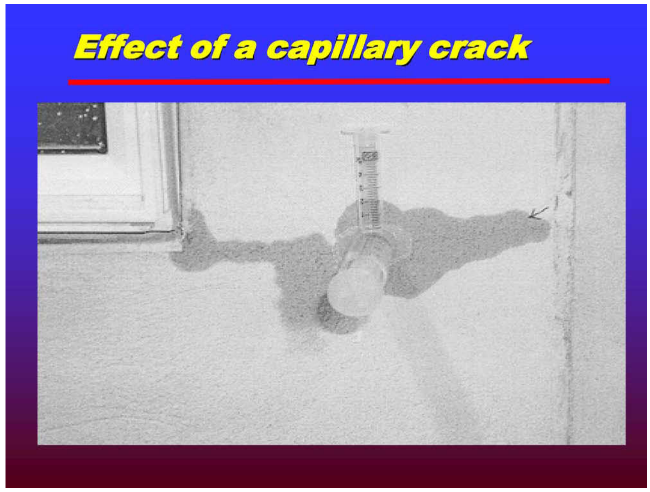


Fig. 2—Water absorption rate measured at a cracked surface is several times higher than that measured at a noncracked material surface.

is made in Europe [5] or the ASTM publication [5] the use of HAM models in physical design is limited and they remain as tools for comparative assessments.

Moisture transport in porous materials is a very complex subject. While a simplified method, e.g., dew point approach, can be used to find if there is a potential problem, this tool is not suitable for decision making. Similarly, as we said before, the current computer codes are only suitable for sensitivity analysis and finding the relative significance of climatic or material factors. Thus, it is ultimately a designer who makes the decision on how to avoid potential moisture problems.

Selected Issues in Understanding of Moisture Transfer

While mechanisms of moisture transfer are reviewed elsewhere, to enhance a designer's ability for making right decisions the authors explain a few critical aspects of this topic.

First, we must state that one element of moisture control, namely the vapor barrier (retarder), has received a disproportionate amount of attention. This is mainly because of the simplicity of water vapor transport calculations used in the past. To make the situation worse, practitioners try to avoid moisture condensation and use barriers impermeable for air and vapor on the warm side of the construction. This type of approach is called moisture design with barriers. Conversely, design based on moisture balance (alternatively called a permeable envelope approach) permits temporary moisture accumulation on an intermediate basis. Figure 1 illustrates these two design principles using the analogy of a barrel with and without a leak. No liquid is delivered to Barrel A that has no leaks and none is flowing out of it (design with barriers). In the case of Barrel B, the same quantity flows into it as flows out and the moisture balance does not change on a yearly basis.

The moisture balance approach is more difficult to design for than the barrier approach. It requires performing HAM calculations of the moisture balance over the entire year over which the wall assembly is exposed to the worst set of probable climatic conditions. Based on those calculations one may estimate how much moisture will accumulate within the building envelope during the critical season. Then, one must assess the potential effects of this moisture on the structural durability. If the durability of the materials and components is not adversely affected, one must check whether the drainage and drying capability over the remaining part of the year will lead to safe levels of moisture. Moisture may be allowed to accumulate during the heating or cooling seasons, but it is not allowed to accumulate beyond safe levels from one year to another.

Note that the moisture flow in building enclosures is seldom one-dimensional, and that flow-through invariably involves both liquid flow and vapor diffusion. Actually, the more drainage that can occur as a result of phase changes of moisture[4] entrapped within the enclosure, the more efficient the moisture balance design can be. A well-designed building system is not significantly affected when some moisture enters the structure because of mistakes or unforeseen circumstances. There is no damage to materials, and the system allows for subsequent drainage and drying. Therefore, we often talk about the moisture tolerance of assemblies.

Second, what is not appreciated enough is the fact that moisture always moves to materials at a lower temperature. The equilibrium moisture content of a porous material depends primarily on the relative humidity (RH) of air. When temperature is lowered, the maximum partial pressure of water vapor is also lowered and the relative humidity above pore water is increased. In turn, the equilibrium moisture content is also increased. In effect, moisture in the form of vapor always moves to materials at a lower temperature, while liquid moisture always moves to material having a lower moisture content. In many instances, these two different moisture movement processes can occur simultaneously and in opposite directions.

Third, also not appreciated enough is the role played by cracks in materials and material terminations. Figure 2 shows a device to measure the water absorption rate placed on a hairline crack in exterior stucco. This shrinkage originated crack extends from a window corner to the vertical construction joint (the crack width was about 0.3 mm). It was observed that water was first drawn into the crack and then it spread on the material surface.

[4] Phase changes may occur daily because of solar or night radiation.

Fourth, not appreciated enough are the interactions between heating and ventilating systems and the building enclosure. Lstiburek et al. [6] investigated connected multizonal air flows with spaces inside the building enclosure:

"Actually, exterior wall, roof, interior floor and interior wall/partition assemblies are often hollow or multi-layered with numerous air gaps or void spaces and can operate under air pressure regimes (fields) that are largely independent of the air pressures on either side of them. Buildings also contain numerous service chases that provide complex three-dimensional linkage among the exterior wall, roof, interior floor and interior wall/partition assembly cavities and void spaces. These interstitial air pressure fields within building assemblies and their linkage to chases and service cavities can lead to lateral flow paths or more intricate three-dimensional flow paths that may or may not connect to the interior or exterior spaces that the building assemblies separate.

As the result of these interstitial air pressure fields, direct cross assembly (one-dimensional) airflow does not always hold. To account for the presence of interstitial air pressure fields, airflow must be added or subtracted within an assembly, chase, or void space. In this manner, continuity of mass and momentum holds across the volume of the assembly or element. The interstitial air pressure fields often vary with time with complex daily, weekly, seasonal and sometimes random cycles. They may also be affected by fan forces and coupled with duct leakage. Thermal effects, moisture effects and wind forces can also be interstitial air-pressure-field drivers depending on the linkages of interstitial flow paths. These time-variable, interstitial, air-pressure fields help characterize the transient characteristics of the pressure response of buildings. The presence of complex, time-dependent interstitial air pressure fields and associated lateral or three-dimensional flow paths can lead to complex interactions of the building structure with the mechanical system and climate."

One of the keys to understanding the complex interactions of the structure with mechanical systems and exterior climate is the pressure response of buildings. Building analysis typically focuses on flows and attempts to define all flow paths into and out of a control volume. The resistance of the flow paths needs to be characterized (see ASHRAE [7]).

Building Enclosure: Experience-Based Design

Experience has shown that the first priority in environmental design is to control rain penetration.

PRIORITY 1: Rain Penetration Control

Rain falling on the wall surface can be shed (flow down), stored (attached by surface tension or absorbed by material), or transmitted into the wall. Some of the water flowing onto the wall surface may be removed from the surface by features such as drips and ledges.

Mechanism of Water Entry

Shown in Figs. 3 and 4, the driving forces for rain penetration are: gravity, capillary forces (surface tension), force created by the air pressure difference, and force associated with the kinetic energy of rain drops.

One may distinguish between three design strategies: (1) face-sealed or barrier wall, (2) moisture storage system, and (3) screened and drained systems.

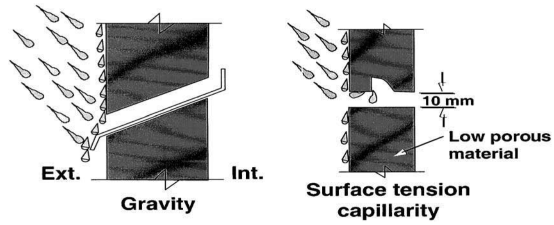


Fig. 3—Control of rain penetration: gravity and capillary forces.

The term "face-sealed" or "barrier walls" denotes assemblies with a single impermeable layer, typically located on the exterior face.

The term "mass walls" indicates assemblies that can prevent penetration of moisture if there is enough storage to absorb all rainwater that is not shed away from the outer surface. The ability of materials to dry is also critical for the performance of such a wall. Performance of mass walls depends on weather conditions. If a series of rain events occurs and drying conditions are poor, the storage capacity may be exceeded, resulting in the failure to limit water intrusion. Therefore, mass walls are routinely provided with drainage capabilities.

There are two special cases of screened and drained systems, where the transmission fraction of the screen is reduced by modifying the air pressure. These systems are called "pressure-moderated" or "pressure-equalized" rain screens.

Straube and Burnett [8] do not accept the simplified picture, where one or two layers provide all necessary controls either through drainage or through barrier functions. They explain that even when one fraction dominates the design, all fractions (drainage, storage, or transmission) play an important role in almost all wall systems. If some storage and drainage is possible in walls considered as face-sealed, these walls may not fail even if the barrier is imperfect. Similarly, many drained brick veneer walls may have poor drainage but function well when sufficient moisture storage is available.

Introducing moisture storage for control of rain penetration broadens the scope of the analysis. Moisture storage is affected by such phenomena as thermally driven redistribution of moisture as well as air leakage. In effect, moisture storage brings all environmental parameters—heat, air, and moisture movements—into simultaneous consideration.

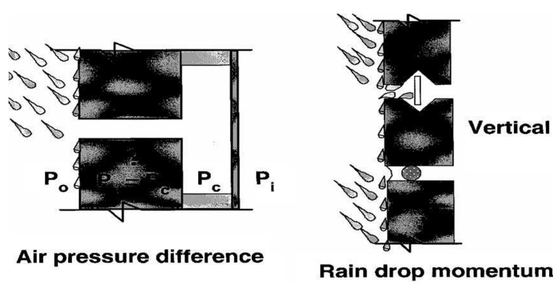


Fig. 4—Control of rain penetration: kinetic energy and air pressure difference.

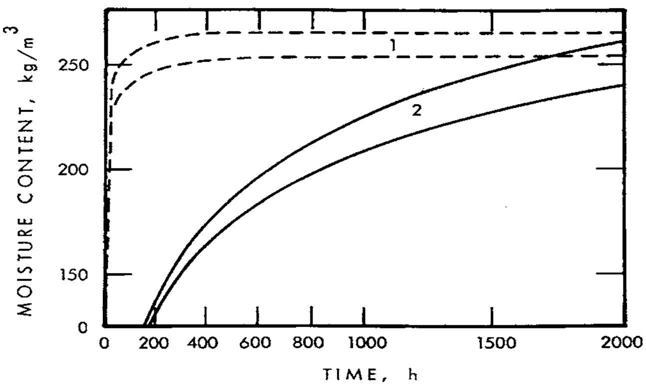


Fig. 5—Moisture gained by initially dry, aerated concrete specimens from wet gypsum specimens. Two levels of moisture content in gypsum and two different conditions at the interface between specimens: (1) samples in direct contact, (2) samples separated by 1-mm air gap (from Bomberg [9]).

Water shedding is the first function of the cladding system. The next environmental function[5] pertains to a capillary break, a function that is often confused with drainage. The capillary break can be achieved by different means. On one hand, we have a water resistive barrier (WRB), a material that selectively stops water transport while allowing transport of water vapor and air. On the other hand, we have an air cavity. A number of materials or components, such as draining mats, self-draining mineral fiber, or grooved plastic insulations are between these two cases.

Figure 5 shows the significance of thin air layer acting as a capillary break. It shows rate of moisture transport when two materials are either in direct contact (total moisture transport) or separated by a thin air gap (allowing only vapor diffusion), cf. [9]). The difference in the rate of moisture transport caused by a break in the contact between two materials is huge. The same moisture equilibrium was reached either in 20 or in 2,000 hours. Obviously, this ratio depends on the capillary nature of both materials, yet it is evident that moisture is moved much faster in its liquid phase than in its vapour phase. Even a small break in continuity breaks the capillary flow of water and presents a dramatic reduction in the rate of moisture transport.

Figure 5 highlights that a capillary break does not require more than 1/16 in. thickness. A thin air gap or even incomplete hydraulic contact can modify the rate of moisture transfer to a very substantial extent. Examples include a contact plane between two layers of WRB and 1/8-in. gaps between ribs of adhesive used for attaching thermal insulation or EIFS lamina. While research into vapor diffusion (convection or phase transition) as a means of moisture removal is scarce, in many instances for removal of small moisture loads this mechanism is all that is needed for successful performance of a wall or roof. The significance of imperfect contact has been also recognized in stucco claddings where a double layer of WRB is required. Typically the WRB that is placed in contact with stucco should be asphalt impregnated Kraft paper that expands during stucco application and provides local capillary breaks.

[5] Each environmental function may be fulfilled by one or many materials or components of the building envelope.

The main reason for recommending air gaps with 4 mm (1/6 in.) or thicker is to facilitate gravity drainage. A drainable cavity helps to remove residual moisture from rain penetration and moisture from vapor condensation. As a rule, any drainage mat or air cavity is protected by WRB on the inner side. In addition to drainage of rain that may find its way to the inner surface of the air gap, the WRB, with some resistance to air flow, reduces the so-called wind-washing effect, when wind enters and exits from the exterior side of the wall. WRB needs to have a specific range (minimum and maximum) of water vapor permeance that depends on climatic conditions.

Selecting a required water vapor permeance of WRB one must observe:

- Prevailing direction of water vapor drive (thermal drive) through the year in relation to moisture storage in the wall assembly (e.g., cellulose versus glass fiber insulation).
- Thermal gradients in the outer layer of the wall varying between day and night, in relation to moisture storage in cladding (stucco versus vinyl siding).
  It has been observed that a too high permeance of WRB placed behind stucco resulted in excessive accumulation of thermally driven moisture in the OSB.

Finally a note about interactions between heat, air, and moisture flows. When we talk about control of water vapor, we think about moisture coming from indoors (in cold climates) or from the outdoors in hot and humid climates. We rarely think about moisture entering the wall from rain. Yet, sometimes the presence of deficiencies provides a coupling between rain ingress and vapor movement. In one case study, rain penetration into leaky masonry walls coincided with negative indoor pressure created by the HVAC [10]. The water evaporated and vapor was carried inward with moving air.

Performance of the capillary break (or lack of it in the assembly) serves to differentiate moisture management strategies:

- Face seal; this strategy requires continuous maintenance and repair of sealants.
- Dual barrier (concealed barrier); WRB can provide local drainage but the system has no weep holes or flashing to facilitate removal of drained water.
- Drain screen, both the weep holes and flashing are used to remove drained water, but the drainage is achieved without employing an intentional air gap.
- Vented drain screen (vented rain screen), weep holes, and flashing are used to remove drained water, and an air cavity provides a capillary break that is connected to external air at the bottom of each story.
- Ventilated drain screen (ventilated or pressure moderated rain screen), weep holes, and flashing to remove the drained water, and an air gap that is connected to external air at the top and bottom of each story.
- Pressure equalized rain screen (PER), flashing is provided to remove the drained water, the air cavity is connected to external air, and the size of openings to it are large enough to ensure that the air pressure in the cavity closely follows that of outside air. The main difference between PER and the previous strategy is the compart-

mentalization of the air cavity to ensure adequate time constant of the wall.

Face Seal Approach (*Barrier Wall*)

Since no barrier is perfect (except that drawn on paper) the assumption that sealant in joints would provide long-term tightness is not realistic. Yet, such a system may function well under limited rain loads if the wall assembly has sufficient storage for moisture. Typical examples of functioning face sealed walls are mass walls, e.g., solid masonry walls with exterior portland cement plaster.

The range of climatic conditions under which this system can be used is difficult to define. These walls do not have other measures for reducing the amount of water penetration through openings and failed joints. In fact, these walls must be evaluated with respect to durability of the wall assembly. Several factors have to be included in such an evaluation, such as building size, shape, and ability to shed water away from the face of the wall, large roof overhangs, the driving rain index for a given climate, etc.

The limits of moisture storage in any material or component of the system depends on the whole system performance, not on the rain penetration control alone. Indeed, to evaluate the durability of the barrier wall, one must be able to predict a degree of system deficiency, actual climatic conditions in the vicinity of building, frequency and duration of wetting periods, and drying capability of the wall. In this context, we must evaluate if, and for how long, the moisture content of any material exceeds the critical moisture content with regard to durability (e.g., freeze-thaw).

The above describes a rather uncertain approach. When this system is used, a few practical measures are recommended:

(a) Avoid using moisture-sensitive materials in the outer wall (wood-based products and gypsum-based substrates are generally disallowed in Europe).
(b) Reduce rain loads through building site considerations such as a maximum three-story building with a large roof overhang placed in the sheltered location, or
(c) Restrict use of this system to such climatic and service conditions in which the drying potential is much higher than the potential for moisture accumulation.
(d) Require development of design details and inspection during the construction period for selected penetrations and flashing details in the cladding.

The uncertainty involved in predicting long-term air and rain tightness of face seal systems has led some building officials to require a multiple-element protection strategy[6] for rain penetration control. In principle, dual barrier is the approach always compatible with barrier walls to introduce a multiple-element rain protection strategy (e.g., for masonry wall it is achieved by an appropriate parging layer).

Dual-Barrier Wall

The term “multiple-element rain protection strategy” can be interpreted as follows:

- The cladding is the first line of defense against rain penetration. It must minimize the passage of water into the wall.
- The second line of defense is a continuous water-resistive barrier (WRB). WRB restricts penetration of rain that passes through the cladding and provides for some local drainage. Typically, a dual-barrier system does not provide full means to remove drained water except at the foundation.

The second line of defense, the WRB, limits entry of liquid water. Materials outboard of the WRB such as stucco or EIFS must have adequate moisture storage and drying capability.

As discussed in Chapters 14 and 18, dealing with construction practices, the balance between entry of moisture and the capability of a system to remove moisture is the key in designing many assemblies. Thus, while in cold climates, highly permeable WRB allows outward drying, yet under reversal of thermal and vapor gradients that take place during solar radiation periods, such a product would allow significant wetting. Effectively the maximum permeance of this product must also be limited.

The extent to which each material feature contributes to the system performance depends on the climate, characteristics of the first line of defense (such as cladding porosity) and moisture susceptibility of the materials in the wall system. Some moisture storage in the cladding may be necessary, as well as assurance that the moisture dries out within a specified time, during which the durability is not affected.

As the moisture storage and drying capability of wall assemblies of this type have limitations, so is the recommended range of climatic conditions for their use. Furthermore, one must consider:

- Air pressure differences often create significant driving forces for rain penetration. To control air pressure difference across the wall assembly, the wall must be provided with an air barrier system.
- The continuity of WRB, flashing, and air barrier must be ensured through proper design of joints, junctions, and penetrations, and built in a proper construction sequence.

Drained Screen

This system comprises all elements of the dual barrier system to which is added some means for removal of drained water. The wall drainage can be provided by one of the following means:

- Drainage mat or drainage plastic sheet material.
- Self-draining insulation material (rigid mineral fiberboard).
- Grooved insulation layer (typically in expanded polystyrene).
- A minimum 6-mm wide air cavity created by lath or strapping.

Redirecting water to the outside by means of flashing is a fundamental feature of any drained screen system.

The acceptance criterion for a drain screen is self-evident, the drain screen system prevents rain ingress to the

[6] In the 1970s, the Canadian metal/glass curtain wall industry decided to abandon the face-sealed approach as a design approach to control rain penetration, after the failure of extensive, and costly, attempts to maintain the integrity of the face-sealed system on metal/glass curtain walls. The architectural precast concrete industry recommends the rainscreen principle to control rain penetration. These systems were typically installed on steel- or concrete-frame buildings, structural systems that put less stress on the integrity of the joint and junction seals. NRC researchers concluded that face-sealed walls are inherently subject to failure, not necessarily all the time and not necessarily during the first rainfall, but certainly within the early life of the building. In all the investigations that have followed, there has never been any evidence to suggest that this situation promises to change. (Commentary to NBC 1995.)

inner part of the wall. Furthermore, the drain screen design may involve different moisture handling mechanisms such as moisture storage, drainage, and drying capability. The extent to which each material feature contributes to system performance and the extent of allowed moisture storage depend on the climate, characteristics of the first line of defense, and moisture susceptibility of the materials in the wall system, i.e., the durability of the whole assembly.

Vented Drain Screen (*Rainscreen*)

This system comprises of all elements of the drained screen system and additional means of moderating the air pressure in the drainage cavity. It has been observed [11] that rain entry in the wall cavity is significantly reduced when the pressure difference between the cavity and external air is as small as possible. Venting openings (weep holes) are located at the bottom of the wall and provided with flashing to remove the drained water.

The differences between performance of a drain screen, rainscreen (vented drain screen), and pressure moderated rainscreen are small and this classification appears to be purely academic. As the degree of connectivity between the cavity and the ambient air depends on several factors related to design, material selection, and workmanship, these concepts are presented mainly to characterize "the design intent."

Ventilated, Drain Screen (*Pressure Moderated Rainscreen*)

This system comprises of all elements of the vented, drained screen system but vents are located at the top and bottom of the drained cavity. Location of vents at both top and bottom of the cavity is expected to introduce a stack effect (a difference in buoyancy of air) causing air movement and thereby removal of moisture from the drainage cavity. As well, external pressure differences between the top and bottom of the cavity drive air flow which can contribute to drying or wetting depending on the sign and magnitude of the pressure difference. To introduce pressure moderation by buoyancy the air cavity needs to be at least 10- mm wide, which reduces the popularity of this design. The difference between vented and ventilated drain screen is also vague. Many arguments for or against the ventilated drain screen relate to variability of aerodynamic conditions at the building surfaces that may cause an undesirable action, namely wetting from rain carried into the vents.

The term "ventilated drained systems" describes a broad range of cavity designs. It is important to distinguish between:

- Pressure moderated rainscreen, and
- Pressure equalized rainscreen (PER), that controls the size of compartments and uses openings that are large enough that pressure is quickly equalized with little flow to compensate for the compression of air.

Comments on "Multiple-Element Rain Protection Strategy"

While scientists like to differentiate between several moisture management strategies, in reality we are dealing with a continuum often denoted as "moisture managed walls." For example drained screen with 1/4 in. air gap is no different from the vented rain screen. Perhaps the only moisture management system that stands out is the one used in high-rises and large buildings exposed to severe exposure conditions, and discussed in the next session.

Pressure Equalized Rainscreen (*PER*)

PER system, in addition to redirecting water outside, through drainage, vents/openings, and flashing, also limits liquid water entry by reducing the air pressure difference between the cavity and external air. An adequate width of air cavity is connected to external air and the large size of openings ensures that the air pressure in the cavity follows that of outside air. PER reduces the moisture loads and permits a higher degree of moisture susceptibility for the materials in the wall system providing the basic requirements are met. Control of air movement in the rainscreen cavity is a particularly important feature of this design. The inward leakage from the rainscreen cavity must be as small as possible, i.e., a good structural air barrier system is necessary. This will determine the effectiveness of cavity ventilation in preventing rain ingress behind the rain screen. Furthermore, to achieve pressure equalization with limited volume of air flows the cavity must be divided into compartments. Practical recommendations for design of PER may be found in the literature [12].

While pressure equalization may be a theoretical goal for control of rain entry, the required area of openings may or may not be practical. Furthermore, opinions are divided regarding the role of ventilation in the extreme climatic conditions, i.e., either very cold, or hot and humid climates.

Note: Principles of PER are used in precast panels in the so-called two-stage design of vertical joints that are comprised of three elements:

- rainscreen (rain and wind screen)
- decompression chamber
- air seal (air barrier)

Neglected Moisture Management System—A Buoancy-Driven Drying

Previously discussed management systems deal with the drainage of water droplets. There is, however, one moisture management system that is seldom discussed because it is slower than the drainage and requires either two surfaces with low permeability or one placed on the cooler side of an air gap and some air movement capability. An air gap as small as 1/16 in. and a few inches wide, over a prolonged period of time may, however, remove significant amounts of moisture.

Typical application of the buoyancy-driven drying is drying through the grooved (partially filled) adhesive layer in EIFS or drying of water entrapped between two layers of WRB.

Priority 2: Control of Air Flows (*Air Barrier Systems*)

A Historic Background

Despite a number of publications that stressed the importance of air leakage control [11,14–16], over the past four decades, building practitioners were preoccupied with controlling vapor diffusion and ignored issues related to air leakage. The breakthrough came only when practical experience by practitioners confirmed the scientific knowledge of the few. Only then did the significance of moisture carried by air become appreciated by the whole building community.

Builders were attracted to electric heating because it reduced the initial costs and eliminated the need for a combustion flue. Higher energy costs were compensated by increased levels of thermal insulation. The construction of flue-less houses and the use of higher levels of insulation led to poor air exchange compared to traditional construction which employed combustion furnaces which drew air through typically leaky wall construction. With the reduced air exchange, condensation problems in attics became more frequent [17], both in cold regions of the country [18] and in flat wood-frame roofs [19]. Several studies showed that moisture accumulation in attics and roofs increased as a result of increased indoor relative humidity caused by two interrelated factors: changes in efficiency of natural ventilation, and changes in the position of the neutral pressure plane [20]. Measurements of air pressure in houses showed that substantial air leakage occurred in attics and joist spaces in flat roofs. This led to recommendations that air tightness of the ceiling construction and partition-to-ceiling details needed to be significantly increased.

During this period, the concept of an air/vapor barrier was introduced [21]. To ensure that a polyethylene vapor barrier could act to control air leakage, the Canadian standard was revised to require a 6-mil (0.15 mm) thick film that uses virgin material only. The perceived simplicity of this requirement resulted in popular application of polyethylene film, much to the concern of some knowledgeable contractors. There was no need for a 6 mil thick polyethylene as a vapor barrier. From a scientific point of view, as long as air tightness requirements are fulfilled, as shown by Karagiozis and Kumaran [22], most of North America does not require the permeance of the vapor barrier to be lower than 3 to 6 perms or 200–400 $ng/(m^2 \cdot s \cdot Pa)$.

With shortcomings in a combined polyethylene air/vapor barrier, it was desirable to separate the functions of air and vapor control [23,24]. Finally, while the combined polyethylene air/vapor barrier was still permitted, in the 1995 edition of the NBC [25] the air barrier system was required to satisfy the following requirements:

- A layer intended to provide the principal resistance to air leakage shall have air permeance not greater than 0.02 $L/(s\ m^2)$ measured at a 75 Pa difference.
- The system shall be continuous across joints, junctions, and penetrations.
- The system shall be capable of transferring wind loads.
- The system should be evaluated with deflections reached at loads 1.5 times the specified wind load.
- All components of the air barrier system shall comply with durability requirements specified by respective material standards.

New systems were introduced in the marketplace, namely the Airtight Drywall Approach (ADA) and the External Airtight Sheathing Element (EASE) when the vapor and air barriers became separated. ADA was developed by Lstiburek and Lischkoff [26] by extensive use of gaskets and controlling joints in the drywall sheets. The vapor resistance was provided by use of paint on the drywall and no polyethylene film was employed.

While ADA systems have been shown to work well in the single-family houses, other considerations including those of flanking sound transmission in row housing and apartment blocks gave preference to other solutions. Application of an external insulating sheathing was found to be beneficial for several reasons. First, by providing a continuous layer of thermal insulation on the outside of the framing, it reduced thermal bridging. Second, by increasing the temperature of the interior surface of the sheathing facing the wall cavities, it reduced the risk of condensation in the cavity of framed walls.

With time, a membrane applied on the exterior OSB sheathing (e.g., peel-and-stick membrane or liquid applied membrane) became a third solution for the design of air barrier systems.

Air Barrier as Part of the Strategy for Controlling Air Pressure in Buildings

A strategy to control air pressure in building spaces includes the following steps:

- Examine the building mezzo-climate for differences in wind and solar shading conditions.
- Enclose the analyzed air space.
- Use controlled mechanical ventilation.
- Control air pressure differences and fluctuations induced by operation of HVAC.
- Eliminate interconnected internal cavities communicating with HVAC systems.

To design and build safe, healthy, durable, comfortable, and economical buildings, we must control the air pressure fields. To control the air pressure field, one must enclose the air space and control the flow of air across the enclosure to a required degree of air tightness. To this end we have introduced the air barrier system.

The air barrier system, however, may not control flow through pathways created by external cavities and interconnected internal cavities communicating with HVAC systems [27]. Lstiburek [28] showed that air leakage/pressure relationships are the key to understanding the interaction between the building envelope and the HVAC system. Thus, in addition to air barrier systems one needs to eliminate undesirable interconnected internal cavities communicating with HVAC systems and control the air pressure differences and fluctuations induced by operation of HVAC systems.

Requirements for Airtightness of Building Assemblies and Enclosures

Air transport control has been recognized as a critical issue in design of the building envelope. Air flow is related to all facets of environmental control because it affects transports of heat, moisture, VOC, and the durability of the building envelope. While the need for airtightness is now well recognized, there is confusion about terminology and criteria used for various types of measurements.

We shall define three concepts,[7] namely:

- Material airtightness (air leakage), is the volumetric, unidirectional air flow measured in laboratory over a range of air pressure differences and determined at 75 Pa (0.3 in. water head) and expressed as flow per unit of area and unit of time [29].
- Assembly airtightness (air leakage) is the volumetric air flow across an assembly isolated from the environment, measured in laboratory over a range of air pressure differences and determined at 75 Pa (0.3 in. water head), and expressed as flow per unit of area and unit of time

[7] This qualification is necessary, because technical publications use different concepts expressed in a similar manner and with identical units.

TABLE 1—Airtightness of building enclosure when tested at 50 Pa under field conditions.

Recommended at 50 Pa		Corresponding values at 75 Pa[h]	
ft³/min-ft²	(L/s-m²)	ft³/min-ft²	(L/s-m²)
0.3	1.5	0.4	2.0

[h]Recalculation is performed for a selected house (bungalow with specific characteristics).

[30]. The wall assembly is provided with the specified type of window and penetrations [31].

- Envelope airtightness (air leakage), is the volumetric, multidirectional air flow measured under field conditions under a wide range of air pressure differences and determined at 50 Pa (0.2 in. water head) and expressed as flow per unit of area and unit of time. Typically, a large area of building enclosure is evaluated in one test and the related to the tested area to establish an average envelope leakage [25,32]. Currently there are no acceptance criteria for envelope leakage that is measured by HVAC or blower door pressurization methods [33,34].

Recently proposed [35] criteria for three types of airtightness are listed in Tables 1 and 2.

Experience in housing has shown that the airtightness criterion established in the curtain wall industry 0.30 L/(s m^2) can be further reduced. The presence or absence of moisture sensitive materials, the composition of layers in the assembly, and conditions of service and local climate are some of the many factors affecting durability of the assembly. The criterion for airtightness depends on a wall construction [36] and, in particular, to the use of thermal insulating sheathings. Ojnanen and Kumaran [37] showed that in a cold climate, thermal insulating sheathing increases temperature in the wall cavity and reduces accumulation of moisture in frame walls. It is not possible to set one criterion for the assembly independent of how and where it is built. Since the above proposed criterion is a benchmark for design that includes allowance for reduction of airtightness as well as experimental errors, setting it at 0.2 L/(s m^2) appears to be an appropriate recommendation for small buildings and housing.

At the moment, some North American authorities use the same airtightness criterion for a masonry wall built on the Pacific Coast as for a wood frame wall in the far North. Yet, Fig. 18 presented in Chapter 2 of the previous version of this manual (chapter replaced by Manual 40) showed that under the same air flow conditions the moisture accumulation would be about 100 times different between those two locations. In effect, while the energy related requirements can be set independently from the climate and service conditions, the durability requirements cannot be set independently of climate and of the materials used in the assembly.

TABLE 2—Airtightness of building enclosure determined at 75 Pa under laboratory conditions.

	Recommended at 75 Pa	
Type of Test	ft³/min-ft²	(L/s-m²)
Assembly	0.040	0.20*
Material	0.004	0.02**

The envelope airtightness relates to the design and performance of mechanical systems and heat losses (or gains) associated with air control. Yet, the problem is complicated because no direct relation between airtightness of the assembly and the envelope has ever been established, and probably cannot be established because each represents a different process modality. This difference is caused by interzonal airflows, possible stack effects, connectivity of places with different air pressure conditions, and HVAC induced pressure variations. One should also remember that the actual pressure difference across the wall is different in various parts of a building. In effect, the envelope airtightness is just another benchmark to indicate how well the building has been built. If testing is done during construction, as is required in certain energy efficient construction programs, it can be used to find if there are built-in defects that need to be fixed while it is still possible to do so. This value should not be used for legal purposes, unless it has been introduced in the design documents.

Priority 3: Insulation to the Exterior of the Condensing Plane

This concept is self-evident in cold climate constructions. The higher the risk for condensation the larger the fraction of thermal insulation is needed on the exterior of the condensing plane. Ultimately, when designing walls in sub artic climate, we do not place any thermal insulation in the frame wall cavity but place all insulation as an exterior layer.

The same principle applies for warm climates although for a different reason. The continuous external thermal insulation increases the effect of thermal mass and, even though it does not reduce the risk for condensation on the inner side of the wall, it may reduce the time of cooling to temperature brings the risk of condensation. In such a climate the continuous air and vapor barrier is typically combined with the WRB function as one membrane product.

Priority 4: Control of Water Vapor Diffusion

If the building enclosure is provided with air barrier system to control air flows, the control of water vapor can be achieved with less stringent measures than previously recommended in some building codes. We use the following terminology (Lstiburek [47]):

- Vapor impermeable; less than or equal to 0.1 perm (5.7 ng/(m$^2 \cdot$s$\cdot$Pa)
- Vapor semi-impermeable; between 0.1 perm and 1 perm (57.2 ng/(m$^2 \cdot$s$\cdot$Pa)
- Vapor semi-permeable; between 1 perm and 10 perm (572 ng/(m$^2 \cdot$s$\cdot$Pa)
- Vapor permeable; greater than 10 perm

Contrary to many guides, we do not provide any general recommendation for the selection of the appropriate range of permeance for vapor retarders. This is because wetting or drying of exterior or interior finishes depend not only on its water vapor permeance but also on the moisture transmission and storage property of the adjacent materials. This is particularly true when discussing requirements for water vapor permeance of water resistive barriers (WRB) used in various assemblies and different climatic zones. Because of heat flow reversal between day and night it is not enough to provide minimum permeance for vapor retarders. When selecting WRB one must consider both the minimum as well as the maximum of the allowed permeance of the material.

Building Components: Specific Elements of Protection

ASTM Standard Practice for Increasing Durability of Building Construction Against Water-Induced Damage (E241) 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.

Exterior Walls

Walls can be subject to all the potentially deleterious moisture transfer processes. The lower few feet of a wall at the foundation can become wet by rain water splash and capillary rise of water from the earth in areas of high water table. Site grading (minimum 2 %) and preparation for draining off rain water are important, particularly as soils always settle in the vicinity of the foundation wall. A horizontal capillary break is needed between the foundation and the bottom of the wall to eliminate this source of wetting. This capillary break can be made in the form of a wide enough strip of a compressible material (flat gasket) to function effectively as air leakage control. Note that frequent impingement of water on the wall from lawn sprinkling or splashing from the ground can also wet the lower part of the walls, and, of course, this source of water may bypass 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.

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 air and vapor barrier materials installed as close as possible to the exterior of the wall to prevent condensation occurring during the summer [38].

Air-conditioned buildings constructed from masonry blocks and finished with furring strips, insulation, vapor retarder between furring strips, and plasterboard interior [39] 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 can be 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. The best solution is to install a WRB that has also a vapor barrier quality between the masonry block and the exterior insulation.

A limited amount of research on moisture transfer in buildings located in the fringe climates north of the humid climate zones [40] indicates that areas of the country with moderate winter temperature and less extreme humid summers may perform satisfactorily with a painted vapor retarder. Extreme summer or winter conditions do not last long enough to cause severe condensation problems. The absorption and desorption cycle in the wood and other hygroscopic materials in the walls is effective in preventing premature decay.

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. Some of conditions associated with the onset of decay were measured 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 and 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 heavy wind-driven rain, the "rainscreen" concept [41] is often used. This concept utilizes an exterior cladding or siding backed by an air space, 1/2-in. wide or more, which is vented to the outside air. The air space, open at the bottom, allows water that penetrates the cladding to drain to the outside. A water resistive barrier must be placed on the inner side of the air space to prevent water and moist air from being forced into the back-up wall. At the floor level, the WRB must overlap the flashing leading water outwards.

In drier climates, a "rain screen" may not be required; water penetration can be prevented by application of WRB over the exterior of the back-up wall.

Windows and Doors

Air barrier material must be continuous, i.e., AB plane material 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 flashing materials must be such that rainwater is diverted to the outside without wetting the construction beneath the windows.

Double and triple pane windows should be used where there is extended period of condensation. Research by Wilson [42] has shown that indoor relative humidity of 40 % at a temperature of 70 °F (21 °C) can be maintained without excessive condensation on double-glazed windows for outside temperatures down to −26 °F and on triple-glazed windows for outside temperatures down to −40 °F.

Air leakage through window sash affects heating, cooling, humidification, and dehumidification loads, but does not directly contribute to the amount of concealed condensation in the walls. It is therefore important to measure the rain and air leakage through the wall-window interface.

Floors

Floors that perform functions of the exterior envelope include those separating the indoor environment from unconditioned space whether that be outdoors, sheltered unconditioned space, or the ground. Several problems with moisture control by floors include the following conditions:

1. Capillary moisture intake through concrete slabs and foundations.
2. Condensation on concrete slabs at the perimeter.
3. Transfer of moisture from the earth through wood floors over crawl spaces.
4. Mold and fungus growth on wood in poorly designed crawl spaces (high RH).
5. Poor grading of earth surrounding the building to drain rain water.

Concrete slab floors should be laid with a minimum 4-in. (10 cm) 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 tearing and puncture by the gravel during construction. The vapor retarder should be placed underneath the grade beam in that type of construction. In areas of expansive soils thicker reinforced slabs may be required. In areas subject to termite infestation, special considerations are also needed including thicker slabs using stronger than typical concrete, and extra reinforcing to control the thickness of cracks as well as use of special barriers at penetrations.

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 depending on the severity of the climate.

Traditional requirements for crawl spaces underneath a building are that the earth be covered with a continuous vapor retarder of 6 mil (0.15 mm), polyethylene or equal, to reduce moisture migration from the soil. In vented crawl spaces, the vapor retarder is required to be turned up several centimetres on the wall perimeter. In unvented crawl spaces, the ground cover vapor retarder is normally continued up the inside and over the top of the foundation wall. Ventilated crawl spaces have been provided with distributed vents with an area not less than 1/200 of the floor area of the building [7] with the additional requirement that openings should be open only during spring and fall seasons.

The traditional requirements for crawl spaces have been copied in building codes around the world and in most places they have been a source of failures. Vented crawl spaces are particularly problematic because the temperature of the mass of soil under the building is out of phase with the outdoor temperature. As a result, the local environment provides a moisture load that often leads to decay in the case of wood, or rusting in the case of steel floors. The requirement that openings be controlled by the occupants at particular times of the year is unlikely to be followed. Instead, some codes now require an advanced approach to design of crawl spaces. Simply, crawl spaces are to be considered entirely outside at all times, or entirely inside at all times. In cold climates, except over permafrost, crawl spaces should most logically be designed as shallow basements with as much attention to detail as would be undertaken for basements. That would include a concrete slab and treating the air in that space as one would in the living spaces. Use of a simple ground cover is too susceptible to damage and can never be cleaned. This avoids many of the difficulties in construction that are currently associated with typical crawl spaces as noted above.

Floors acting as part of the building envelope, particularly when exposed to exterior conditions, should be insulated and with proper attention to vapor and air control as for exterior walls. Care must be taken to seal penetrations of floors acting as part of the building envelope. This includes even plumbing and water lines, electric service, ducts, and other utility services to prevent passage of outside air, including soil gases, into the conditioned indoor space as driven by natural chimney effects or by 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 centimetres of coarse gravel will typically 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

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 several times. 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 snow falls followed by cold sunny days combined with excessive heat loss from below.
4. Condensation or frost forming on the underside of roofs due to excessive entry of moist air through the ceiling.
5. Snow entry.

Pitched and low-sloped 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 promotes circulation. Except during 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.

Most building standards require that a vapor retarder with a permeance equal to or less than 1 perm be installed on the inside of the ceiling in moderate and cold climates [43]. This vapor retarder, also serves to control air flow, and should be continuous at the top of the walls by overlapping and sealing to the wall retarder. 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 cold or severe cold climates for heavily insulated cathedral ceilings, a vapor barrier with permeance less than 0.1 perms is required.

In the inverted roof system, in which the insulation and a layer of ballast are placed on top of the waterproof membrane, closed-cell insulations must be used since the insulation is exposed to 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 removed 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 by increasing resistance to heat and air transfer through the ceiling often combined with adequate ventilation of the roof through soffit and ridge vents to reduce snow melting. One often uses 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 an air-conditioned building will cause condensation. In such a case, a vapor barrier 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. In 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 [7]. Air penetration of the insulation at these locations could deposit moisture at the top plate and adjacent ceiling gypsum board.

Alternative solution involves unvented cathedralized (UC) ceilings see Ref. [47]. For a detailed discussion on effect of moisture in roofing systems consult Ref. [44] and Chapter 16 of this manual.

Design Review: Ensuring Environmental Control

The design process compels professionals to address the building system as a whole while recognizing that both the choice of materials and design of the envelope details will affect the environmental performance of the building envelope system. Achieving the right harmony between materials, design, and system performance depends on integrating two extremes in conceptual thinking: qualitative assessment based on experience in use and quantitative evaluation based on results of testing and analysis.

On the qualitative side of the environmental control picture is the knowledge of what makes a building envelope function plus a general understanding of how suitable the materials are for a given use. While many of today's achievements in building science demonstrate successful understanding of both the scientific principles and the art of construction, there is no formal procedure underlying the process of designing for environmental control. To this end one should include considerations of:

- Continuity, one must strive for the continuity of barriers.
- Redundancy, one must incorporate a second line of defense.
- Buildability, one must ensure that the design is easy to build, or at least buildable.

Continuity of Environmental Barriers

While most designers consider air barrier systems carefully, some aspects of air barrier performance, such as details of joints and differential movements of construction, may pass unnoticed. Likewise, details involving steel columns, roof/wall junctions, or brick ties in masonry walls are often overlooked.

Differential movements in the structure also affect the continuity of air barriers. These movements develop after construction because of thermal expansion or contraction of the building elements, deflection of beams, or mortar shrinkage. In addition, air barrier materials differ in crack-bridging ability. (Rigid parging materials usually do not offer protection from cracks developing in masonry walls. However, reinforced flexible membranes with adequate thickness may perform well.) While some structural movements can be predicted, in many cases designers must rely on experience and judgment to anticipate the impact of differential movements on the specific design.

In reality, the discontinuity of air barriers is critical because moisture condensation in the walls is primarily related to concentrated local deposition of moisture. In other words—it is not the plane of air tightness, but its discontinuities that decide on performance of the air barrier system.

Redundancy of Design or the Second Line of Defense

Through experience, environmental design incorporates designing a second line of defense. Theoretically, building professionals—be they designers, or builders—can design and build a perfect structure. Yet, experience shows that in construction, eventually something goes wrong. It rains during construction, a roof leaks some time later. Alternatively, water enters for other reasons, for instance, roof drainage does not lead water away from the building but directs it right to the basement, or caulking in a face seal design is not maintained during the service life. For these and many other reasons some moisture finds its way into the envelope. So, as the second line of defense, walls are constructed to permit draining and drying of any excess moisture. But how long would the drying take and what effect would the moisture have on other materials? As there are no quantitative answers, designers must look to logic and experience.

Designing the second line of defense forces designers and builders to prepare for the issues they can not predict, such as material changes or workmanship issues that may escape notice. Typical unplanned air flows occur when air traveling across the BE passes unfinished masonry walls behind radiators, or through holes used for wires to the suspended ceiling or corrugated roof decks. The list of cases of this nature also includes partition walls that extend above the roof, openings cut for electrical heating, ventilation, and plumbing services, cladding materials that are not drawn tight to metal studs, and furred partition walls connecting with a suspended ceiling.

Using external insulating sheathing has a number of advantages. The sheathing increases temperature in the wall cavity, thereby reducing the potential for condensation in the wall cavity. Use of external thermal insulation helps achieve continuity in thermal insulation of the basement walls and roofs. If, however, the external sheathing acts as both the air and vapor barrier material, placing it on the cold side requires consideration for increased risk of moisture accumulation, and ensuring some capability for drying on the warm side.

Well, how does the principle of the second line of defense apply in cold climate design when an external insulating sheathing functions as an air barrier and the wall cavity is filled with fibrous thermal insulation?

The designer may either choose an external insulating sheathing that is sufficiently permeable for thermally driven water vapor (e.g., expanded polystyrene) or a relatively impermeable foam (e.g., extruded polystyrene) and fibrous insulation in the cavity. In the latter case, one may use one of the three options:

1. Increase the thermal resistance of external insulating sheathing to a level high enough to reduce the risk of moisture accumulation if a defect develops during the service period.
2. Improve the drying ability on the warm side. The wetting potential is not reduced but the designer ensures that for a given climate and use the wall will dry out in a sufficiently short time.
3. Choose a different thermal insulation in the frame wall cavities. By selecting a thermal insulation that provides resistance to air and moisture flows (e.g., spray polyurethane foam) the potential for moisture accumulation is reduced.

Whatever the choice, the basis for the selection should be building science principles together with the designer's experience.

Buildability

Just as the second line of defense, buildability relates to judgment and knowledge and reflects whether various trades can assemble the designed element without compromising its functional requirements.

Contrary to a frequent misconception, buildability is more related to a good design than to superior workmanship because, as experience indicates, only good design can combine all environmental factors while presenting an easy construction pattern. For the most part, it is the designer who attends to the aspects of buildability such as material installation under different weather conditions, level of skill required for installation, and construction tolerances. Often buildability problems arise when different trades are involved; for instance, when neither a window manufacturer nor a building designer considers the window/wall interface as their concern.

It is clear that the design of building envelopes for environmental control requires a number of iterations. Each material must be examined with regard to its compatibility and interaction with the adjacent materials and components. Each modification of the performance requirements or change in the material selection must be followed by a review of architectural details. These issues highlight the importance of review (troubleshooting) of drawings of the assembled system and on the design details. To maintain a high standard of quality and clarity, some designers prefer to have one section of the specification addressing the joints and junctions of various subassemblies within the building envelope system. In this respect, it is difficult to draw the line between concepts of buildability and the second line of defense. Both address the aspects of the system during its construction and its service life. Yet, so often the key to good and long-term performance of the system depends on the quality of the architectural details.

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 hours per day, so the cyclic nature of moisture generation may be taken advantage of 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, that are 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 isolate one floor from another to reduce cumulative stack (chimney) effects and to avoid high indoor-outdoor pressure differences 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 stack effect on the surrounding rooms.

Some types of rooms or buildings 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 deterioration 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.

Conclusions

An architect or designer must design a durable structure. It is not a simple matter because the moisture transfer processes that are more likely to affect building deterioration are seasonally variable in direction of flow, in magnitude, or in continuity. There is indoor/outdoor air exchange with building cavities, air flow through cracks and condensation from moisture laden air, local accumulation of moisture in material and entrapment because of high diffusion resistance of some materials, migration of groundwater upward into building foundation and walls, excessive indoor relative humidity, leakage of rain, and solar effects driving moisture inwards of the wall assemblies. There are so many unknowns that experience and fundamental understanding must be the dominant resource that a good design team must rely on.

In 1946 Johansson[9] discussing cold climate design required that exterior walls have an outer rain screen, provided with a drained and vented cavity and that the thermal insulation is placed "between the actual wall and the rain screen." Hutcheon [44] expanded those principles requesting:

1. Control of heat flow, with an insulation applied to the cold side of the structure.
2. Control of air flow through the wall assembly.
3. Control of vapor flow (a vapor barrier applied on the warm side of the insulation).
4. Control of rain penetration with a capillary break between the outer skin and the inner part of the wall, that preferably as an air cavity, vented to minimize transfer of vapor to the inner wall under summer conditions.

These principles were reiterated in many publications, e.g., Brand [45] provided a set of architectural rules as follows:

1. Enclose the building in a continuous air barrier (AB).
2. Provide a continuous support for the AB against wind loads.
3. Ensure that AB is flexible at joints where movement can occur.
4. Provide the continuous thermal insulation.
5. Keep the insulation tight to AB.
6. Protect the insulation with a rainscreen/sunscreen supported out from the structure in a way that does not penetrate the insulation with excessive thermal bridges.
7. Provide enough open space for drainage and construction clearances between rainscreen and insulation.
8. Drain the wall cavity to the outside.

While these rules are as valid today as they were 60 years ago, their application priorities might have been altered. Heat and rain control had always a high priority; yet, a few well-publicized cases of moisture-originated damage in wood frame walls in the lower mainland of British Columbia and North Carolina have brought our attention to the need for more effective drainage techniques. The significance of air control, though postulated as being critical by Hutcheon [44] many years ago has only recently been acknowledged.

The recent enhancement of our understanding is the need to modify design to adapt to the requirements of the local climate. From a design point of view, the most difficult climatic exposure is in the mixed climates.

In some ways, however, not much has changed in the design process. Despite wide advice specified in different codes and material standards, despite many computer-based tools available for assessment of the environmental performance of building assemblies, the decision is still in the designer's jurisdiction. The designer's ability to integrate experience with the results of testing and analysis and the designer's attention to architectural details makes the difference between a building envelope that works and one that merely frames an indoor space.

[9] Report written in Swedish.

Acknowledgments

As this text is based on several discussions and joint publications of Mark Bomberg with Dr. Donald M. Onysko, one should observe that his input became an integral part if not the basis of this chapter. That fact is here gratefully acknowledged.

References

[1] Bomberg, M. and Onysko, D. M., "Heat, Air and Moisture Control in Walls of Canadian Houses: A Review of the Historic Basis for Current Practice," *Journal of Thermal Envelope and Building Science*, Vol. 26, 2003, pp. 3–31.

[2] Flynn, J. E. and Segil, A. W. *Architectural Interior Systems, Lighting, Air Conditioning, Acoustics*, Van Nostrand Reinhold, NY, 1970.

[3] Morrison Hershfield Ltd, "Survey of Building Envelope Failures in the Coastal Climate of British Columbia, Canadian Housing Information Center, Technical Series 98–102, 1998, see also Chouinard K. L. and Lawton, M. D. "Rotting Wood Frame Apartments—Not Just a Vancouver Problem (reprint from MH), 2001.

[4] Crandell, J. and Kenny, T., "Investigation of Moisture Damage in Single-Family Detached Houses Sided with Exterior Insulation and Finish Systems in Wilmington, NC," NHAB Research Center, Upper Malboro, MD, 1996, and Brown, W., Ullett, J., Karagiozis, A., and Tonyan, T., "Barrier EIFS Clad Walls," *J. Thermal. Insulation. and Building Envelopes*, Vol. 20, 1997, pp. 206–226, see also Vol. 21, pp. 23–44.

[5] *Moisture Analysis and Condensation Control in Building Envelopes*, H. R. Trechsel, Ed., ASTM MNL 40, ASTM International, West Conshohocken, PA.

[6] Lstiburek, J. W., Pressnail, K., and Timusk, J., "Evaluating the Air Pressure Response of Multizonal Buildings," *Journal of Therm. Env., and Building Sci*, Vol. 25, April 2002, pp. 299–321.

[7] *ASHRAE Handbook*, "Fundamentals, Chapter 26," American Society of Heating, Refrigerating and Air-Conditioning Engineers, Atlanta, GA, 2003.

[8] Straube, J. F. and Burnett, E. F. P., *Building Science for Building Enclosure*, Building Science Press, 2005.

[9] Bomberg, M. "Moisture Flow Through Porous Building Materials," Ph.D Thesis at the Lund Institute of Technology, Sweden, Report 52, Lund, p. 188.

[10] Lstiburek, J. W., "Two Case Studies with Failures in the Environmental Control of Buildings," *J. Thermal Insulation and Building Envelopes*, Vol. 19, pp. 149–172.

[11] Garden, G. K., "Control of Air Leakage is Important," CBD 72, DBR: NRC.

[12] PER design, see URL http://irc.nrc-cnrc.gc.ca/ctus/17.html

[13] NBRI Design of Joints, see Bomberg Concordia University Compendium for Course of Building Science, 2002.

[14] Wilson, A. G. and Nowak, E., "Condensation Between Panes of Double Window," *ASHRAE Transactions*, Vol. 65, 1959, pp. 551–570, see also Wilson, A. G., Solvason, K. R., and Nowak, E. S., *Evaluation of Factory-Sealed Double-Glazed Window Units, ASTM/STP 251*, ASTM International, West Conshohocken, PA, 1959, pp. 3–16.

[15] Wilson, A. G., "Influence of the House On Chimney Draft," *ASHRAE J.* Vol. 2, No. 12, 1960, p. 63.

[16] Wilson, A. G. and Garden, G. K., "Moisture Accumulation in Walls Due to Air Leakage," *RILEM/CIB Symposium on Moisture Problems in Buildings*, Vol. 1, 1965, Helsinki, see also Wilson, A. G., "Air Leakage in Buildings," CBD 23, DHR: NRC, see also Tamura, G. T., and Wilson, A. G., "Air Leakage and Pressure Measurements on Two Occupied Houses," *ASHRAE J.* Vol. 5, No. 12, 1963, pp. 65–73; see also Tamura, G. T., and Wilson, A. G., "Pressure Differences for a Nine-Story Building," *ASHRAE Transactions*, Vol. 72, Part 1, 1966, pp. 180–189, and Tamura, G. T., and Wilson, A. G., "Building Pressures Caused by Chimney Action, and Pressure Differences Caused by Chimney Effect in Three High Buildings," *ASHRAE Transactions*, 73, Part II, 1967.

[17] Stricker, S., "Measurement of Airtightness of Houses," *ASHRAE Transactions*, Vol. 81, No. 1, 1975, 148–167.

[18] Orr, H. W., "Condensation in Electrically Heated Houses," *2nd International CIB/RILEM Symposium on Moisture Problems in Buildings*, 1974.

[19] Tamura, G. T., Kuester, G. H., and Handegord, G. O., "Condensation Problems in Flat Wood-Frame Roofs," *2nd International CIB/RILEM Symposium on Moisture Problems in Buildings*, 1974.

[20] Dickens, H. B., and Hutcheon, N. B., "Moisture Accumulation in Roof Spaces Under Extreme Winter Conditions," *RILEM/CIB Symposium Moisture Problems in Buildings*, Vol. 1, 1965.

[21] Eyre, D., *Air-Vapor Barrier Manual*, Sask. Res. Council, Saskatchewan, 1981.

[22] Karagiozis, A. N. and Kumaran, M. K., "Computer model calculation on the performance of Vapour Barriers in Canadian Residential Buildings," *ASHRAE Transactions*, Vol. 99, No. 2, 1993, pp. 991–1003.

[23] Quirouette, R. L., "The Difference Between a Vapour Barrier and an Air Barrier," Building Practice Note 54, IRC: NRC, 1985, see also Quirouette, R. L., "The Air Barrier Defined, an Air Barrier for the Building Envelope," NRC, *Bldg. Sci. Insight*, 1986, pp. 1–7.

[24] Lux, M. E. and Brown, W. C., "Air Leakage Control, an Air Barrier for the Building Envelope," NRC, *Bldg. Sci. Insight.*, 1986, pp. 13–19.

[25] Nat. Building Code of Canada, Part 5, Section 5.4.1. on Air barriers + Appendix.

[26] Lstiburek, J. W. and Lischkoff, J. K., "A New Approach to Affordable, Low Energy House Construction," Alberta Department of Housing, 1984.

[27] Lstiburek, J. W., "Toward an Understanding and Prediction of Air Flow in Buildings," Ph.D. Thesis, U. of Toronto, 2000.

[28] Lstiburek, J. W., Pressnail, K., and Timusk, J., "Transient Interaction of Buildings with HVAC Systems—Updating the State of the Art," *Journal of Thermal Envelope and Building Science* Vol. 24, Oct. 2000, pp. 111–131.

[29] Bomberg, M. T. and Kumaran, M. K., "A Test Method to Determine Air Flow Resistance of Exterior Membranes and Sheathings," *J. Therm. Insul.*, Vol. 9, 1986, pp. 224–235.

[30] "Air Barrier Systems for Walls of Low Rise Buildings: Performance and Assessment," NRC Canada, 1997.

[31] "Testing Air Barrier Systems for Wood Frame Walls," Report IRC/NRC, 1988.

[32] Ganguli, U., "Wind and Air Pressures on the Building Envelope, an Air Barrier for the Building Envelope," NRC, *Bldg. Sci. Insight*, 1986, pp. 7–13.

[33] Grot, R. A., and Persily, A. K., "Measured Air Infiltration and Ventilation Rates in Eight Large Office Buildings," *Measured Air Leakage of Buildings, ASTM, STP 904*, ASTM International, West Conshohocken, PA, p. 151.

[34] Tamura, G. T., "Measurement of Air Leakage Characteristics of House Enclosures," *ASHRAE Transactions*, Vol. 81, No. 1, 1975, pp. 202–211; Bomberg, M., Onysko, D., and Lstiburek, J., "Review of the Air Barrier Issues," *Proceedings IXth Building Envelope Conference*, ASHRAE, Clearwater Beach, FL, 6–9 Dec. 2004.

[35] Desmarais, G. and Bomberg, M., "Design of the Wall-Window Interface: Performance Requirements and Water-Managed Stucco Examples," *8th Canadian B. Sci. Conference*, 2001.

[36] Ojanen, T. R. and Kumaran, M. K., "Effect of Exfiltration on Hygrothermal Behaviour of a Residential Wall Assembly," *J. Thermal Envelopes and Bldg. Science*, Vol. 19, 1996, pp. 215–228.

[37] Moore, R. J., Spielvogel, L. G., and Griffin, C. W., "Air Conditioned Buildings in Humid Climates, Guidelines for Design, Operation and Maintenance," Southern Division Naval Facilities Engineering Command, Charleston, SC, NTIS, 1980.

[38] Trechsel, H. R. and Achenbach, P. R., "Field Studies of Moisture Problems in Exterior Walls of Family Housing Units at Naval Air Station, Pensacola, Florida," Contract Report to Naval Civil Engineering Laboratory, Port Hueneme, CA, 1984.

[39] Tenwolde, A. and Mei, H. T., "Moisture Movement in Walls in a Warm Humid Climate," *Proceedings, Conference on Thermal Performance of the Exterior Envelopes of Buildings III*," SP 49, ASHRAE, 1986

[40] Lstiburek, J. and Carmody, J., *Moisture Control Handbook, New Low-Rise Residential Construction*, ORNL/Sub/89-5D350/1, Oak Ridge National Laboratory, Oak Ridge, TN, 1991.

[41] Wilson, A. G., "Condensation on Inside Window Surfaces," *Canadian Building Digest*, Vol. 4, National Research Council of Canada, Ottawa, 1960.

[42] Achenbach, P. R. and Trechsel, H. R., "Evaluation of Current Guidelines of Good Practice for Condensation Control in Insulated Building Envelopes," *Proceedings, Thermal Performance of the Exterior Envelopes of Buildings II*, SP 38, ASHRAE, Atlanta, GA, 1982.

[43] Powell, F. and Robinson, H., "The Effect of Moisture on Heat Transfer Performances of Insulated Flat-Roof Construction," *Bldg. Science Series 37*, Nat. Bureau of Standards, Washington, DC, 1971.

[44] Hutcheon, N. B., "Requirements for Exterior Walls," CBD 48, NRC Canada, http://irc.nrc-cnrc.gc.ca/pubs/cbd/index_e.html, 1963.

[45] Brand, R., *Architectural Details for Insulated Buildings*, Van Nostrand Reinhold, 1990.

[46] Lstiburek, J. W. 5.C.2.1 Vapor Barrier Journal Paper, on BSC server /BA_Deliverables_2004.

[47] Rudd, A., "Field Performance of Unvented Cathedralized (UC) Attics in the USA," *J. Building Physics*, Vol. 29, Oct. 2005, pp. 145–177.

MNL18-EB/Oct. 2009

15

Details and Practice

Peter Baker[1] and Chris Makepeace[1]

HOW MANY TIMES HAVE YOU HEARD PEOPLE IN the construction industry say, "The Devil is in the Details"? Details are far more important than just conveying the aesthetic of a building design. Estimators use the documents and their details to establish budgets. Contractors produce bids and schedules based on how they perceive the details can be constructed and coordinated for completion of the project. Subcontractors submit bids based on the scope of work they would under take to complete the details. Why is it then, that universities and technical schools have given their students little or no formal training in how to develop details? Even if they do provide such courses, these courses rarely present constructability reviews of the details presented so the student enters the work force with a false perspective on how details are executed on sites. Individuals in these institutions are instructed in how to draw with the computer, but not what to draw and how it relates to the finished performance of the finished system. The Internet may provide information on particular systems or products, but the details often do not show how the individual products should be detailed in the context of the variety of building designs that are now present. Many in the design community fail to realize the limitations imposed by the contractor's capabilities and that of the products they install.

Design details and documents for the building enclosure have been the most visible area of construction where a lack of workable details has led to building failures and lawsuits over the past years. Failures of cladding components to perform have occurred in many cities throughout North America. Leaking walls and windows in house construction in Carolina, and the leaking condos in Vancouver, and the issues of mold in new building construction are just a few that have been in the news.

Details can indicate the use of materials which are specified incorrectly or materials chosen for an inappropriate use. Weaknesses in material selection can be further compounded by a lack of understanding of construction sequence, material tolerances, building movements, material compatibility, and buildability problems. When the details presented overlook some or all of these issues, the failures may not be catastrophic or instantaneous, but the expected performance life for the owner can be significantly reduced.

In the mid 1980s the Alberta Provincial Government—Public Works Department, Technical Resources Branch, produced a series of drawings to be used by consultants in the production of documents for new and retrofitting of government owned and funded facilities. The details presented were based on reviews made of the technical literature of the time, discussions with manufacturers, trades personnel, building operators, and design professionals. While the National and Provincial Building Codes set a minimum standard for performance of buildings, the Provincial Government details presented additional requirements based on requirements for durability and buildability for its buildings. Facilities built to house government operations or funded by taxpayers' dollars are often a long-term investment for the taxpayers so their performance, long term, is a concern.

These building enclosure details became part of a package of information, which also included specifications, mechanical, electrical, and acoustic requirements. Onsite investigations of existing building stocks and investigations of problems confirmed successes and shortcomings of the details. The details were changed when new products and findings were made, to provide the best workable solutions.

The details presented in this paper are a compilation of the Alberta Government details. The details are based on the Pressure Equalized Rain Screen Insulated Structure Technique (PERSIST). PERSIST follows the functional approach as outlined in the *Requirements for Exterior Walls* by Neil Hutcheon, "Canadian Building Digest—48," where individual materials provide a single function. A more complicated variation of the details can be made to work when the designer appreciates the materials, systems, their function, and their limitations in the environments they are to be placed. This said, experience has repeatedly shown that the simpler the approach taken in the design of details, the more likely the end result will perform as expected for a long service life.

This chapter presents several critical details in the exterior enclosure and attempts to also describe the methodology behind the details. Some of the details are two-dimensional as they are normally shown in contract documents. To emphasize some of the complexities and sequence problems encountered with the construction process, some of the details have been drawn as a series of isometric drawings to clarify the issues.

PERSIST is based on a design which layers the functions of the wall and roof. The first layered element found in any detail is the structure of the foundations, walls, and the roofs. The structure carries the dead load of its own weight and also the imposed loads from forces such as seismic movement stack affect, mechanical pressurization, and wind transferred to it by the building enclosure system. While the structural components themselves can provide a degree of air tightness, their incorporation in a fully func-

[1] *Building Science Engineering Ltd., 9733 89 Ave., Edmonton, Alberta T6E 2S1, Canada*

tional system often has led to problems in continuity and thermal bridging. There will be joints and penetrations with any construction. If these can be minimized, then the probability of functional success is increased. The more changes in plane and penetrations lead to a greater probability of some degree that problems may occur. In the case of a steel building we would have a structure of beams and columns with an infill system. If the design details align the exterior surface of the structure with that of the infill panels or provides clearance for tolerances and allows the exterior sheathing to continue past the structural components, that surface could be sealed with any number of materials to provide a simple plane of air tightness. Penetrations through this plane have to be designed to maintain continuity of the plane of air seal. At the same time consideration for how to minimize thermal bridging by such penetrations must be dealt with in the development of the details.

The type of material used to provide the air seal must consider the environmental separation required, movement of the components to be sealed, construction season for installation, and loads imposed on the air seal. The details presented show a styrene-butadiene-styrene (SBS) membrane adhered to the exterior of the structural infill. This bonded material acts as the sealing component of the air barrier system. It may be structural enough depending on the type of material specified to act as the air barrier system where it bridges small gaps between components, but these membranes are bonded to a backup component and together they act as the air barrier system. These membranes can be either a peel and stick (1–1.5 mm SBS on a release paper or film with polyethylene as the reinforcing on the exterior surface) or a torched application membrane (2–3 mm torchable SBS with internal reinforcement of polyester or fiberglass). This has been a common approach in Alberta. While these products are not without their limitations they have proven their ability to function long term (they have been in use in Alberta since the 70s and have been used in Europe and North America in the area of roofing before that). There are other products such as spray applied products, mastics, and other sheet goods, but they have presented problems of consistency of application and problems with temperature and weather constraints which have limited their use and acceptability.

Thermal resistance for the PERSIST enclosure is provided by the installation of insulation tight to the exterior of the air barrier system. The construction components exterior of the air seal may from time to time be wetted; therefore the type of insulation used must consider whether or not it might be affected by water infiltrating the cladding system or by vapor condensing within the assembly but exterior of the air barrier system.

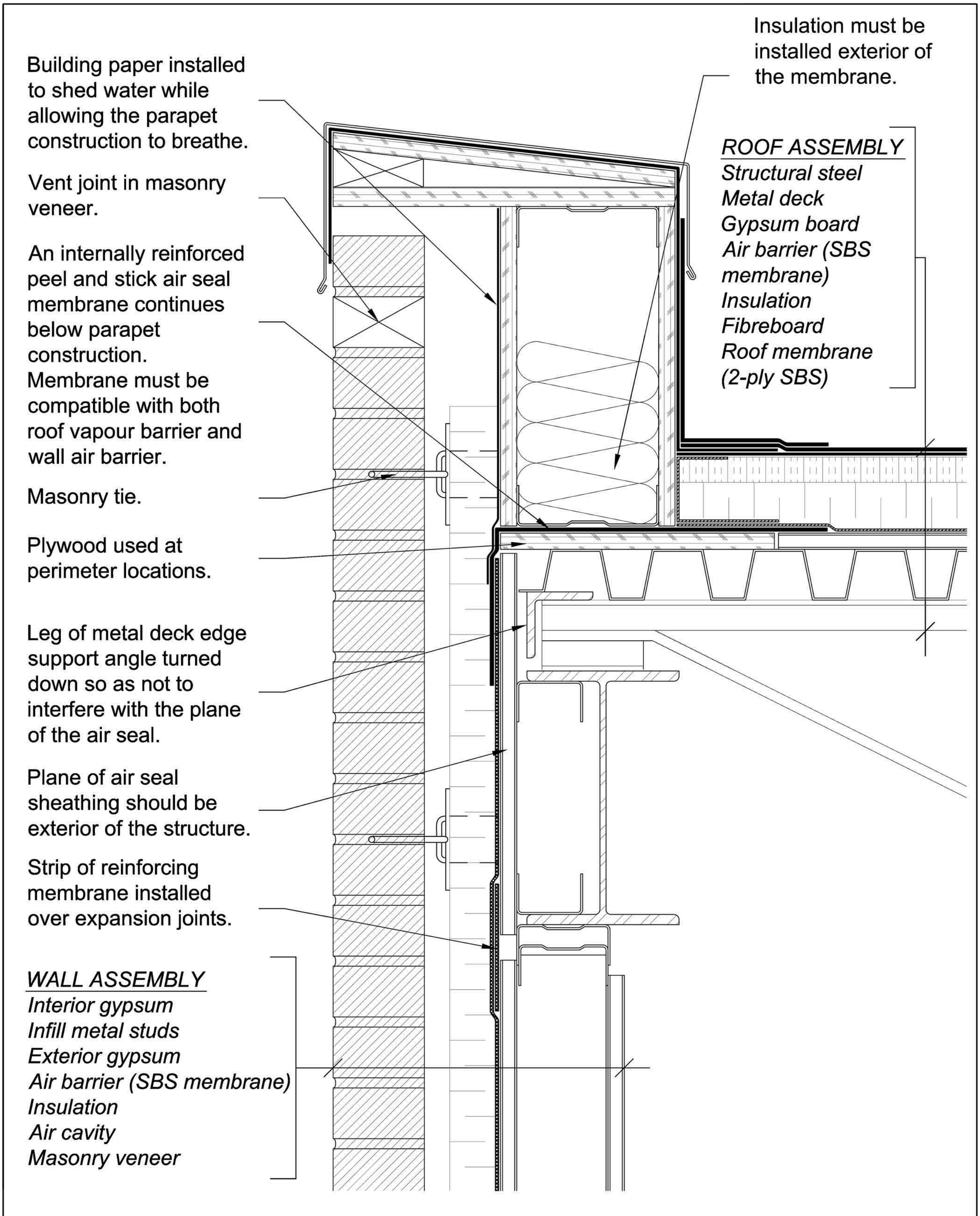
An air cavity exterior of the insulation provides a water break and drainage plane, while providing an area for air movement, which could dry out the cavity and insulation. Compartmentalization of the wall cavity between the air seal and cladding (both horizontally and vertically) is promoted in the theory of rain screen designs. Such efforts have, to my knowledge, not been economically viable and tested to provide the design community with constructible details. Canadian Mortgage and Housing Corporation (CMHC) did research into wetting of walls and cavities, but we are not aware of any published documents. It is best to acknowledge that some water may pass through the cladding system and that water should be expelled to the exterior at purposely designed weeps and flashings. Retained water can, with time, degrade the materials of the construction so it is imperative to minimize its entry. When water does get past the exterior cladding system it must be controlled to divert it back to the exterior and allow the components to dry.

The design of the cladding should minimize water entry into the cavity, minimize thermal bridging of the structural attachments, and provide the desired aesthetic. Penetrations for signage, electrical, and mechanical penetrations should all be detailed by the designer to show the intent of expelling water, maintaining the air seal continuity and water management within the enclosure.

Detail 1: Parapet, Light Gauge Steel Assembly

A two-dimensional detail section of a parapet for a steel structure using light gage metal studs as an infill panel is presented. The structural steel elements are offset from the plane of the infill gypsum sheathing in the detail to acknowledge the inherent tolerances of the materials used and their on-site installation. The edge support angle for the metal deck is turned down so it does not interfere with the installation of the membrane at the transition from horizontal roof plane to vertical plane of the wall. This angle is often installed with the leg upward to facilitate the placing of the steel deck, but it interferes with the placement of the plywood and membrane as the leg is often longer than the thickness of the deck and sheathing combined. In Canada it is a code requirement to provide a thermal barrier between the interior and expanded polystyrene (EPS) insulations, which are fire sensitive. To facilitate this requirement gypsum board sheathing is fastened to the metal deck. This sheathing provides a uniform surface on which to install the air barrier (vapor barrier/air barrier). The sheathing also supports the membranes during the installation process from puncture at the lower flutes. The parapet structure is often installed by a separate crew or trade and may be exposed for a duration of time prior to full roof completion. The use of a limited percentage of combustible construction is still allowed by the code. The use of a strip of plywood at the edge perimeter provides a solid base for the parapet and membrane. This construction can withstand on-site construction abuses before the final gypsum sheathing and roof placement.

In the past a poly-based peel and stick membrane has been used to lap down over the SBS membrane of the wall. The SBS membrane would then be sealed to the roofing membrane on the sheathing. If hot asphalt was used, the polyethylene reinforcement of the membrane would be melted leaving the potential for an unreinforced joint which may, with time and movement of the system, fail to maintain an air seal. There have been new peel and stick membranes introduced into the market based more on the torchable membranes. These membranes are internally reinforced



DETAIL 1: PARAPET - LIGHT GAUGE STEEL ASSEMBLY

SECTION

1

with polyester and glass. One side has a peel and stick format of SBS with a release sheet, while the other surface hasa torchable SBS format. This flexibility of a peel and stick membrane at one surface and at the same time on the opposite surface of the membrane an SBS that is compatible with hot asphalt or torching to fuse the joints is perfect for this detail.

Placement of the membrane under the parapet construction simplifies the plane and continuity of the air seal. While the air seal could continue up and over the parapet, such a detail design would create an area within the parapet interior of the air seal where the surfaces could reach the dew point of the air when the exterior environment is very cold, even though the exterior of the parapet would be insulated. Insufficient heat and air movement in the parapet, especially if the parapet was tall, could result in condensation in the construction. The potential for condensation to occur in the parapet would be further increased if the interior environment was humidified.

The metal stud structure of the parapet is clad with plywood sheathing on the interior to allow for nailing of the first ply of the membrane after it is adhered. The exterior sheathing can be either plywood or mold resistant gypsum. Building paper or breathable wrap is used on the exterior of the sheathing to protect the sheathing from water infiltration while at the same time allows moisture which may enter the parapet structure to diffuse to the exterior. It is not necessary to fill the entire height of the construction with insulation especially if the detail is a high parapet. Penetrations for steel reinforcing for the parapet must be detailed to ensure that the continuity of the air seal is achieved while, at the same time, minimizing thermal bridging. This can be achieved by supplying a steel plate at the plane of air seal. Steel structural sections can be welded to this plate with sufficient area to provide at least 50 mm (2 in.) on which to adhere the SBS membrane (manufacturer's recommended minimum surface for adhesion guarantee).

In this detail the first ply of a two-ply SBS roofing system is carried up and over the parapet on the interior to terminate the roofing and prevent water from entering the parapet construction. The second ply of granular surfaced SBS membrane is carried up the vertical interior face of the parapet. The parapet coping is sloped back onto the roof to minimize staining of the exterior cladding. The metal coping can be installed to visually finish the termination of the roofing but it should not be considered a complete waterproofing element. In high wind areas of the country it is best to mechanically fasten the flashings rather than rely on hidden clip fasteners.

The vertical plane of air seal is continued down the wall by SBS membrane adhered to a strip of sheathing that is supported by galvanized metal tracks between the flanges of the steel beam. Sheathing below the steel beam is supported by infill galvanized stud walls set into a deflection track beneath the beam. A gap is left in the sheathing to allow for movement. If deflection of the structure is expected to be large, an initial strip of SBS membrane can be installed over the gap with the final membrane installation carrying over that. If deflection of the structure is expected to be small, then a single ply of membrane can bridge the gap. There is no need to loop the membrane into the gap as this would make it very difficult to seal the unsupported membrane at laps. The structure will deflect as the remainder of the construction takes place and built and loads are imposed on the structure. Such deflection may then create a loop in the sealed membrane. In rare instances (cantilever structures) the joint may open and for those instances the recommendation would be to be a profiled sheet metal "V" backer on which the membrane could be adhered. (Remember never install movement joints in the fashion of gutters which would trap or contain water and may act a pathways for water to travel to find a hole in the membrane.)

Insulation is installed tight to the exterior of the membrane. Cavities behind rigid board insulations may create areas where convective movement of air will reduce the effectiveness of the insulation to retard heat flow. Mechanical fasteners should be installed through the membrane and the sheathing into the studs. The membranes should have self-sealing capabilities to accommodate such minor penetrations. Some anchors designed for claddings may also provide anchoring for the insulation at the same time.

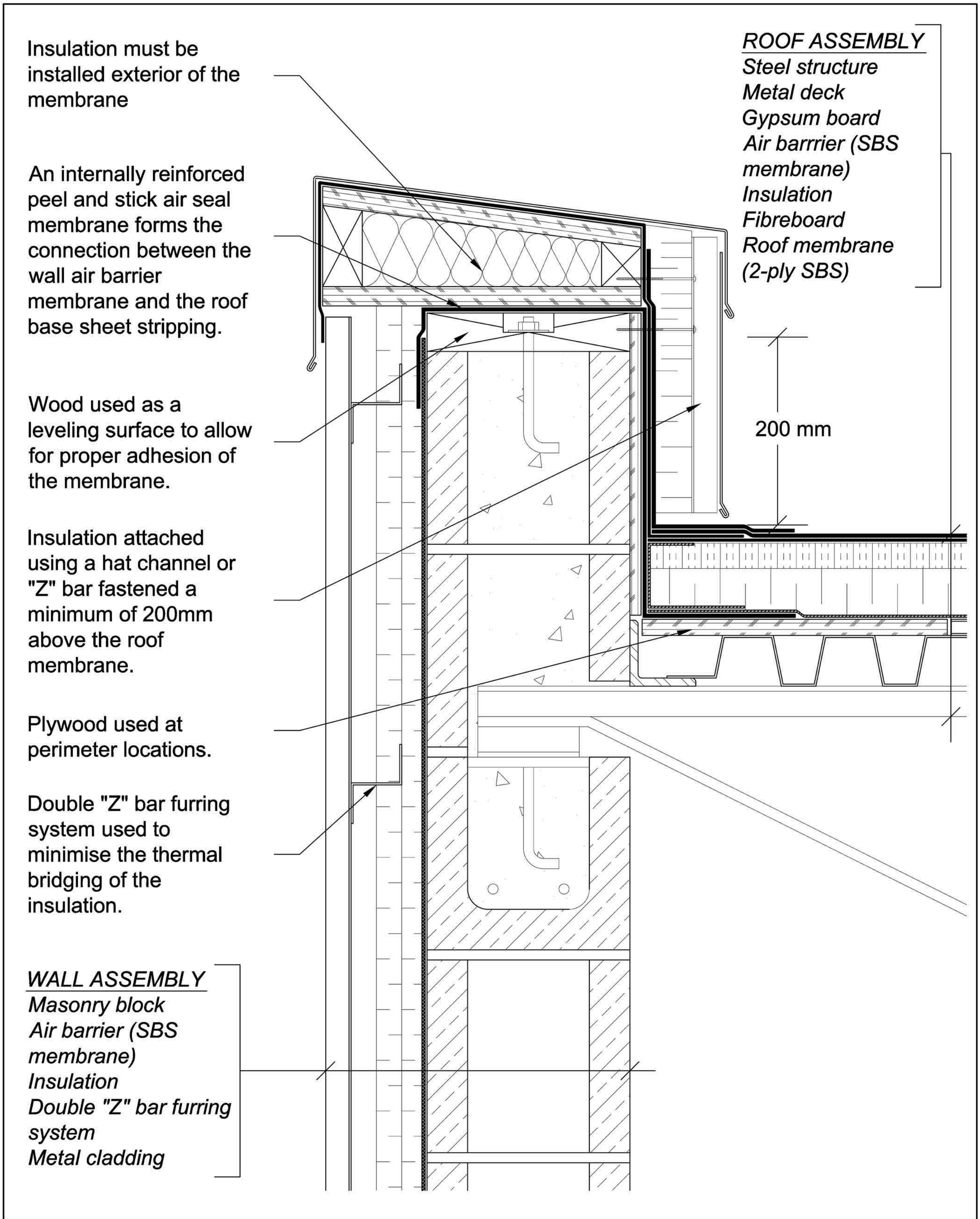
In this particular detail the cladding is masonry. Masonry ties that cut through the plane of the air seal and sheathing to be fastened to the sides of the metal studs are difficult to seal as the membrane must be cut at each penetration and the resulting joint does not provide a backing or surface on which to adhere the membrane. Achieving long-term continuity is suspect even when mastic caulks are used. Ties that are designed with long screw fastenings require some planning for placement, as the screws must be fastened through the flange of the stud, which is not visible. This type of anchor provides a better performance long term from our review.

The cavity created between the insulation and the masonry allows the water to drain to flashings in the construction where it can be redirected to the exterior. It also allows for the movement of air within the cavity which can aid in the drying out of this area. Mortar droppings in the cavity should be minimized as they could block drainage and act as a bridge for water to access the insulation and the membrane plane. The materials used exterior of the air seal plane should be chosen with the idea that from time to time the materials will be wetted.

Detail 2: Parapet, Masonry Wall Assembly

The backup structural wall assembly for this two-dimensional detail is concrete masonry block. In the detail the SBS membrane is adhered to the concrete block providing the plane of air seal for the detail. As with all materials, concrete block has an allowable tolerance in all dimensions for fabrication and installation of the product. Masons often align the interior face of the concrete block for aesthetics; however, if the interior finish is not critical, then it would be advantageous to install a smooth surface to the exterior especially if a nonadjustable cladding anchor is to be used.

This detail shows a double "Z" bar used to minimize thermal bridging through the insulation. The installation of the "Z" bar or any anchor should not retain water or carry water further into the wall. If possible, the horizontal "Z" bar should have at least a 2 % slope to ensure drainage to the exterior. Thermally enhanced or thermally broken clip anchors with adjustment capability are becoming available due to



DETAIL 2: PARAPET - MASONRY WALL ASSEMBLY

SECTION

2

the market demand and are preferred for anchorage of both insulation and claddings.

A strip of plywood is installed on the interior face of the parapet and around the perimeter of the roof parapet junction. The plywood may not be necessary but it is consistent with the other details in this package. This will simplify the construction on site and will ensure that it is installed where it is required.

The membrane air seal of the roof continues up and over the parapet to be sealed to the membrane of the wall and thereby ensuring continuity of the air seal. The roofing insulation is end wrapped to prevent a failure at the joint between roof and parapet, allowing water to enter into the insulation of the roofing. The roof membrane carries up and over the parapet to protect the construction from water penetration. Insulation is installed exterior of the membrane on the interior of the parapet and is protected from UV degradation by a sheet metal flashing that is fastened to vertical “Z” bars. Fastening of the “Z” bars to the parapet should not be made below 200 mm from the roof membrane. Hold the “Z” bars back from the top of the roofing membrane by 50 mm (2 in.). The metal coping flashing is installed over the parapet as before in Detail 1.

Detail 3: Roof to Wall Connection

The roof to wall junction follows many of the features presented in the previous two details for parapets.

Plywood on the perimeter of the deck and wall allow for fastening of roofing and air seal membranes and will allow for the fastening of “Z” bars to secure perimeter flashings. This plywood also allows for some abuse by the trades during construction. In the past gypsum would be used and installed by the general contractor. The gypsum is often damaged by weather conditions before protection or by construction activity over the detail prior to the arrival of the roofer.

The membrane layering follows the same configuration as shown in Detail 2. The SBS membrane in this detail must be capable of adhesion of both surfaces without destroying the reinforcement. Again the peel and stick/torchable membranes provide this while at the same time minimize the potential for fire if a torchable roofing product is specified. The base ply of membrane is taken from the roof plywood plane up the wall to the top of the plywood. This will allow the membrane from the wall to be brought down over this termination in a shingle fashion to ensure air seal continuity. Because we are using the SBS membrane, this layer also provides the detail with a waterproof plane once this membrane is installed. Once the roofing membrane is adhered to the vertical surface the insulation is essentially end wrapped.

If movement is expected at this joint (not this detail) then a bent profile of sheet metal can be fastened on the deck and to the wall to provide the flexibility necessary. Do not profile the joint in a gutter profile as this will make the sealing of joints difficult and will act as a collection trough to transfer water if there is leakage through the membrane.

Roofing insulation is installed tight to the vertical wall. There is no need for the installation of a cant as the detail is using a two ply SBS roofing system.

The roofing is brought up the vertical face of the wall with stripping plys of SBS membrane. Vertical “Z” bars are fastened above the 200 mm (8 in.) level to ensure there are no penetrations in the lower roof plane. The “Z” bars do not extend to the roof plane as this might damage the membrane. They should be held off the roof by 50 mm (2 in.). Extruded polystyrene insulation is installed between the “Z” bars which retain the insulation tight to the membrane. The membrane and insulation are protected from physical abuse and UV damage by the sheet metal flashings which extend from under the flashing of the wall cladding system above and are fastened to the “Z” bars. The wall flashing should be installed to divert water from the wall to the exterior but should water pass by the construction below it can accommodate it.

In the future when reroofing is undertaken the flashings, “Z” bars, and insulation can be removed and reused. The roofing plys of the wall can either be removed or tied into new roofing plys.

Detail 4: Foundation to Wall

Detail 4 shows a two-dimensional section detail of the grade where the cast in place concrete foundation wall is air and water sealed by an SBS membrane. The membrane extends to a metal stud and sheathing exterior wall to ensure continuity between the constructions.

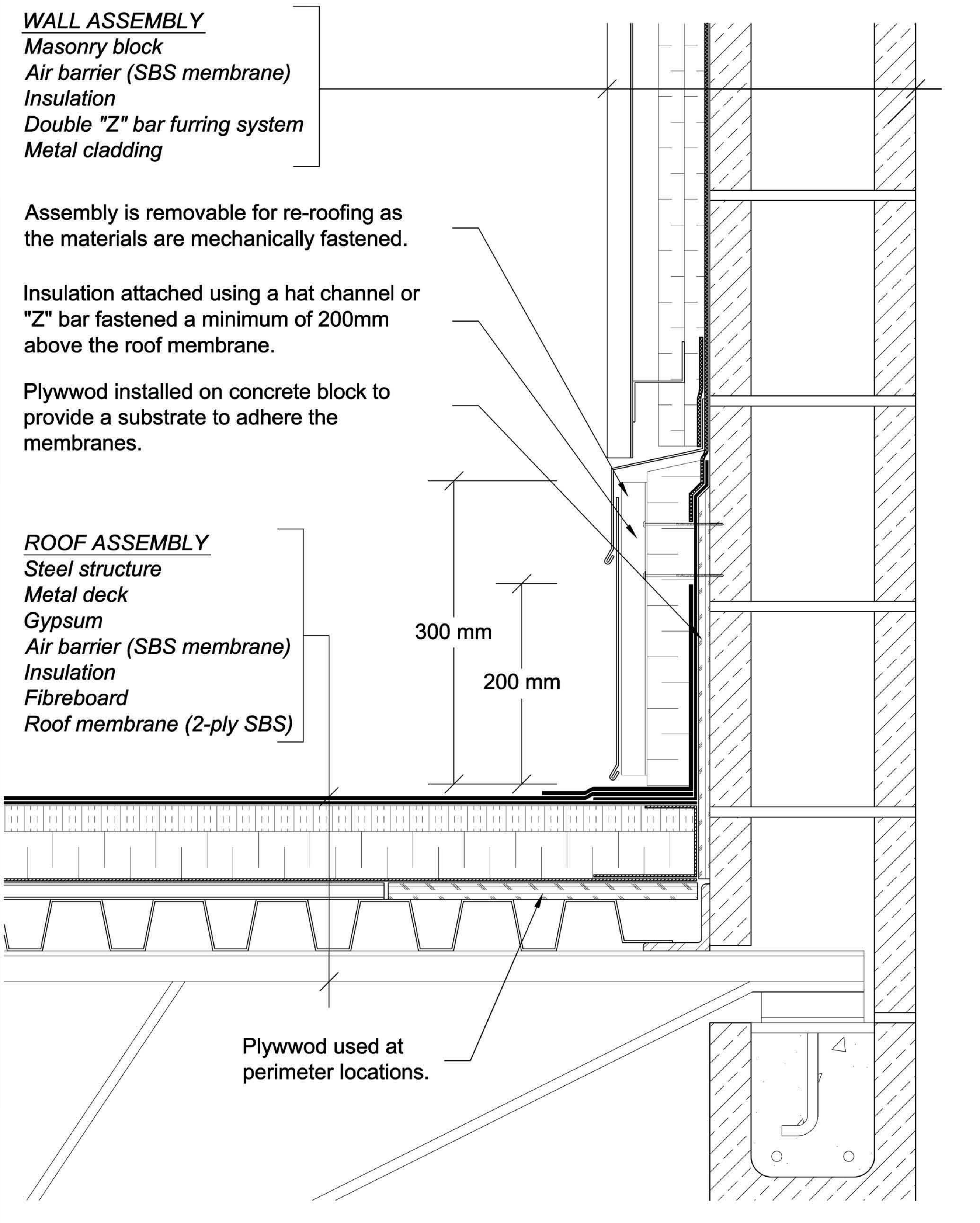
A shelf angle is welded to a cast in place steel plate to support a masonry veneer cladding. The steel plate has a minimum surface of 50 mm (2 in.) on all surfaces to the gusset steel from the edge of the imbedded plate to allow for the adhesion of the SBS membrane (required minimum surface by manufacturers of SBS membranes to guarantee that their products will remain bonded to a substrate). The gusset and steel plate are installed below the top edge of the foundation structure to ensure that variances between the foundation and the wall do not interfere with the terminations of the various scopes of work, and adhesion of the membrane to all surfaces to provide continuity of the air seal at the joint. The installation of a flashing from the membrane to the edge of the shelf angle has often been used in the past to drain the cavity. This detail allows water in the cavity to drain to the grade rather than be retained and drained through weep slots. The cavity should be protected from the passage of insects into the space by the installation of a minimum metal insect screen installed from wall to shelf angle.

The gusset shelf angle and plate minimize thermal bridging at this transition by allowing the insulation to be installed continuously across the joint, while still providing structural support for the masonry cladding. Similar details can be used at floor slabs in high rise construction.

The membrane installed on the concrete foundation wall functions as a waterproofing. The below grade insulation must be capable of wetting/drying/freezing for extended periods of time depending on the local conditions. Some UV protection is required as is protection from site grooming practices.

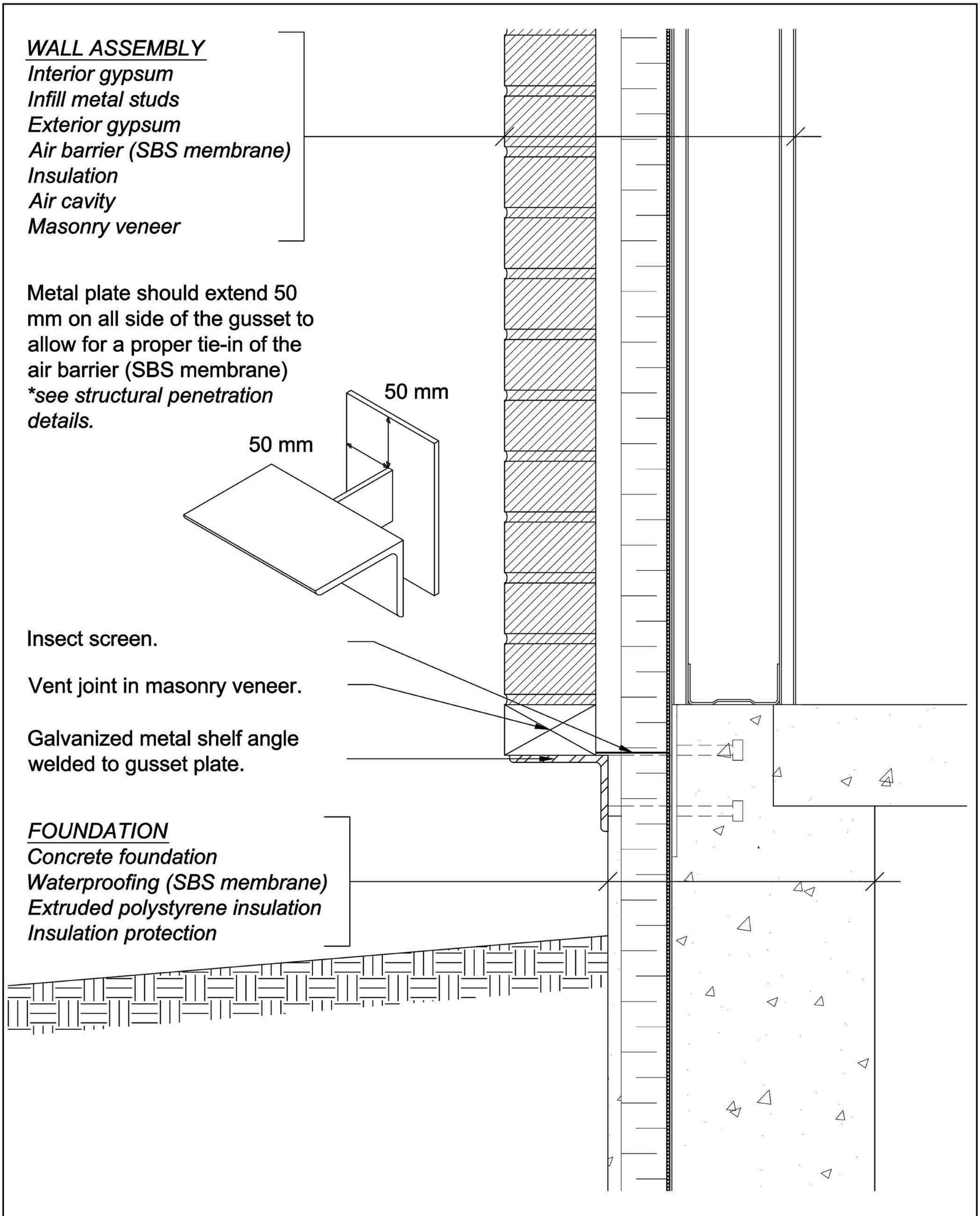
Detail 5 Series: Isometric Construction Sequence of Parapet/Wall Termination for Steel Structure

This detail provides a sequence of isometric drawings for a steel structure at an inside corner. The one wall extends to another floor or greater. This creates a roof wall junction



DETAIL 3: ROOF TO WALL CONNECTION
SECTION

3



DETAIL 4: FOUNDATION TO WALL
SECTION

4

and a parapet detail terminating at the wall. The details show that the roof and parapet of the lower portion of the buildingabutting the wall must be sequenced to maintain continuity of the air seal where the parapet abuts the wall. Two-dimensional drawings would not address the sequencing issues adequately, leaving much of the work to the various trades for their interpretation. Some of the critical tie-ins of air and water seals may be missed creating a problem that will only be discovered after completion and the detail is opened up to resolve the problem.

Detail 5A

This shows the structural steel components placed to the column of the corner. Open web steel joists (OWSJ) are placed on the steel beam of the lower roof. The joists for the floor behind have not been shown for clarity. Steel brackets and plates are shown aligned to the plane of the future sheathing of the wall. The gussets exterior of the plate will allow for the welding of a support gusset to a shelf angle support for the masonry veneer cladding. The gussets and plates provide the support and surface for adhesion of the SBS membrane seal while at the same time minimizing thermal bridging. Edge stiffener angles for the deck are installed with the one leg turned down in order that it does not interfere with the installation of the air seal membrane through the parapet (Detail 1).

Detail 5B

This shows the installation of the sheathing of the exterior walls and roof and the plywood edging of the perimeter of the roof edge and wall. A continuous simple series of planes has been created to which the SBS membranes can be adhered. Together they provide a continuous structural air seal plane for the detail. There are no structural elements that the membrane installer must weave around to achieve continuity of the air seal.

Detail 5C

This shows the first pieces of membrane installed at the transitions. SBS membrane is manufactured in approximately 3 ft widths (1 m) and roughly 90 ft lengths (30 m). Contractors often try to use the largest pieces of membrane they can; however, such practice often results in poor installation when the membrane has to be bent or conformed to a detail. It is much better to use smaller pieces of membrane to achieve a tight and fully adhered membrane making sure that the joints of the smaller pieces are fully bonded to each other and the penetrations. Larger rolls of membrane can then be handled on large flat surfaces.

Detail 5D

The parapet structural construction is added after the installation of the air seal membrane on the roof edge and where the parapet abuts the wall. Continuity of the air seal has been maintained at the critical parapet to wall junction. The SBS membrane can now be installed over the pieces of membrane that extend from under the parapet construction and where the parapet abuts the wall. This seems simple and logical but is often missed by designers and contractors as there are no details for this junction in the documents. The detail now follows the sequence of the previous details (1 and 3) that indicate the typical two-dimensional drawings at mid-span of the detail.

Detail 5E

This shows the tie-in of the roofing as per Detail 3 where the roofing membrane is separate from that of the air seal membrane. The building is air tight and waterproof at this stage. In cold weather construction, once the SBS membrane is installed on the wall, the installation of the insulation should follow immediately. If the building is being temporarily heated, the SBS membrane interior surface could provide a plane for condensation in the construction without the insulation and may result in wetting of the sheathing. In cold climate construction dry heating methods are recommended.

Detail 5F and H

The interior of the building may be heated as soon as the building is enclosed to facilitate the interior construction trades. It is recommended that a dry heat or vented heating systems be used to minimize the humidity created by non-vented systems. Even though this wall is insulated, the membrane and construction on the interior is often below the dew point of the highly humidified air. Drywall and plumbing trades can also produce conditions where moisture can create problems in cold climate constructions.

Detail 5G

The roofing is completed in this detail.

Detail 5H

Installation of the insulation is made. The contractors must ensure that the insulation is tight to the SBS membrane by mechanically fastening it through the membrane into the studs of the backup wall with either purpose made clips and screws or in conjunction with the cladding anchorage system. The screws, while penetrating the membrane should self seal, it must be stressed to the trade's installation crews that if a screw is removed the membrane must be patched. This is where preplanning and marking of the backup structure during membrane installation should be specified and reviewed in the preinstallation meetings.

Detail 5I

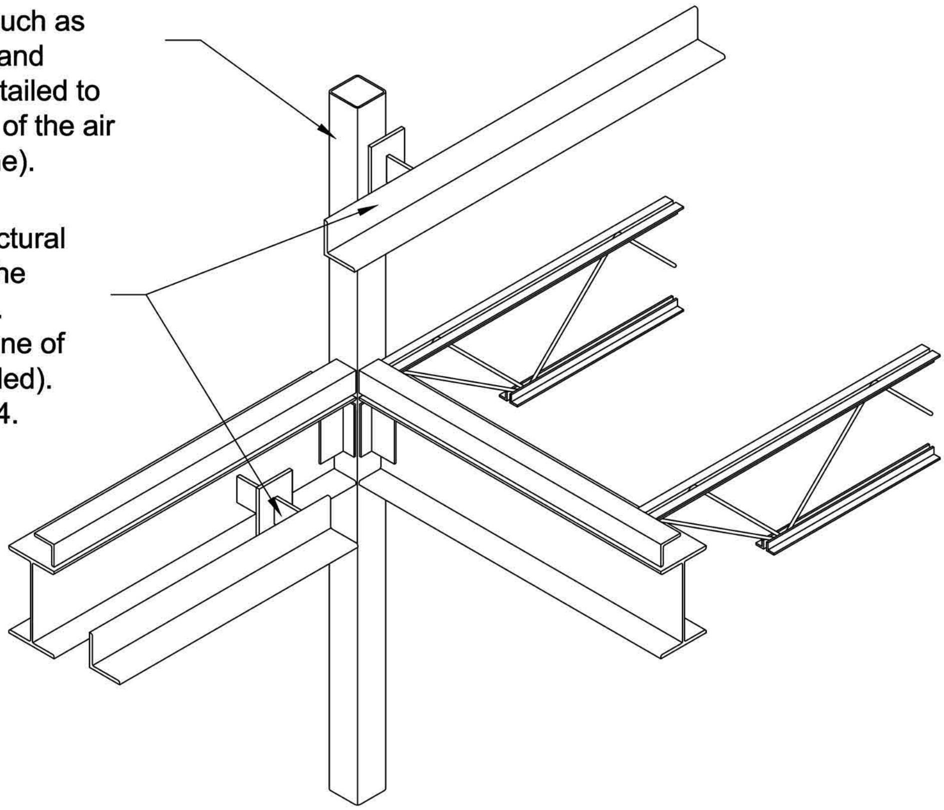
The shelf angle to support the masonry above the roof could have been installed at any point, but was purposely left off the details for clarity of the other terminations of materials. With it installed the masonry can be installed as well as the interior parapet flashings.

Detail 6: Wall to Window Details

Probably the most common complaint of building owners and operators has been about leakage of windows. Windows leak water and allow air to blow around their frames resulting in discomfort, reduced thermal performance, noise and contaminants entering the enclosure. If the edges of sealed units are exposed to water for periods of time, the sealants will deteriorate prematurely resulting in the failure of the unit to maintain its seal. The resulting moisture entering this space can obscure the clarity of the unit.

Curtain wall has been the most tested window system for commercial buildings. Strip or punched windows do not need the structural aspects of the self-supporting framing, The structure should be designed to minimize changes in plane of the exterior sheathing. Features such as overhangs, canopies, and parapets should be detailed to minimize penetrations of the air barrier (SBS membrane).

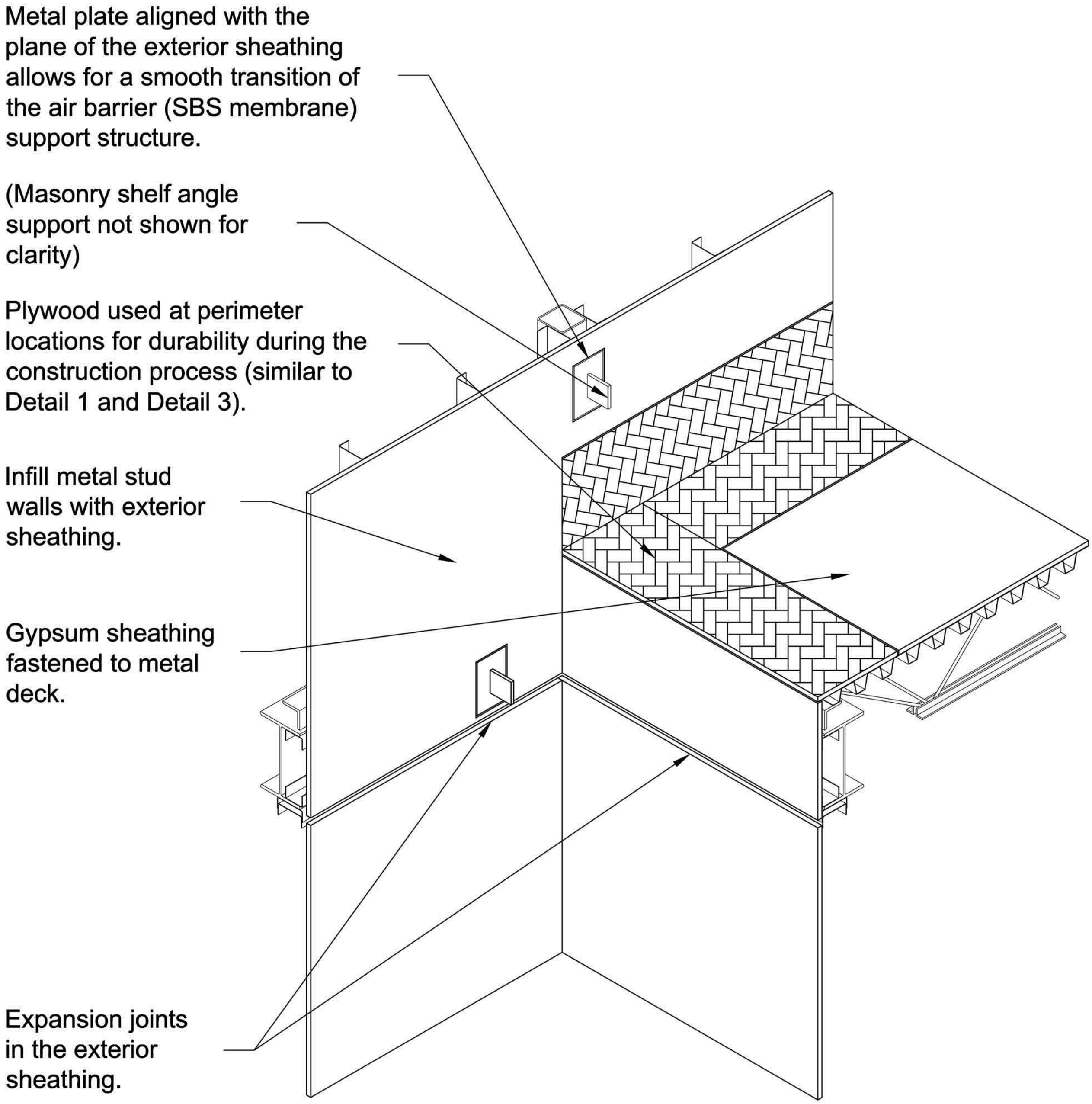
Plates installed at structural penetrations through the plane of the air barrier. Plates aligned with plane of sheathing (to be installed). Detail similar to detail 4.



DETAIL 5: PARAPET TO WALL JUNCTION

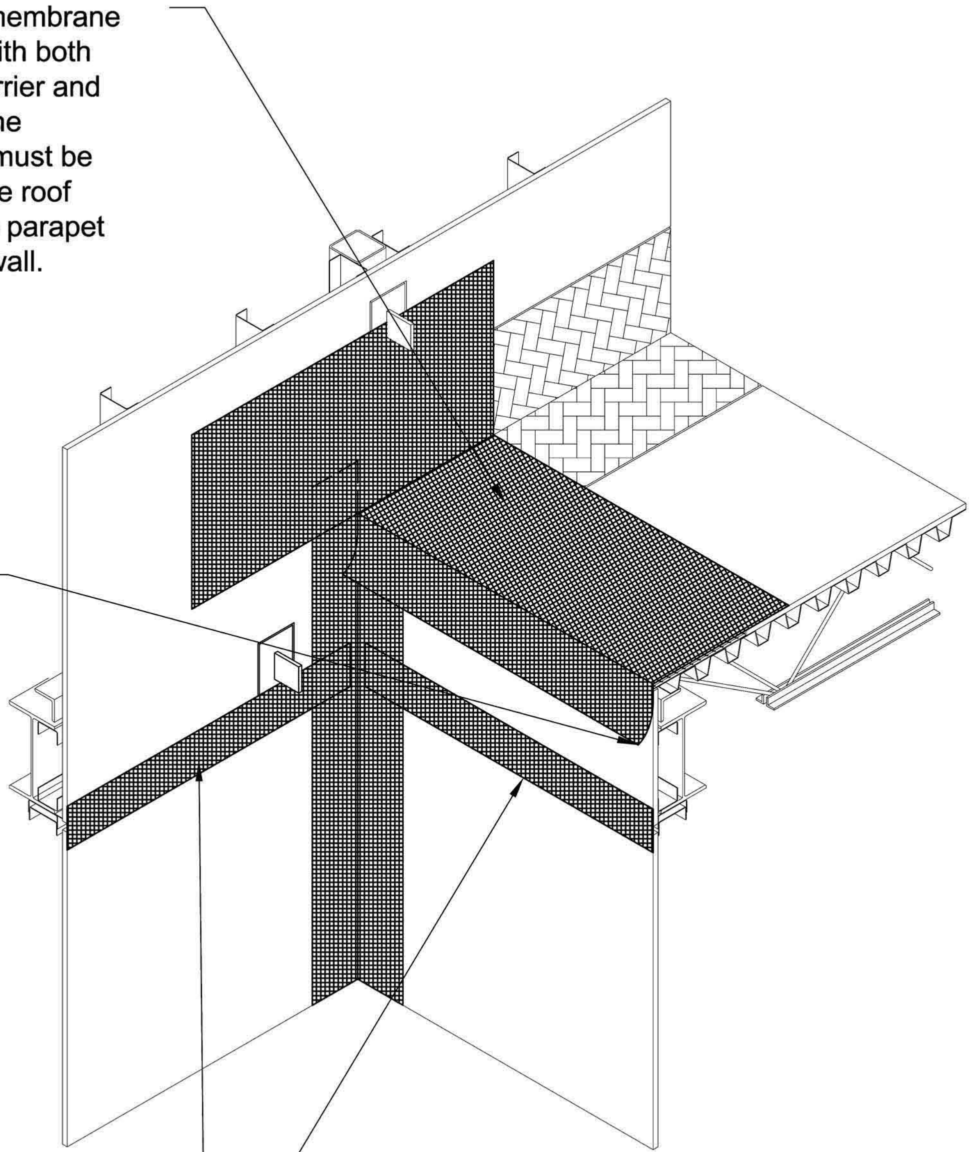
ISOMETRIC CONSTRUCTION SEQUENCE

5A



DETAIL 5: PARAPET TO WALL JUNCTION
ISOMETRIC CONSTRUCTION SEQUENCE

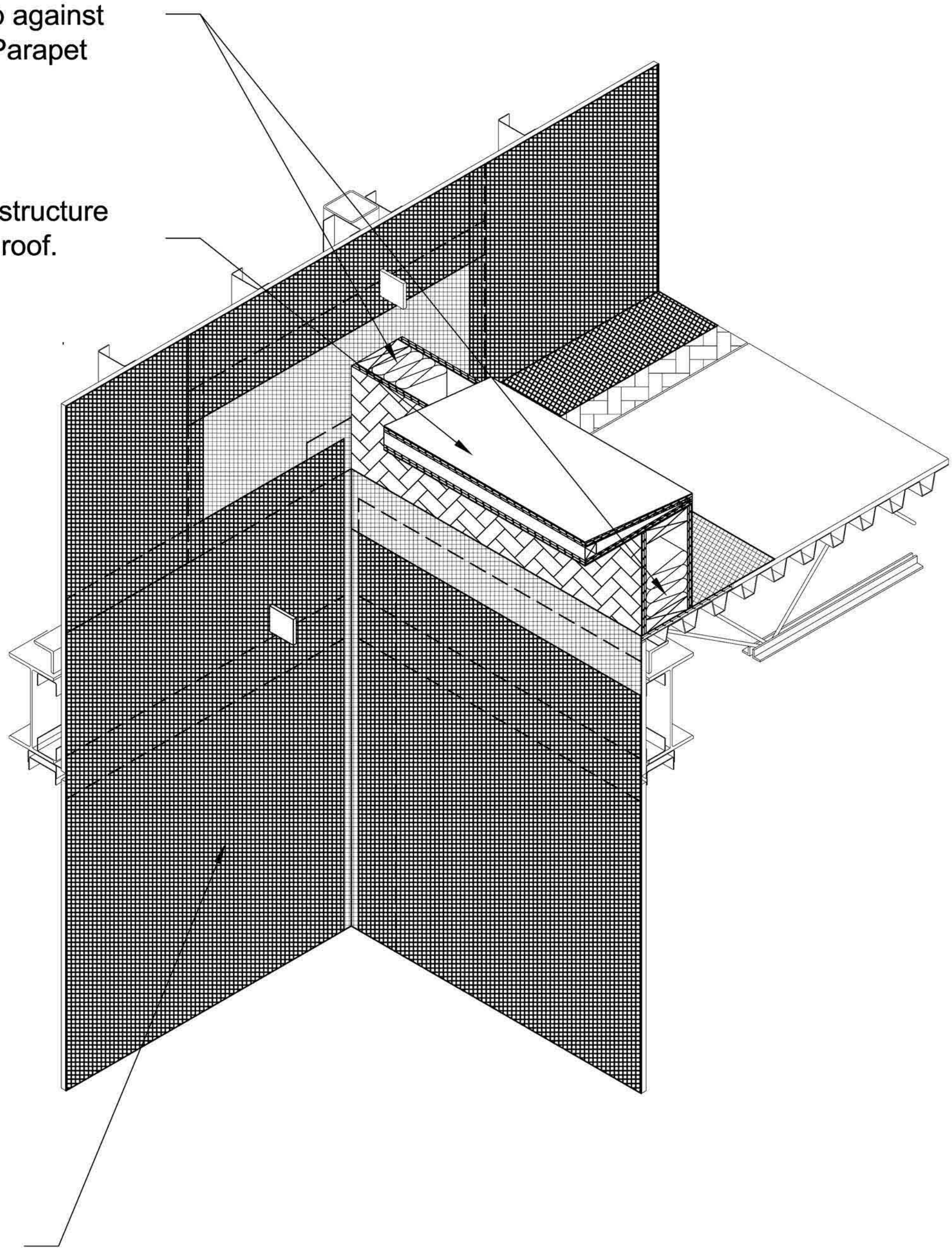
5B



DETAIL 5: PARAPET TO WALL JUNCTION

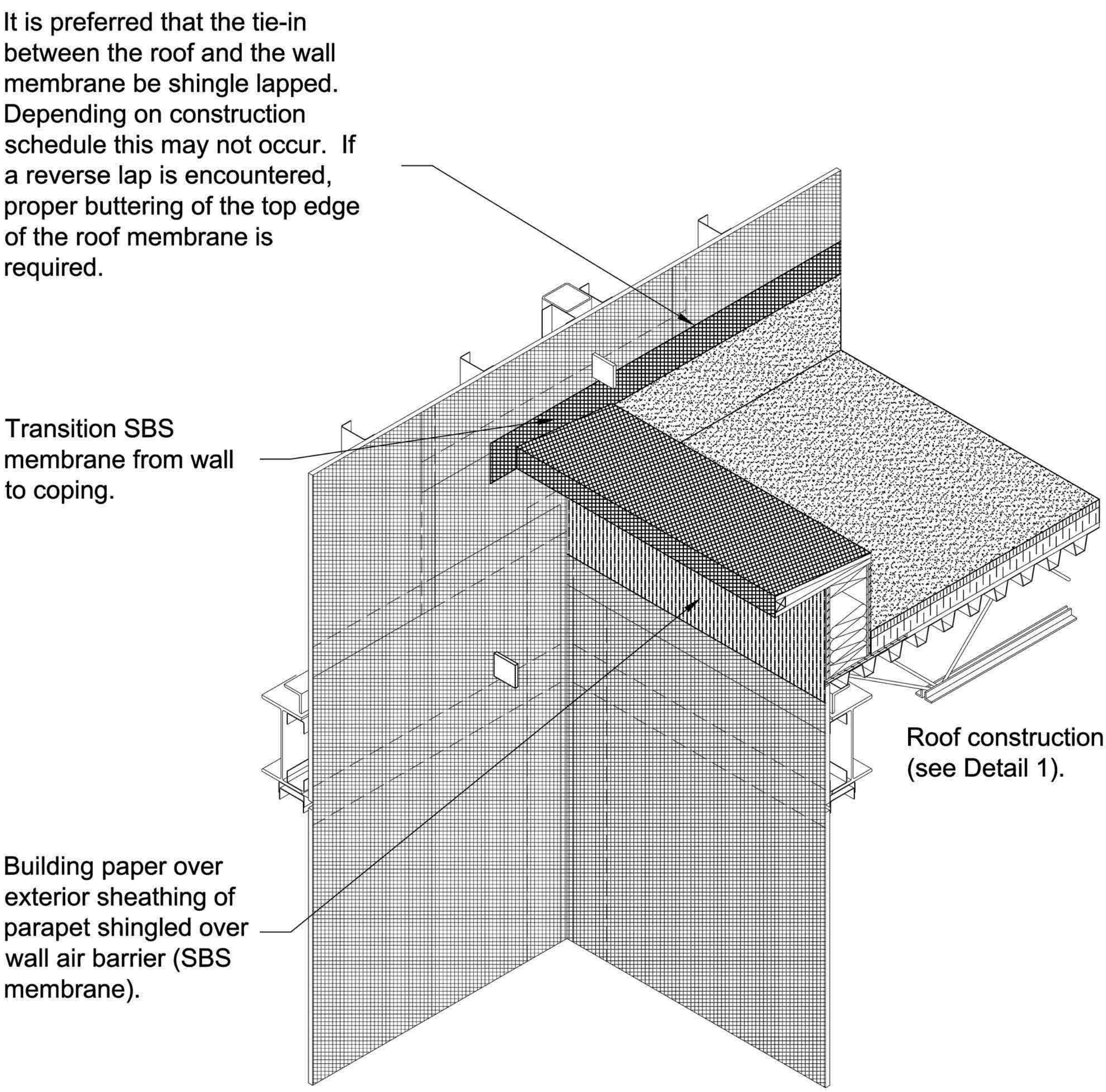
ISOMETRIC CONSTRUCTION SEQUENCE

5C



DETAIL 5: PARAPET TO WALL JUNCTION
ISOMETRIC CONSTRUCTION SEQUENCE

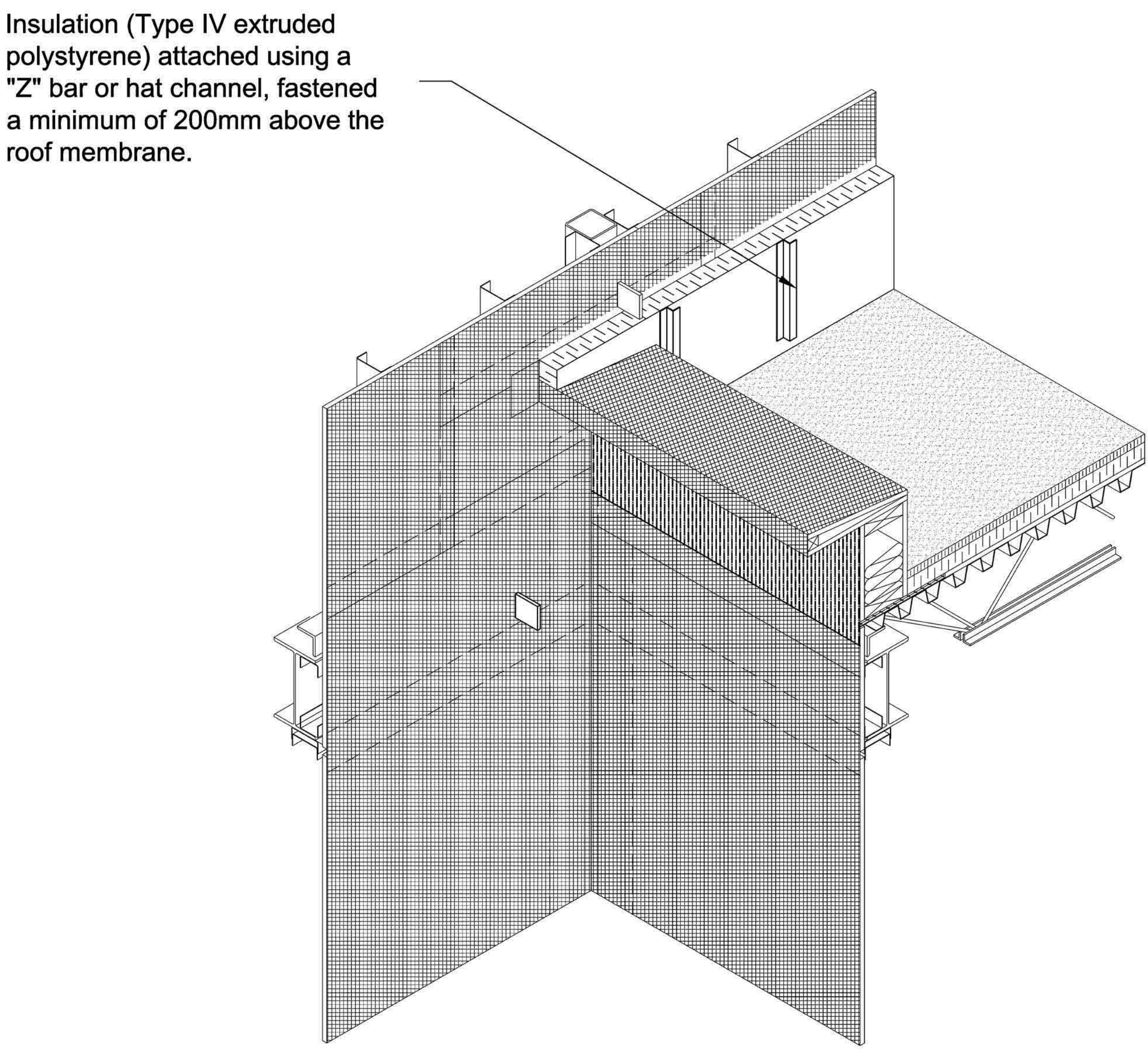
5D



DETAIL 5: PARAPET TO WALL JUNCTION

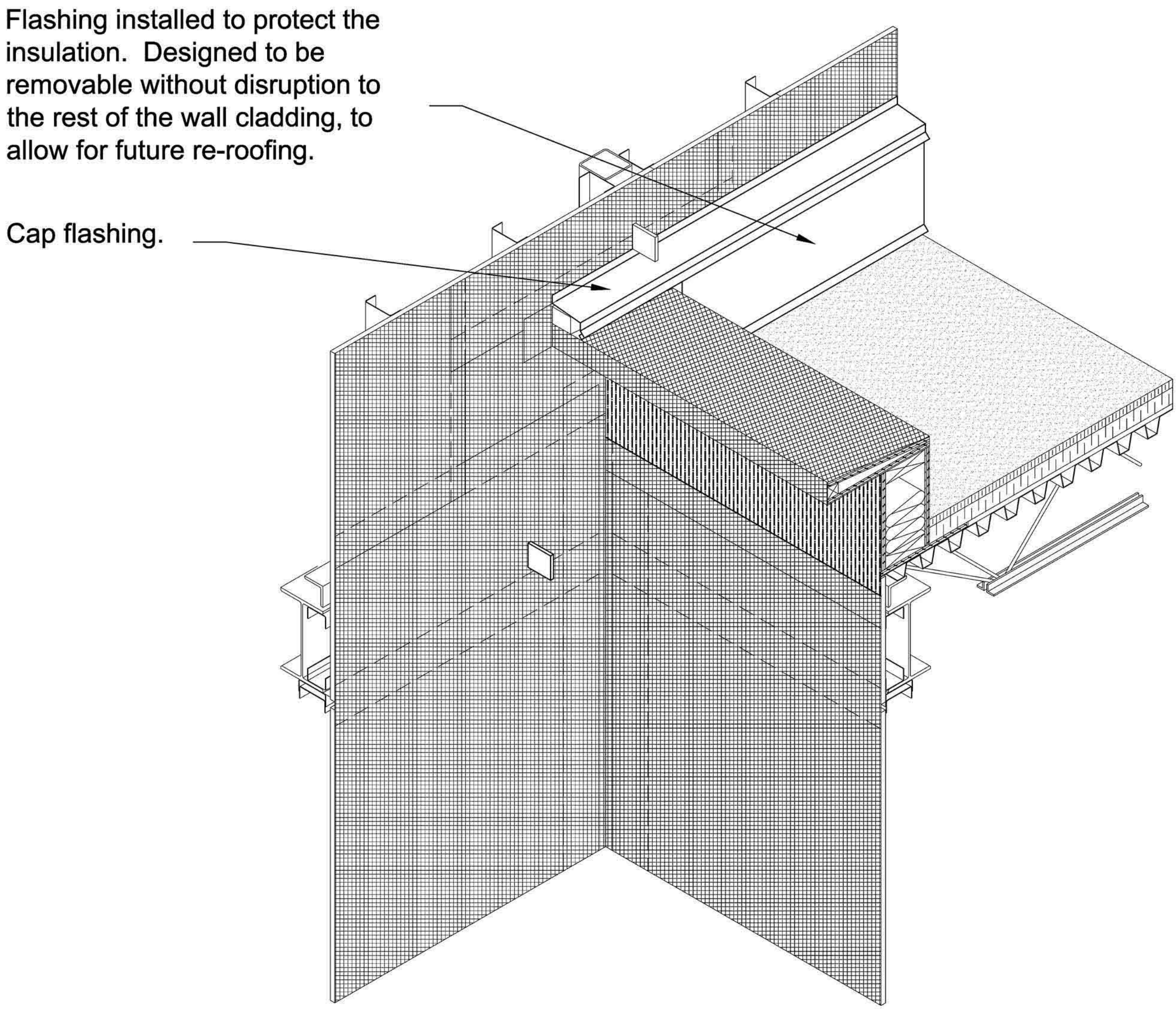
ISOMETRIC CONSTRUCTION SEQUENCE

5E



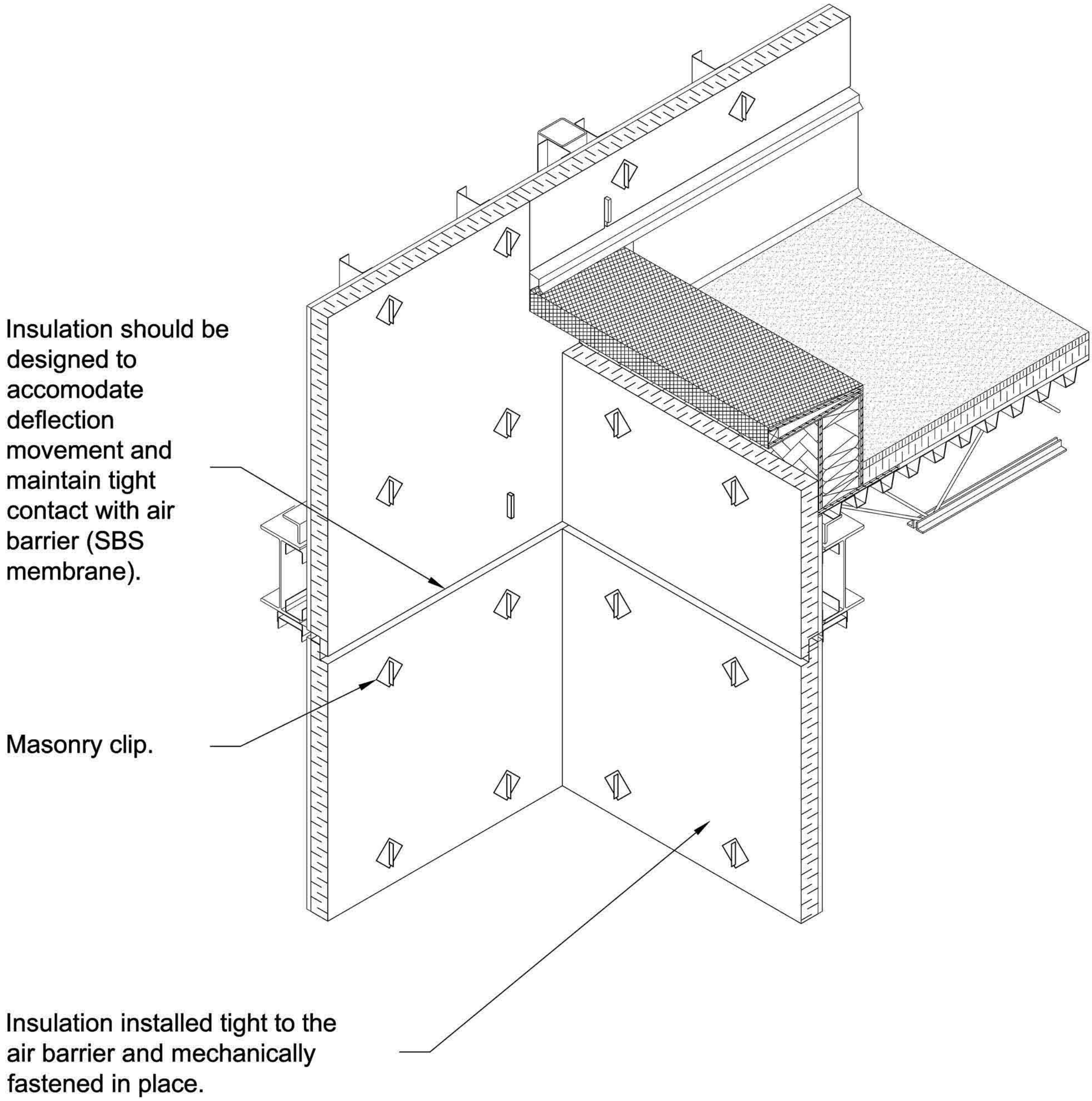
DETAIL 5: PARAPET TO WALL JUNCTION
ISOMETRIC CONSTRUCTION SEQUENCE

5F



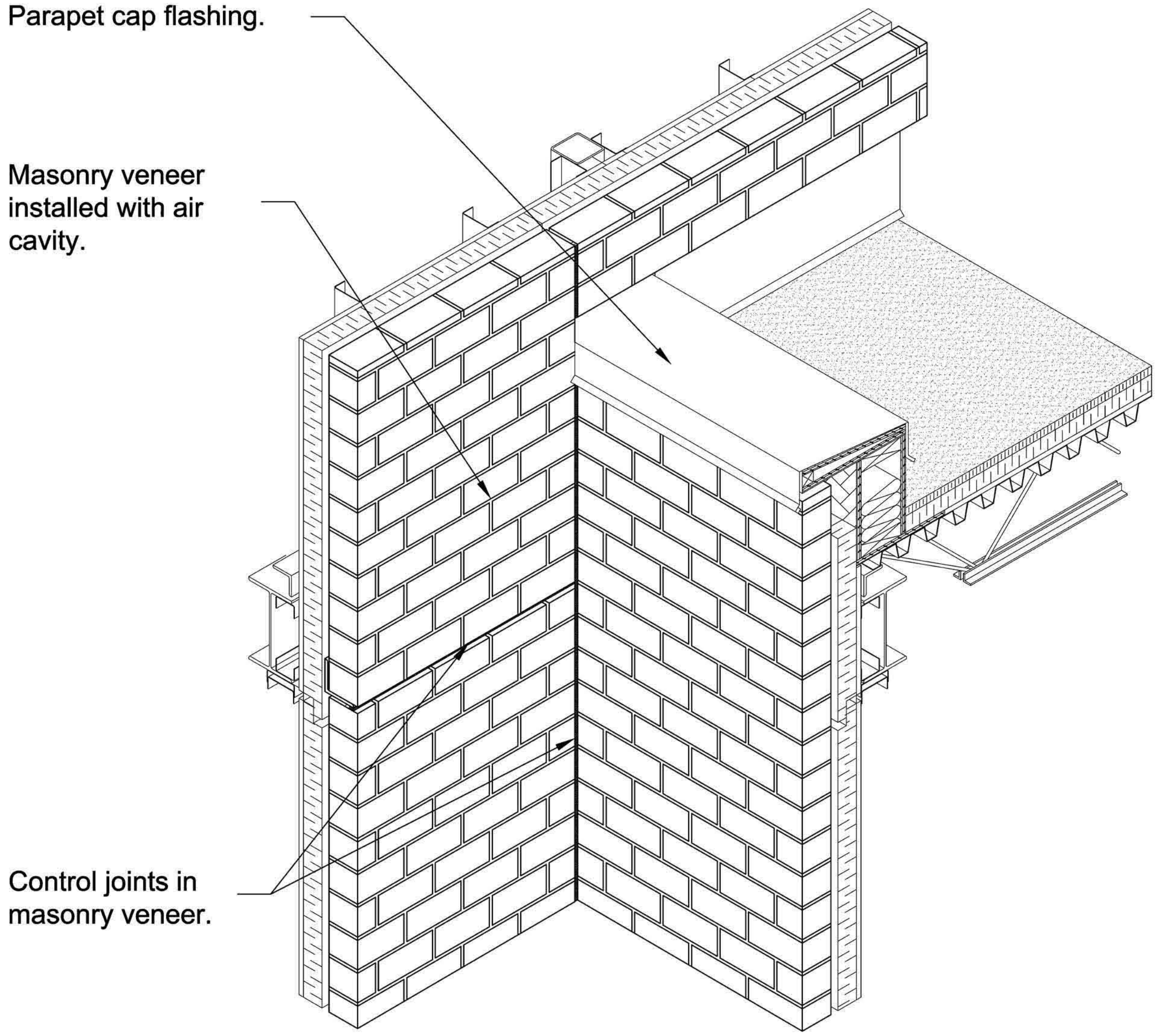
DETAIL 5: PARAPET TO WALL JUNCTION
ISOMETRIC CONSTRUCTION SEQUENCE

5G



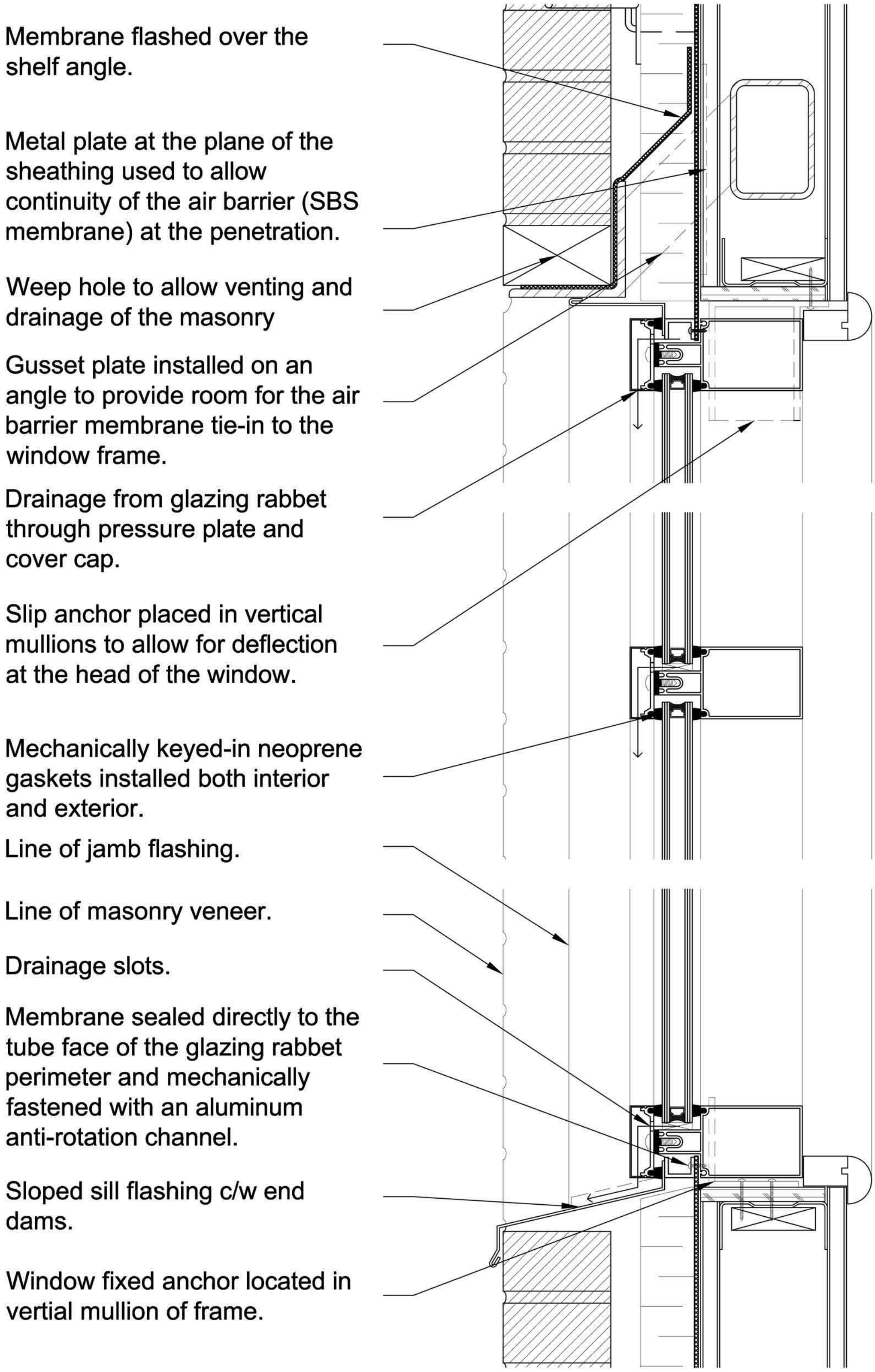
DETAIL 5: PARAPET TO WALL JUNCTION
ISOMETRIC CONSTRUCTION SEQUENCE

5H



DETAIL5: PARAPET TO WALL JUNCTION
ISOMETRIC CONSTRUCTION SEQUENCE

5I



DETAIL 6: PUNCHED WINDOW (SMALL BOX CURTAIN WALL)
SECTION

6

but the water and air sealing performance is worth the minimal additional costs (if any) when one considers the costs of-window problems and long term performance. In the mid-80s the Alberta Government asked the aluminum manufacturers to produce a window frame that followed the design principles of curtain wall framing for water and air leakage but in a smaller and less costly design. The small box curtain wall systems were created. They followed the same rain screen design principles, had drainage of the glazing rabbets (pocket that retains the glass), similar thermal performance due to their thermal break and allocation of aluminum, good air sealing, and they made it possible to tie in SBS membranes to the aluminum sections in a way to ensure air barrier continuity. Many manufacturers now supply these systems in Canada today for government and developers alike. These systems were more expensive than "face seal" systems that were commonly used, but are now priced comparably. The systems small box curtain wall provided less problematic performance for warrantee issues and litigation and better performance.

The design of these systems provides improved performance while at the same time allows the framing to be easily tied into the PERSIST wall. Anchors for the framing are concealed in the vertical tubes of the framing. With the anchors interior of the plane of air sealing they do not interfere with the installation of the SBS membrane to the wall of the tube face of the frame in the perimeter glazing rabbet. Depending on the movement expected and the pressures to be imposed on the joint between wall and frame, the membrane can bridge the gap between the wall sheathing and the tube face. The SBS can be an internally reinforced type of membrane for larger gaps or it could be adhered to galvanized sheet metal aligned to the tube face for even larger gaps or where large deflections are anticipated by the structural engineer. The sheet metal can be fastened to the wall construction and fastened to an aluminum angle secured to the side of the tube offset by the thickness of the sheet metal to the tube face. In this way the sheet metal and membrane act as a system to take the movement and pressures.

Detail 7 Series: Wall to Window Isometric Details

These details are a series of isometric details that show a sequence of construction details for the corner of a punched window. They show how the contractor should put together the framing sections of aluminum and place the window frame in the rough opening. Manufacturers may have their own frame fabrication drawings but these are often not included in the shop drawings and may not meet the requirements for air sealing to the wall with a membrane. Most details seem to show caulking by the installer which is not acceptable with this technique and has proven repeatedly not to perform long term.

Detail 7A

This shows the jamb and sill sections of a small box curtain wall frame and how the aluminum sections are to be sealed with nonshimmed butyl tape. The tape is 12 mm wide and extends above and below the joint to be sealed. This extension of the butyl tape allows each joint to be inspected. The butyl tape should also extend into the glazing rabbet for the same reason. The tape will be cut off during the final cleaning stages with a razor blade cut at the joint and then pealing of the excess tape from the joint. Some manufacturers call for the use of caulking to seal this joint. Caulking is difficult to inspect and if it sets up may shear during the moving of frames before and during the installation process. It has been my experience that the butyl tape may also shear but it remains pliable and usually reseals. When the horizontal section is placed over the aluminum spigot fastened to the vertical mullion it is compressed into the butyl tape of the joint by the screws attached through the face of the tube in predrilled holes. The holes are slightly offset to apply pressure to the joint when the screws are tightened into position.

The screw spline or nosing of the vertical section has been removed at the end of the section to allow for the continuous placement of SBS membrane to the tube face after the frame is anchored.

Detail 7B

This detail shows the placement of the sill anchor for the window frame. The anchor is offset from the face of the wall sheathing by the thickness of the aluminum tube section. This will allow the SBS membrane to transition between the two surfaces evenly. While some tolerance can be accommodated by the SBS membranes, it is difficult to bend membrane in tight applications so it is preferred to align the surfaces.

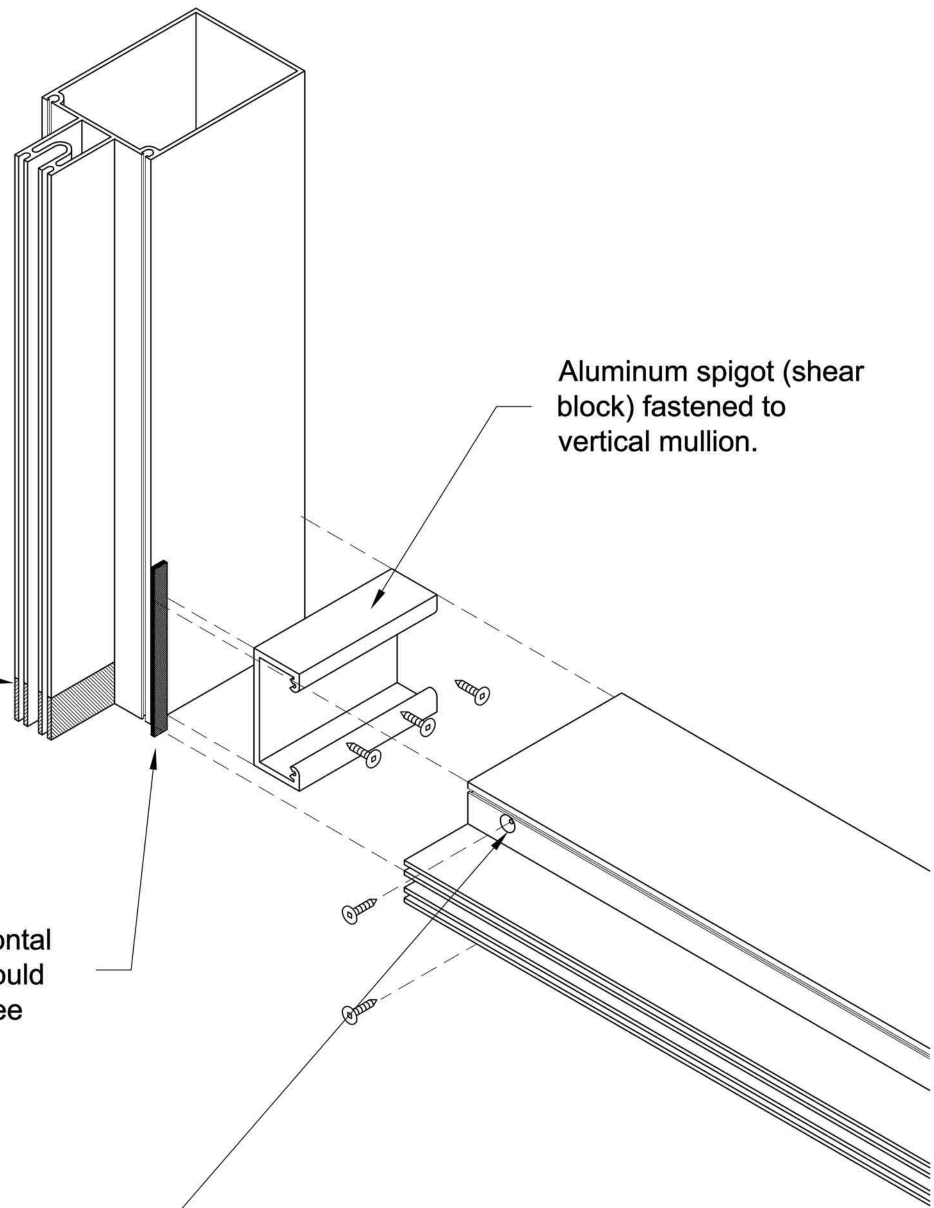
Detail 7C

The assembled frame is lifted over the preset angle anchors of the sill. A deflection tube anchor would have already been placed in the top of the vertical mullions to provide securement of the frame at the top (see Detail 6 section). This deflection anchor can be a manufacturers purpose designed anchor or an engineered installer bracket, but it must resist the in/out movement of the frame as well as side to side movement without interfering with spigot screws that penetrate the tube and deflection of the wall above in relation to the frame.

The frame is aligned in the rough opening at the sill and is set with screws fastened through the exterior face of the tube into the angle anchor of the sill. This should provide a gap around the window frame. Do not fill this gap with insulation as this would be interior of the air seal plane and may result in condensation around the frame.

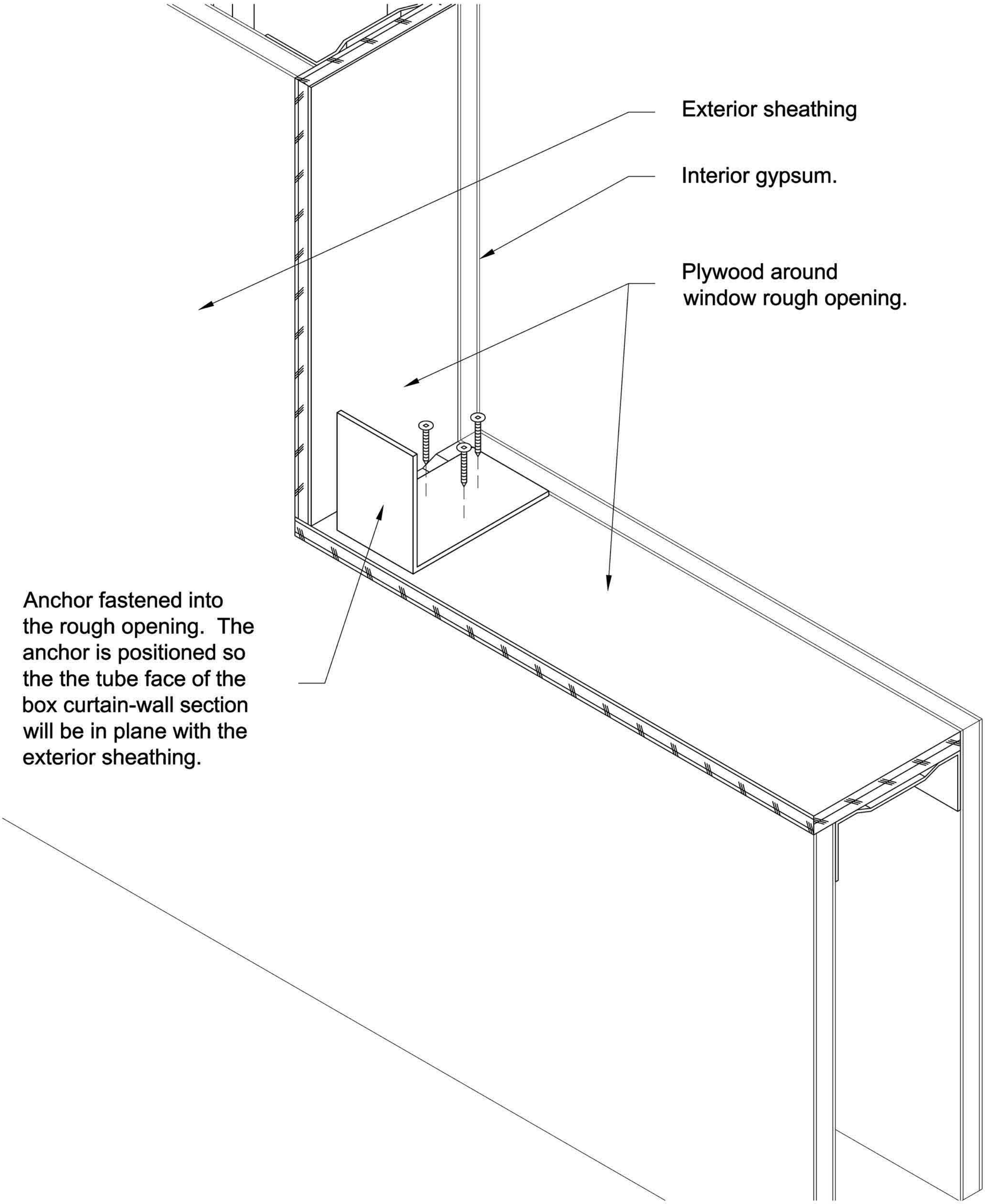
Detail 7D

The SBS membrane is installed from the window frame to the wall in this detail. The membrane is installed in a shingle fashion in order that the joints at the corners overlap and do not retain water or a joint where water could be retained. That would mean that the sill is done first, then the jambs, and lastly the head. If the wall membrane is already on the wall then these membranes will overlap except at the head where the last membrane edge will be nonshingled. Peel and stick membrane manufacturers have a proprietary caulk that should be used along this edge. Torched membranes can be heat sealed by heating the applicator's trowel and heat welding the edge to form a smooth joint. If the membrane is not on the wall then a flap can be left at the sill to overlap the wall membrane when it is installed. The time that a membrane is left to flap in the wind should be minimized as the



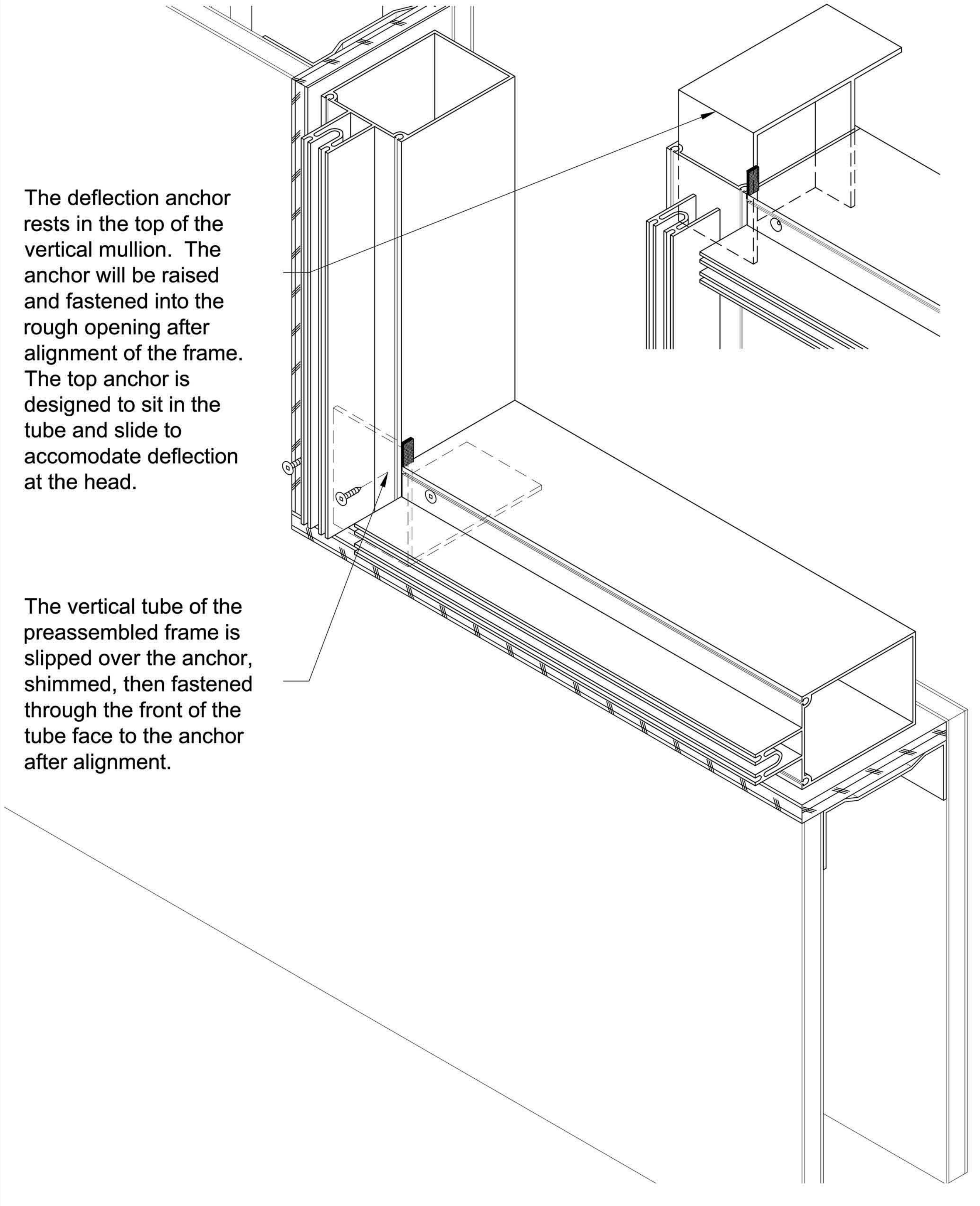
DETAIL 7: PUNCHED WINDOW (SMALL BOX CURTAIN WALL)
ISOMETRIC CONSTRUCTION SEQUENCE

7A



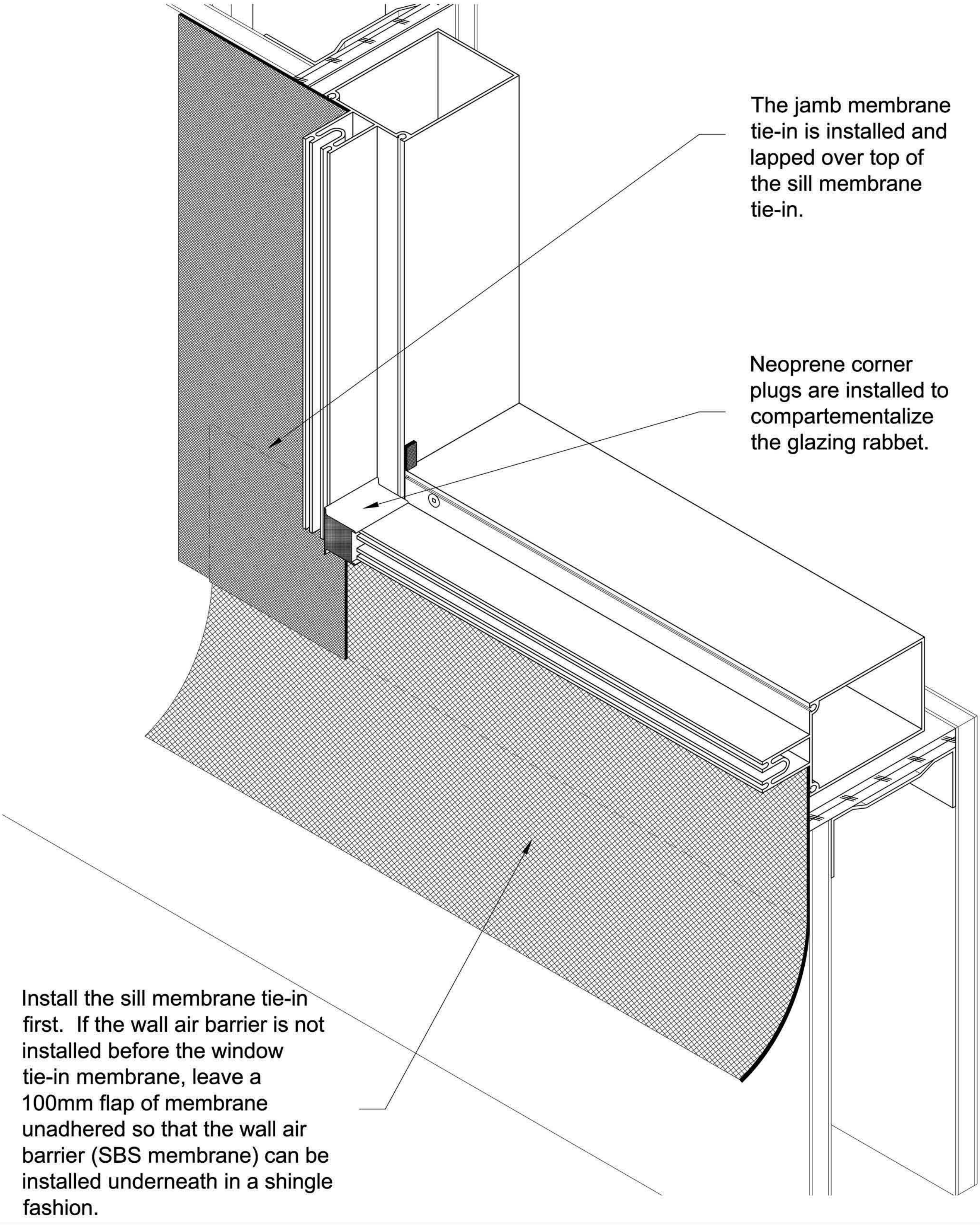
DETAIL 7: PUNCHED WINDOW (SMALL BOX CURTAIN WALL)
ISOMETRIC CONSTRUCTION SEQUENCE

7B



DETAIL 7: PUNCHED WINDOW (SMALL BOX CURTAIN WALL)
ISOMETRIC CONSTRUCTION SEQUENCE

7C



DETAIL 7: PUNCHED WINDOW (SMALL BOX CURTAIN WALL)
ISOMETRIC CONSTRUCTION SEQUENCE

7D

membrane may become contaminated with construct dust in the air and become difficult to seal.

The corner plug is placed between the nosing sections of the members. Some manufacturers are using plastic for corner plugs while others use neoprene. I prefer the neoprene plugs set in place with a skim coat of sealant as they are more forgiving of tolerances encountered during installation. These plugs are meant to compartmentalize the glazing rabbet once the pressure plates are installed. They also direct water that enters the glazing rabbet in the verticals to the horizontals where it can be drained through drainage slots made in the pressure plate and holes in the cover cap.

Detail 7E

An anti-rotation channel or angle is applied to the perimeter of the window to mechanically secure the SBS membrane. It also provides a surface for the fastening of the perimeter flashings, and as the name suggests, prevents the rotation of the pressure plate and cap system that retains the sealed unit. Rotation of the pressure plate would reduce the compression of the keyed in gaskets of the pressure plate allowing the potential for water entry. Membrane manufacturers require a minimum of 50 mm (2 in.) of surface to ensure adhesion of their membranes or the membranes must be mechanically fastened, hence the anti-rotation channels. Some manufacturers have purpose designed angles with keyed in gaskets while others rely on the fabricator to supply either extruded channels or bent metal. Wood blocks rot, plastic warps and may be brittle especially in cold applications resulting in shattering, and insulation blocks may dimensionally change so these are not recommended. The anti-rotation channel has holes drilled right through the lips of the channel. A larger hole is made on the exterior lip to allow the applicator's bit and head of the screw to penetrate to the interior lip. Now the channel lip acts much like a pinch bar in roofing to retain the membrane tight against the tube face of the glazing rabbet.

Interior air seal gaskets of the framing are installed in this detail. The gasket installer should start in the corner and apply the gaskets by pushing them into the key way in the frame, towards the starting corner. By installing the gaskets in this fashion the installer is assured of installing enough gasket in the opening to accommodate for any shrinkage and movement. Do not stretch the gaskets or loop the gaskets as they will not expand to the opening but will shrink with time, leaving gaps in the corners. By pushing the gasket toward the starting corner the installer is installing a compressed gasket over the entire length so shrinkage, when it occurs, will be uniform over the length of the gasket and the corners should remain tight. Some butyl caulking may be applied to the joint of the gaskets in the corners or the gaskets could be heat welded if that is available.

The thermal break gasket is applied to the exterior nosing of the screw spline in the same fashion as the gaskets.

Detail 7F

The glass sealed unit is placed in the glazing rabbet from the exterior. It is placed on neoprene setting blocks minimum 38 mm (1–1/2 in.) long by 6 mm (1/4 in.) in height by the thickness of the sealed unit. The setting blocks should be placed at 1/4 points of the opening unless there are specific requirements by the frame or glass manufacturer. Temporary pressure plate pieces are installed to retain the unit for short periods of time, but should not be relied upon to retain glass, especially in high wind areas.

Detail 7G

Insulation is installed tight to the SBS membrane to ensure that there are no gaps between the insulation and the membrane which could reduce the effectiveness of the insulation or create cold spots on the membrane where condensation could occur interior of the membrane. The cladding is designed as a rain screen with an air cavity between the insulation exterior face and the interior face of the cladding (in this case masonry).

Detail 7H

The sill flashing is installed to fit from the anti-rotation channel out over the edge of the cladding. The outer edge can be retained by hidden clips secured into the drip edge, and fastened to the cladding, while the inner lip is fastened to the anti-rotation channel. There should be a *minimum* 2 % slope of the flashing to the exterior. The sill flashing should also be installed with end dams at its termination to minimize water entry into the cavity and behind the cladding.

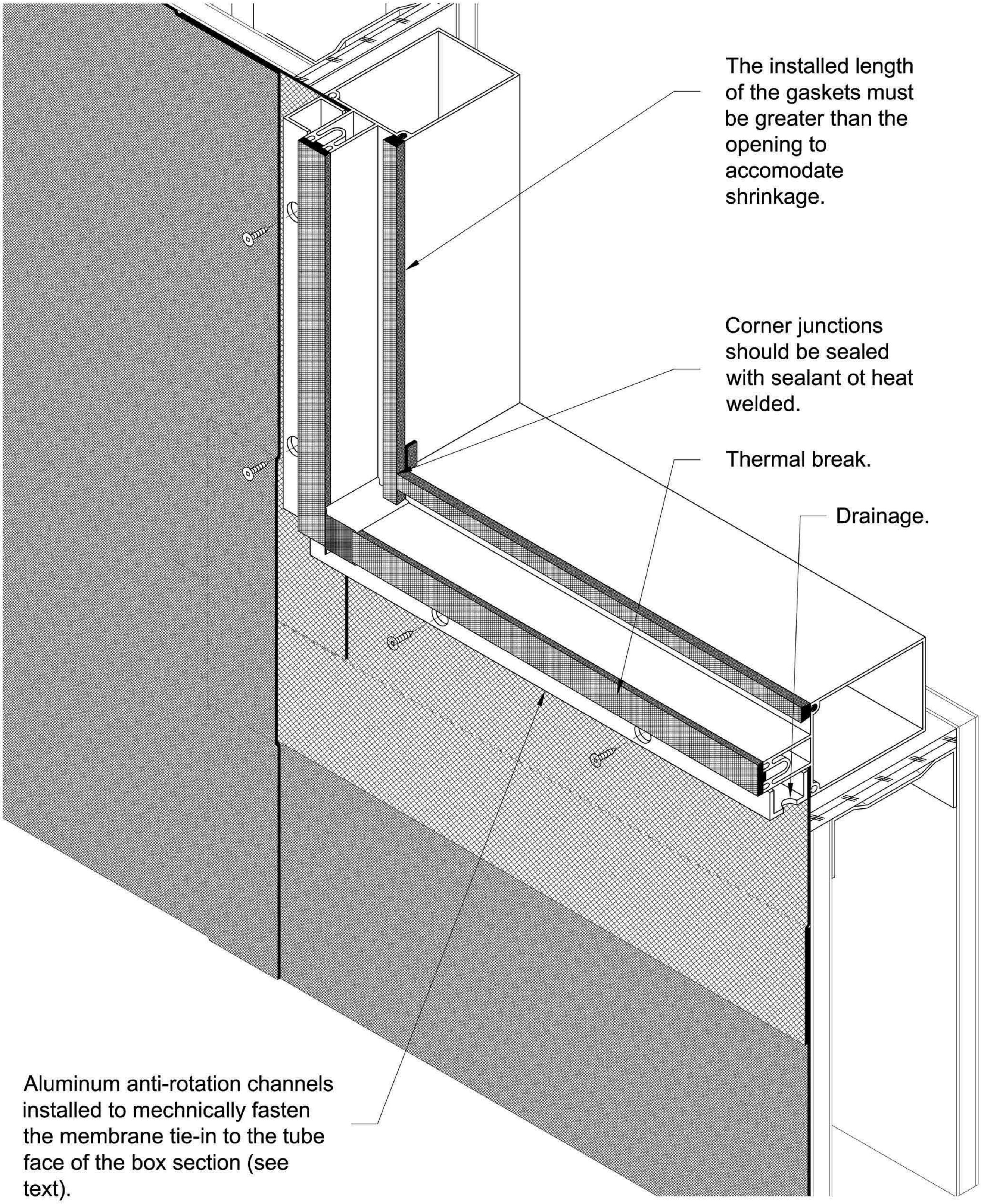
Detail 7I

The jamb flashings bridge the cavity space from the anti-rotation channel and overlap the end dam of the sill. The flashing may need to be retained on its outer edge depending on size and local wind conditions. If the flashing is under bent to its installed right angle it can be pressure fit to the cladding and mechanically fastened to the anti-rotation channel to achieve a tight fit. It is also appropriate to have the hidden edge of the flashing brought long and cut on site to accommodate tolerances between the cladding and the frame.

The pressure plates with mechanically keyed in gaskets are installed by screwing them to the screw spline (nosing) of the frame through the thermal break. There should be gaskets applied to both edges of the pressure plate to provide an even pressure to the system. The horizontal pressure plates should have three 38 mm (1–1/2 in.) long by 10 mm (3/8 in.) in height drain slots made through the aluminum to drain to the exterior any water that does get past the exterior gaskets and into the glazing rabbet. The slots are located with one between the setting blocks on which the glass sealed unit rests, and one on either side of the setting blocks between the setting blocks and the vertical mullion. While some installers use holes, the slots tend to self-clean and not clog like holes do. Predrilling of slots or holes in all pressure plates is not recommended as this does not ensure correct location and may allow water into the system if these pressure plates are used for vertical mullions.

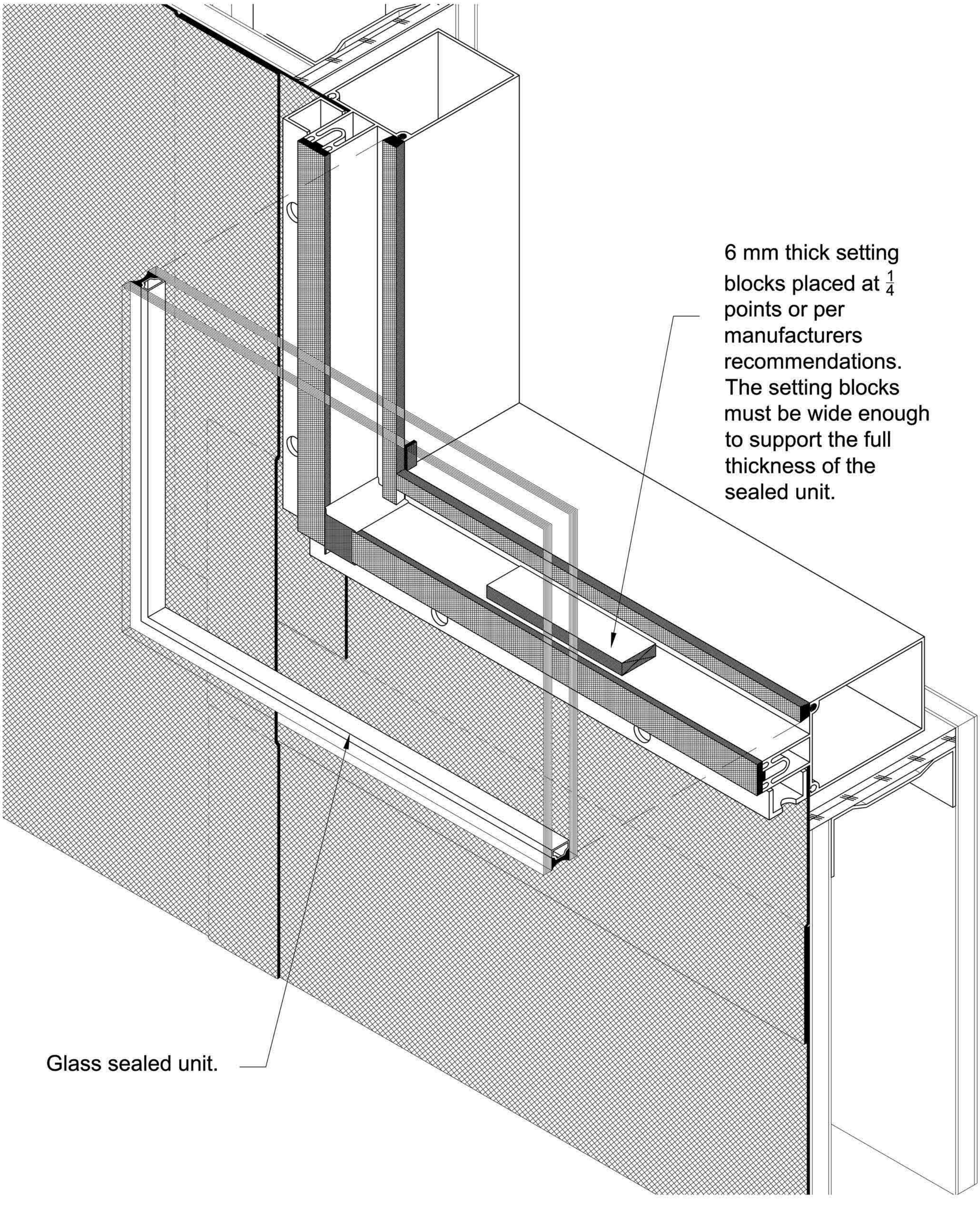
Detail 7J

To provide a finish to the system, aluminum cover caps are snap applied to the of the pressure plates. These caps must be provided with sufficient space between the edge of the cover cap and flashings to allow the cap to clip over the edge profile key of the pressure plate. This is also necessary for the removal of the cap to access the pressure plate screws for unit replacements. A minimum of 6 mm (1/4 in.) is required



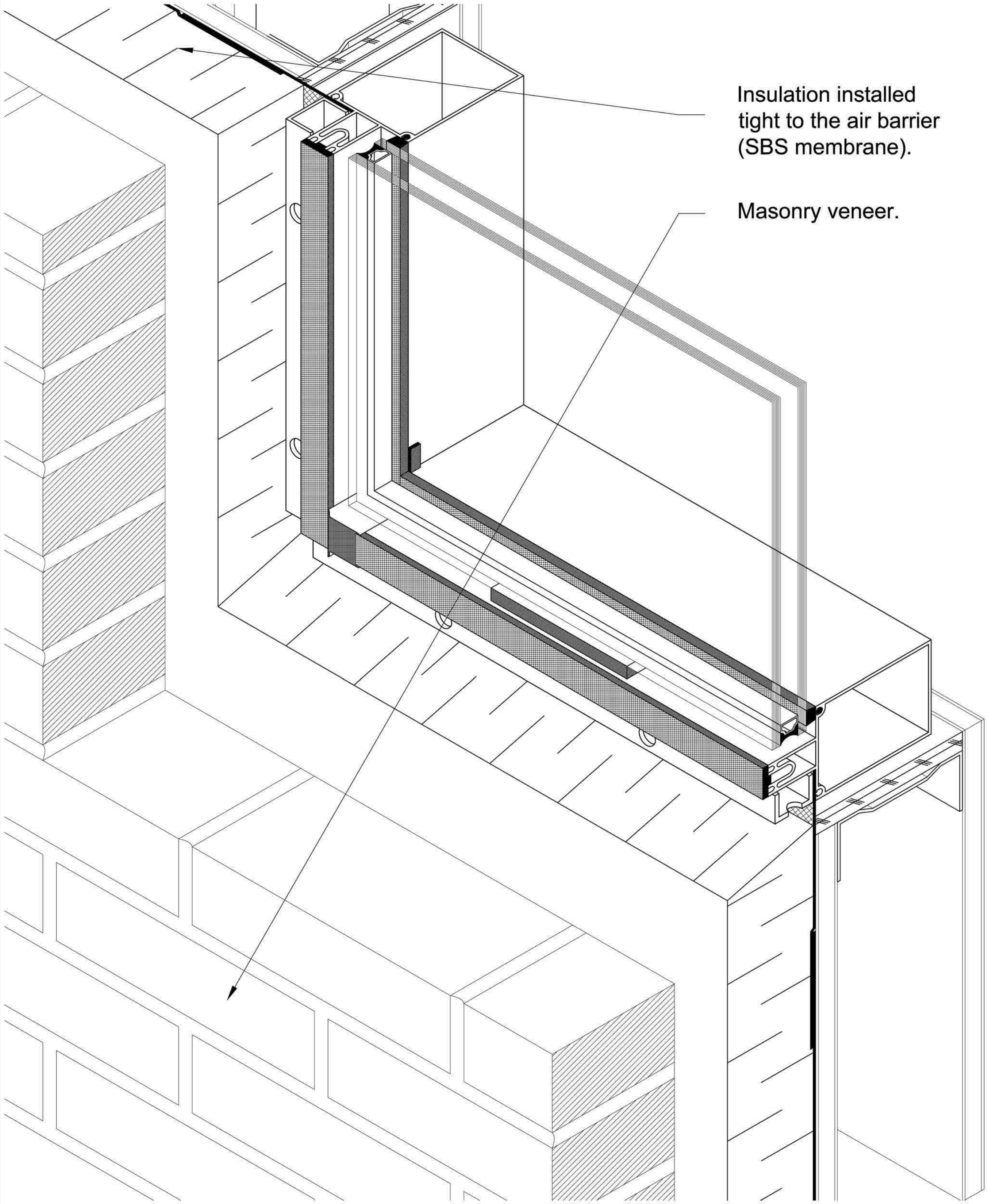
DETAIL 7: PUNCHED WINDOW (SMALL BOX CURTAIN WALL)
ISOMETRIC CONSTRUCTION SEQUENCE

7E



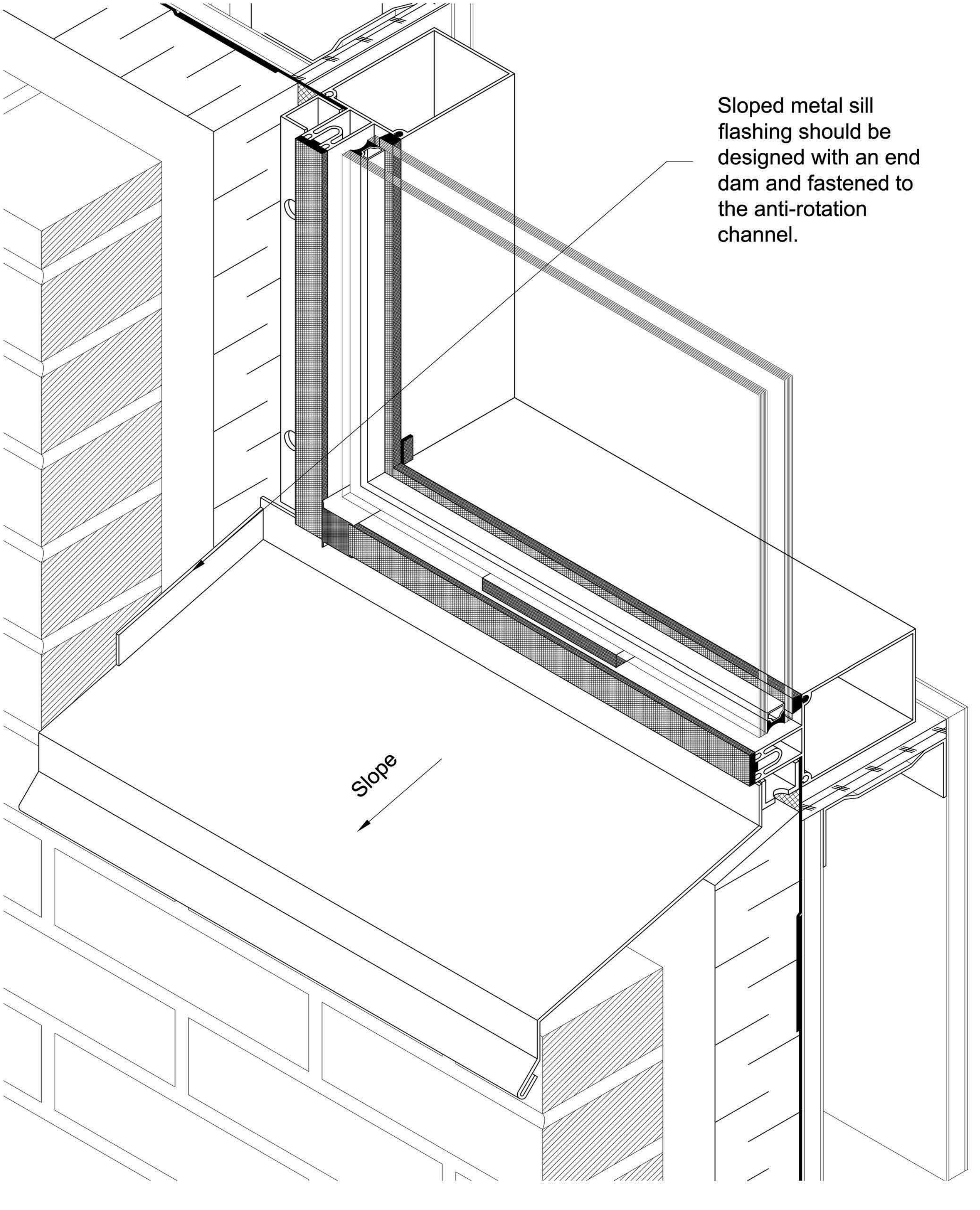
DETAIL 7: PUNCHED WINDOW (SMALL BOX CURTAIN WALL)
ISOMETRIC CONSTRUCTION SEQUENCE

7F



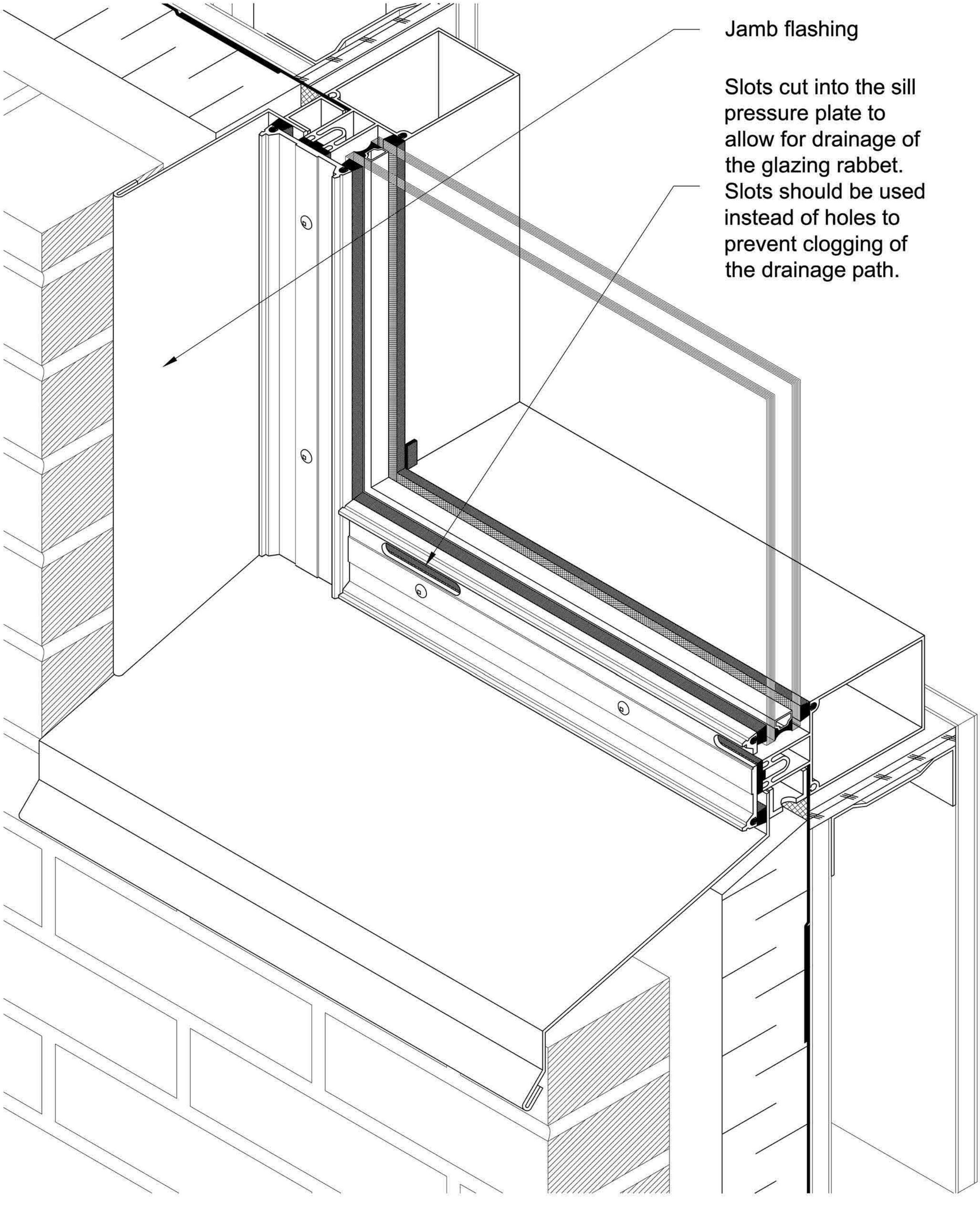
DETAIL 7: PUNCHED WINDOW (SMALL BOX CURTAIN WALL)
ISOMETRIC CONSTRUCTION SEQUENCE

7G



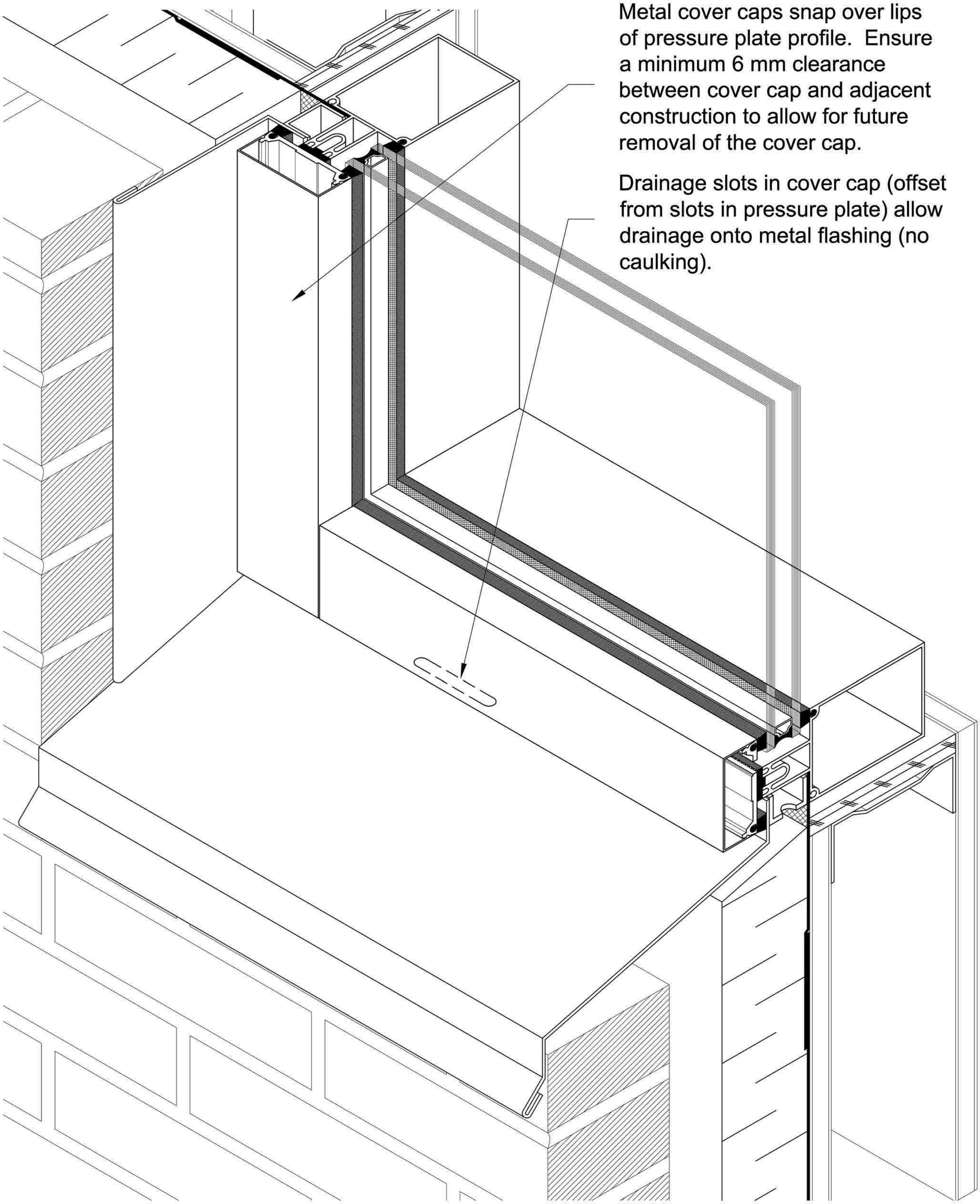
DETAIL 7: PUNCHED WINDOW (SMALL BOX CURTAIN WALL)
ISOMETRIC CONSTRUCTION SEQUENCE

7H



DETAIL 7: PUNCHED WINDOW (SMALL BOX CURTAIN WALL)
ISOMETRIC CONSTRUCTION SEQUENCE

7I



DETAIL 7: PUNCHED WINDOW (SMALL BOX CURTAIN WALL)
ISOMETRIC CONSTRUCTION SEQUENCE

7J

for a standard 12 mm (1/2 in.) cap. The horizontal cover caps cannot butt tight to the vertical cover caps as thermal-expansion of the cap may result in the cover cap releasing from the pressure plate. A minimum 3 mm gap is recommended.

Detail 8: Structural Penetrations

Penetrations for architectural fenestration pose problems no matter what technique is used to provide an air and water seal for the building enclosure. They are often the point of water infiltration into the wall construction and for air exfiltration, which in a cold climate such as Alberta's can result in condensation in the wall construction. Where infiltration occurs the interior surfaces may be cooled to result in interior condensation or freezing of pipes etc.

Detail 8A

This details the attachment of a steel canopy to a structural steel building. The canopy is designed as a cold thin soffit. The canopy structure can be sloped to drains or scuppers. By making this canopy a cold soffit it is not necessary to provide heat and air movement within the canopy soffit necessary to minimize the potential for condensation.

To attach large structural members through the plane of the air seal creates problems. Continuity of the air seal must be achieved and maintained over the life of the building's operation and the detail should minimize thermal bridging of the steel penetrating the plane of air seal. The detail indicates a gusset plate attached to a steel plate in the air seal plane. The SBS membrane is adhered to the plate to provide continuity of the air seal while the gusset minimizes the thermal bridge at this point. This detail allows the interior steel section supporting the gusset to be installed within the interior environment where it can be heated. This heating minimizes the possibility of condensation occurring on the structural steel members. The insulation plane also can run continuously through the detail rather than changing planes to accommodate the structure and penetration.

The details for the roof wall and entrance glazing are similar to those discussed in previous details.

Detail 8B

This isometric shows the sequence of construction for the penetration of the steel gusset on the steel plate and the installation of the SBS membrane. It is important for the installer of the steel to know where to align the plate. It should be located in the plane of the sheathing in order that there is a smooth transition for the SBS membrane.

Detail 9: Overhang Section

Designs may incorporate sloped roof edges around the perimeter of the building for a more residential aesthetic. This detail indicates the construction of an unheated sloped roof perimeter and includes features previously shown in Details 1 and 8 to maintain continuity of the supported SBS membrane. The SBS membrane is maintained exterior of the structure of the roof and wall. Insulation is installed tight to the exterior surface of the membrane. If the structural steel requires a covering of fireproofing insulation it may be necessary to add additional insulation to the exterior to maintain the dew point within the exterior insulation exterior of the SBS membrane.

Detail 10: Sloped Glazing to Vertical Curtain Wall

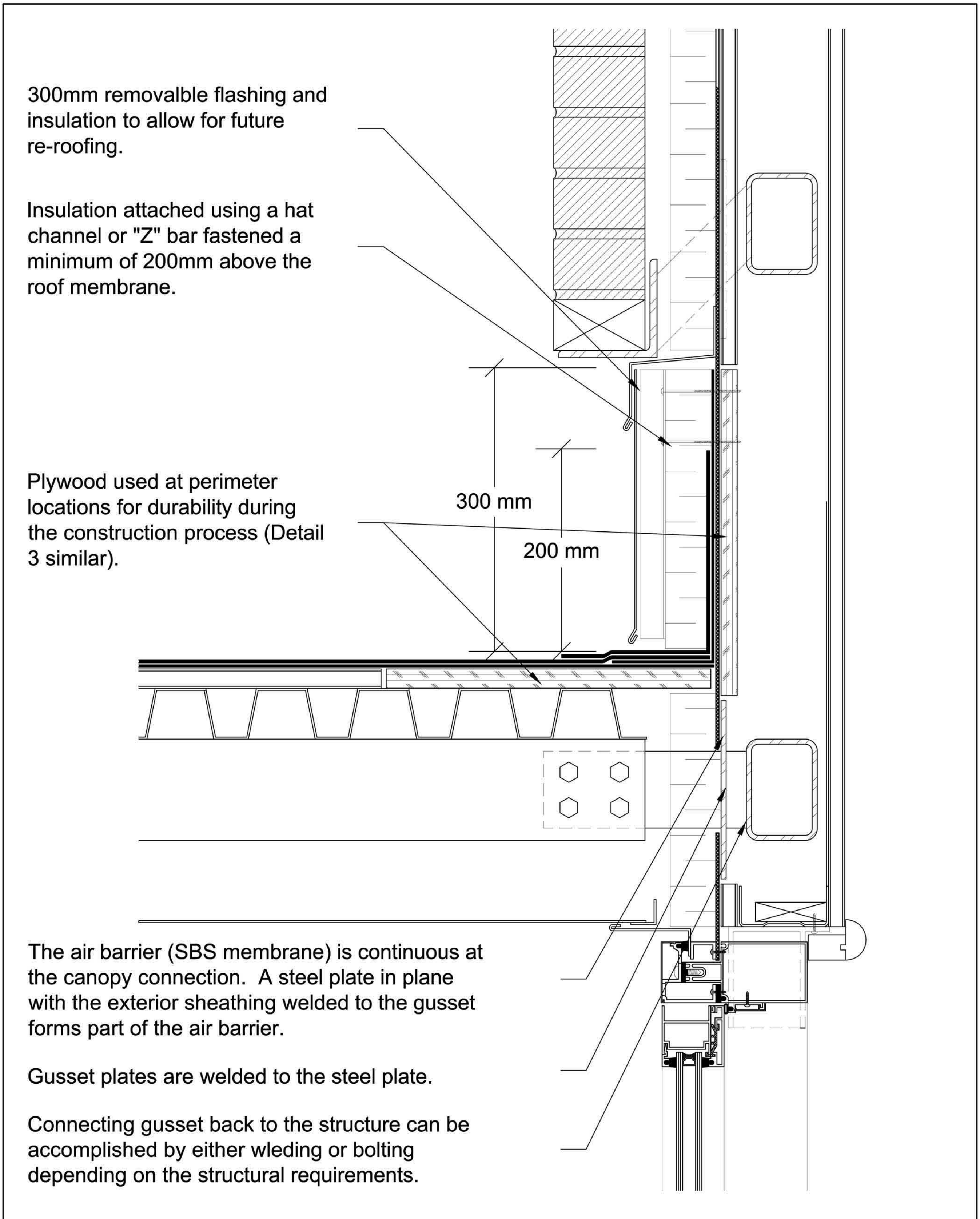
Sloped glazing in buildings can present a major maintenance problem to building owners and operators. Skylights that rely on face seal caulking to maintain water tightness may provide initial performance, but as the movement of components and degradation of the sealants occurs with time these systems fail to function effectively at maintaining water tightness and subsequent retrofits can only provide limited improvement for short periods. Water leakage through skylights may be hidden by the support construction for periods of time. The resulting deterioration of roofing and curbs and wall construction can be a significant cost above fixing the sloped glazing.

Similar to the curtain wall framing, the interior protected seals between the framing and glass should provide both the air and water seals for the system. The exterior seals can minimize water entry into the system, but they cannot and will not maintain water tightness over the life cycle of the skylight. The glazing rabbet of the systems must now be designed to contain, control, and redirect water that passes through the exterior seals back to the exterior while at the same time minimizing that water contacting the interior seals. The glazing rabbets must be of a size to accommodate this water while at the same time not be obstructed by its function to retain the glazing. The following series of details shows a manufacturer's system that has been modified to meet these principles.

The mutins (horizontal mullions) overlap and drain down into the rafters (vertical mullions) in a shingle approach. The rafter gutter at the sill protrudes beyond the plane of mutin to ensure that water draining from the system does not contact the seals created by the SBS membrane tied into the skylight framing. The tube portion of the rafter is cut back and plugged to align with the sill mutin (see Detail Series 12).

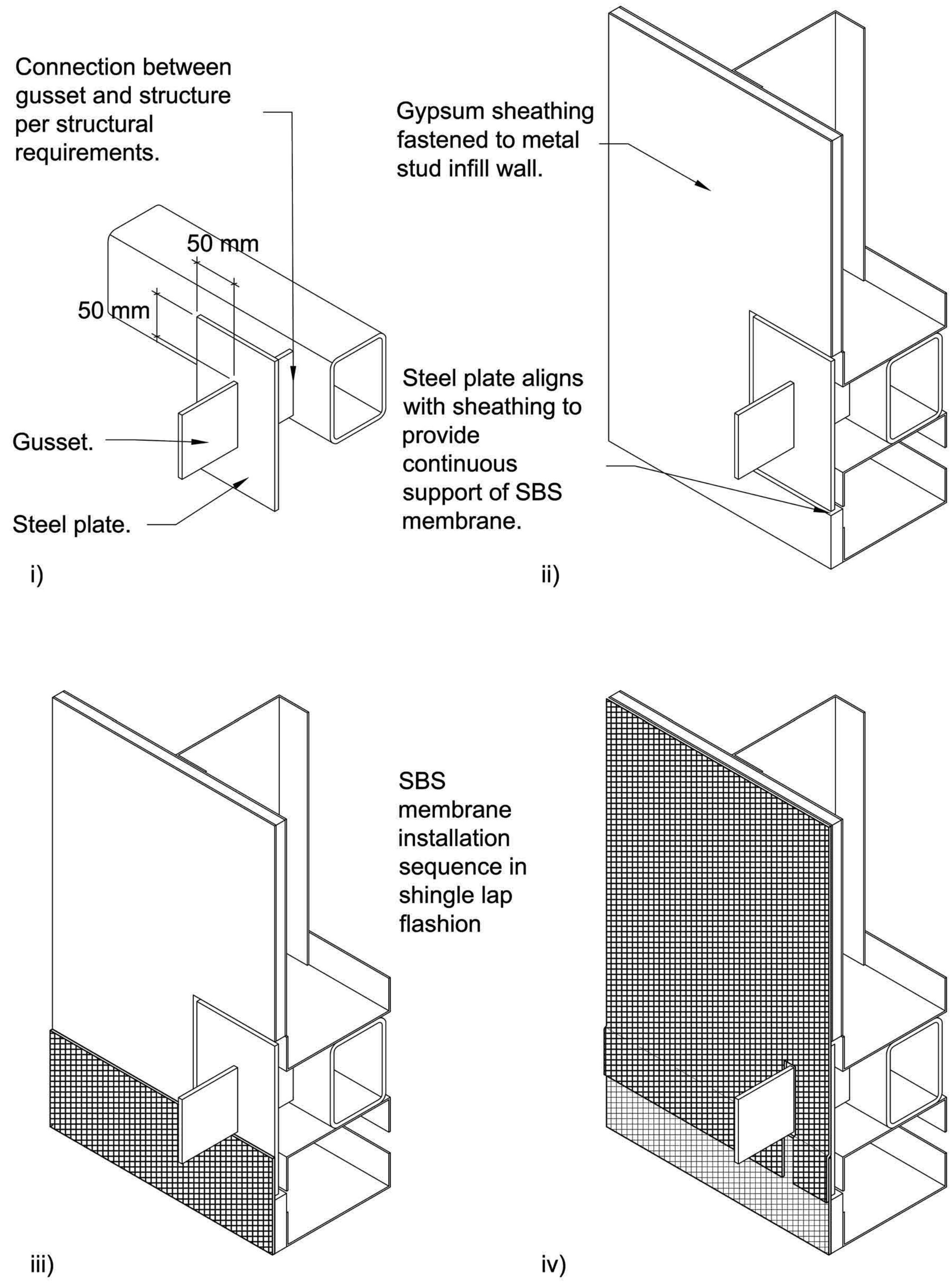
This detail indicates a knee junction of sloped glazing to vertical glazing supported by a structural steel backup structure. The aluminum section design raises the glass sealed unit on a raised leg profile of the frame to ensure the sealant edge seals of the unit do not rest in the water that will be draining horizontally to the rafters. If the seals of the unit were to be placed in the glazing rabbet, the water contacting the edge of the unit would deteriorate the sealants, resulting in premature failure of the unit to maintain a seal. It would also mean the seal between the unit and the frame would be subjected to wetting and degradation. The setting block is designed for the sealed unit between the unit and the curtain wall nosing. When water drains into the glazing rabbet it will build up until there is sufficient water to flow to the rafter. Once in the rafter the water exits the sloped glazing to the exterior of the vertical glazing system below.

The two aluminum systems are positioned to allow for the attachment of aluminum angles and galvanized sheet metal to support an SBS membrane which in this case acts as both a waterproofing plane and continuation of the air seal plane. The SBS membrane is adhered to the glazing rab-



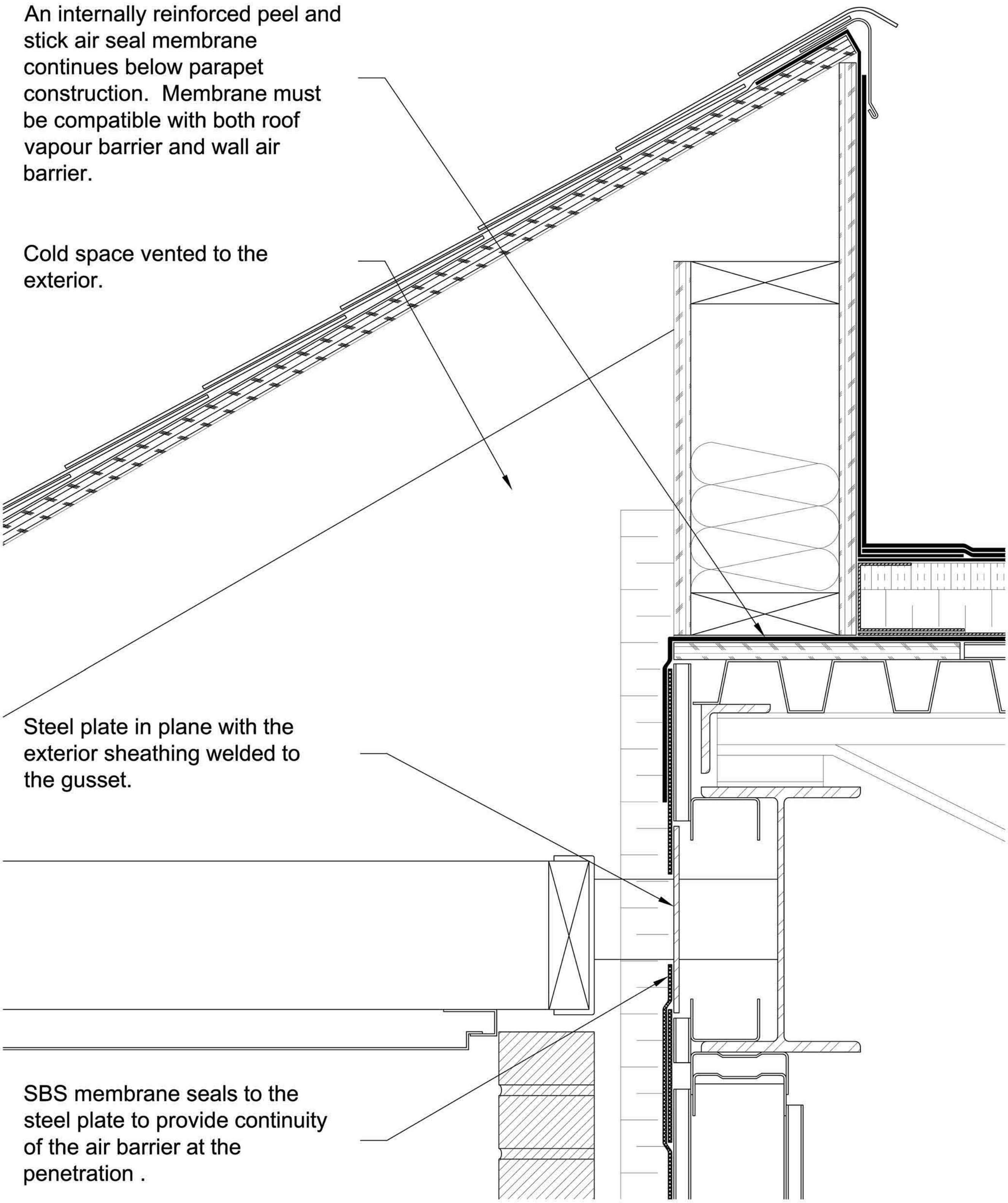
DETAIL 8: CANOPY CONNECTION TO WALL
SECTION

8A



DETAIL 8: STRUCTURAL CONNECTOR
ISOMETRIC CONSTRUCTION SEQUENCE

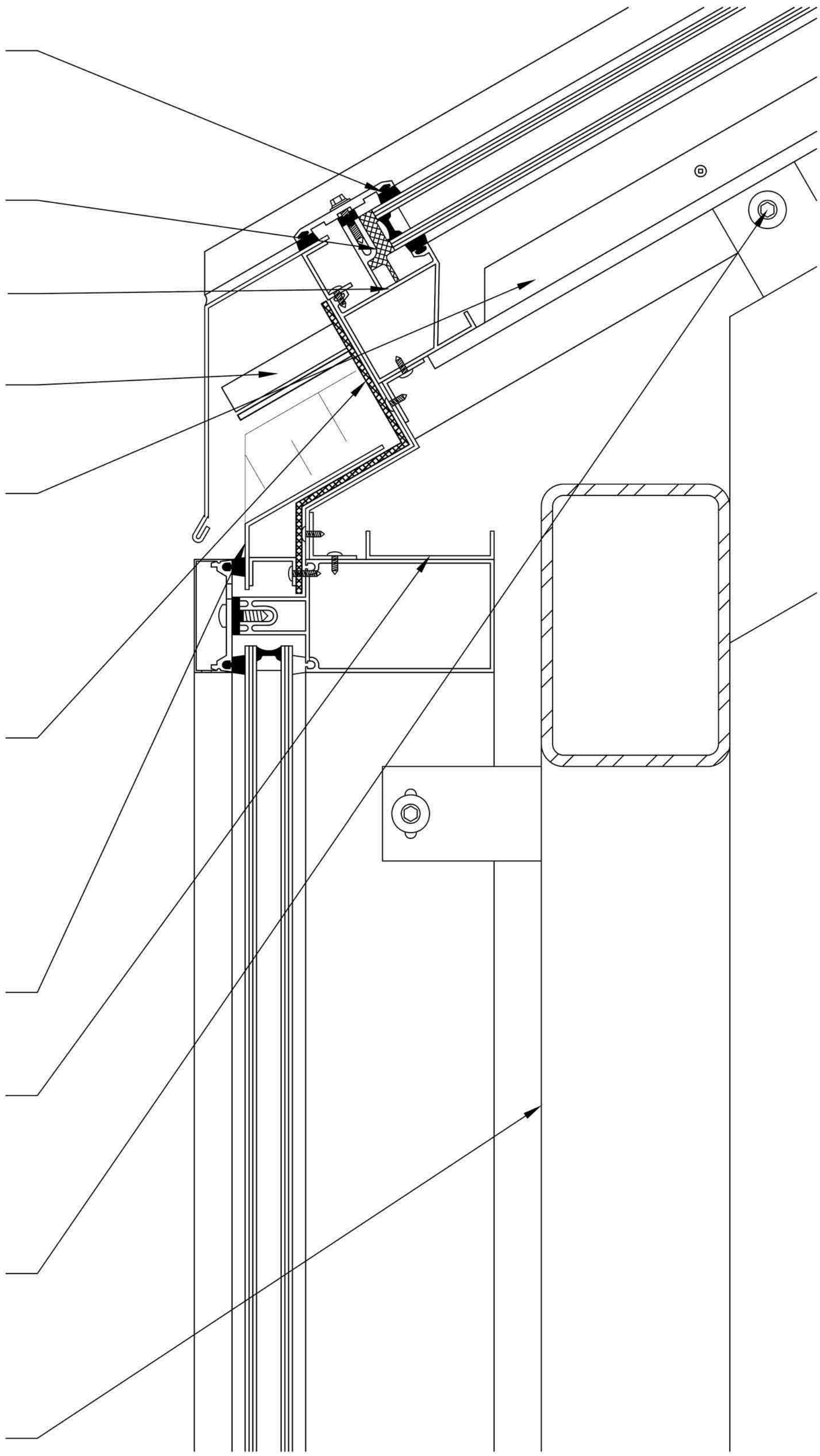
8B



DETAIL 9: OVERHANGING SLOPED ROOF

SECTION

9



DETAIL 10: SKYLIGHT SILL TO CURTAINWALL
SECTION

10

bet of the vertical aluminum section and the mutin section of the sloped glazing system and is supported between by thesheet metal. An additional flashing from the vertical glazing anti-rotation channel to the slope of the SBS minimizes water entry into the glazing rabbet of the vertical glazing. Insulation is added between the aluminum systems but should not hinder the drainage of water from the sloped glazing rafter.

If condensation is expected to occur because of a lack of heat and air flow in the skylight area, a separate condensation gutter system can be attached to the rafters and drained to an interior evaporation gutter at the sill. Mechanical drainage of the sill gutter may be necessary if the skylight is large in a high humidity building.

Detail 11: Skylight Sill to Roof

The requirement for natural light into the interiors of large areas often leads to the tie-in of sloped glazing into a roof. The sloped glazing framing should be constructed as described in Detail 10 and in the next Detail 12 Series as it pertains to drainage of the glazing rabbet from mutin to rafter and rafter to the exterior at the sill. In this detail the sloped glazing system seals to an up stand curb above a two-ply SBS compact roof system. The curb in this case is steel with infill metal studs. The steel provides the support for the aluminum rafter frames rather than the aluminum being self-supporting. Anchors in this case are installed to the side of the rafter mullions. There will be a fixed anchor (usually at the sill) and allowances made for movement at other anchor locations up the slope.

Continuity of the air seal and waterproofing of the detail is provided by an SBS internally reinforced peel and stick membrane that is torchable, and supported on sheet metal that is secured to the aluminum framing by an aluminum angle. The angle is offset from the face of the tube (to allow maximum adhesion of the SBS membrane to the aluminum face of the tube). The membrane and metal are then secured and sealed to the curb sheathing. Drainage from the rafter gutter extension beyond the plane of seal is away from the critical butt joints of membrane to aluminum. Water draining from the rafter in winter may form ice in the cavity once it has drained from the warmed aluminum extension, behind the flashing. The insulation exterior of the membrane is not installed to allow for this ice to form and allow for heat loss at the membrane to melt it. This will keep the water from freezing until it reaches the roof membrane (see Details 12 Series, Isometrics). This would not be necessary in areas where ice formation is not an issue. To minimize the potential for condensation interior of the membrane the construction should have a sufficient movement of warm dry air at this transition area interior of the air seal.

A condensation gutter is provided on the interior to contain water draining from the rafter condensation system. This condensation can either be evaporated or mechanically removed depending on the levels of condensation expected. Sufficient air movement in these areas should be provided to not require mechanical removal of condensate water and to provide sufficient heat to minimize the potential of condensation in the first place.

The curb flashing detail follows similar details in this series in that the flashing metal, flashing support, and curb insulation is all removable in the future for re-roofing.

Detail 12A: Sloped Glazing Isometrics

The previous sill details can be more visually explained if one looks at the following series of isometric details. These details are similar to those of Detail 11 except that the sloped glazing framework is a self-supporting sloped glazing application on a raised curb. The sloped glazing framing is supported by anchors within the tube section of the rafter. These anchors rest on the curb in the condensation gutter.

Insert "A" shows the overlap and fastening of the mutin over the rafter raised leg. A seal between the aluminum sections is achieved by wrapping the aluminum mutin section at the overlap with nonshimmed butyl tape. The tape should be installed longer than required for sealing just the metal to metal interface to also allow it to extend through the joint of the keyed in mechanical gaskets. In this way the seal is maintained through all the joints of all the materials at this junction. There is no need to caulk the fastener screws as water leaking through the joint is sealed by the butyl tape below. Caulking over the screw would more than likely restrict the drainage of water from the mutin. The aluminum is bent at the lower edge of the horizontal mutin to create a drip. This drip causes the surface tension of the water to follow the drip profile where it drips into the rafter below and prevents the water from clinging to the aluminum surfaces and returning to the butyl joint seal.

The rafter tube section of the profile is cut back to provide a continuous plane for adhesion of an internally reinforced SBS membrane along the plane of the exterior surface of the mutin tube. The hollow of the rafter tube must be closed with a metal insert within the tube to support the membrane. Without this closure the membrane will flex too much at this point and fail to maintain a seal over time.

Detail 12B

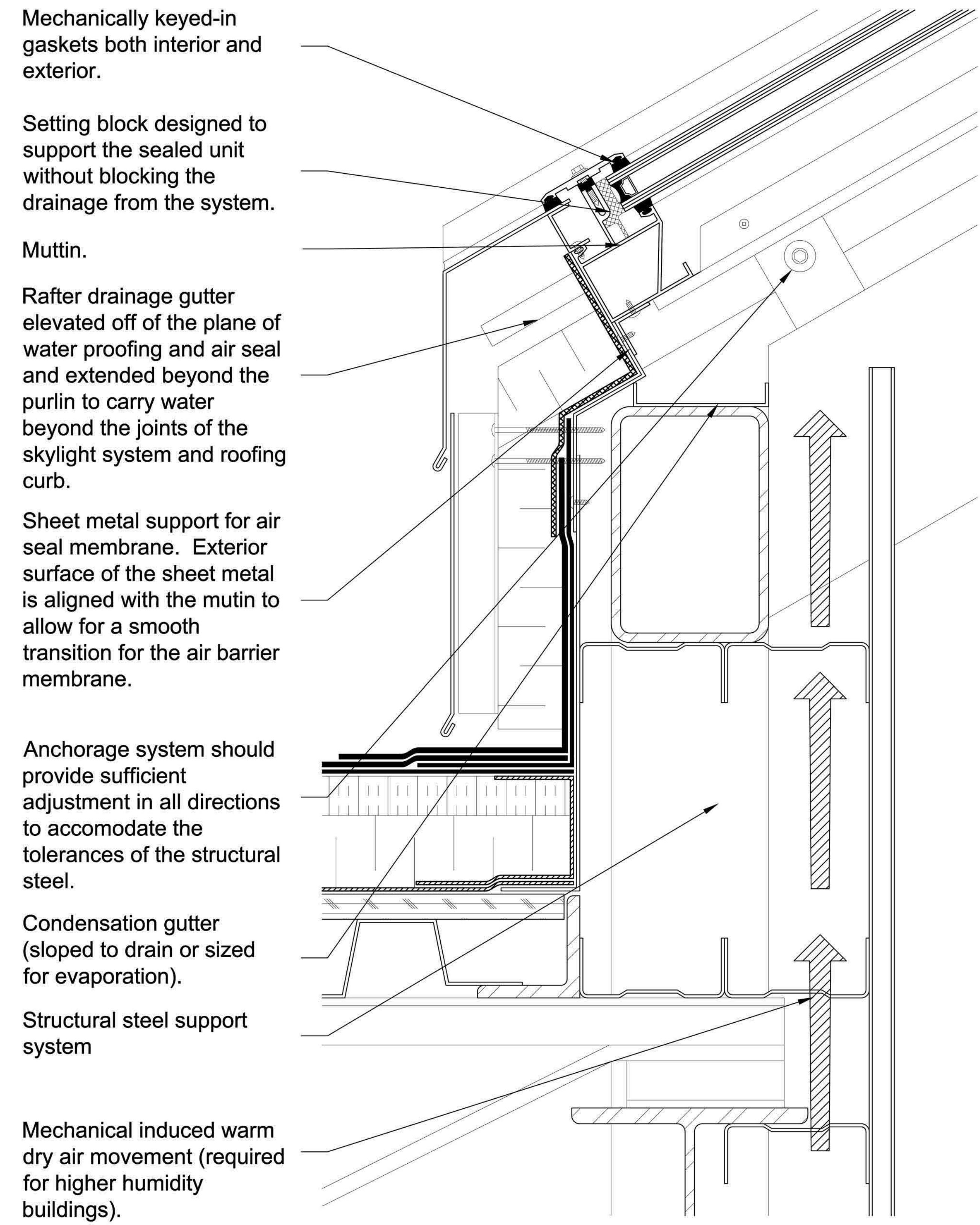
Angles of aluminum or flat stock are installed to the edges of the aluminum sections of rafters and mutins to which galvanized sheet metal is fastened. These sections are offset from the face by the thickness of the sheet metal to allow maximum surface adhesion of the SBS membrane (see Details 12C and D).

Galvanized sheet metal is used to support the SBS membrane which will provide continuity of the air and water seal from the curb construction to the tube sections of aluminum. The outer surface of the sheet metal when installed should align with the tube face of the aluminum sections to provide a consistent surface for the membrane to adhere to. The sheet metal pieces should butt closely together. There is no need to overlap the sheet metal other than for support in some cases, as this would tend to offset the membrane.

The end of the tube of the rafter must be plugged with sheet metal prior to the installation of the sheet metal from the curb construction. The surfaces are cleaned and primed with the membrane manufacturer's primer.

Detail 12C

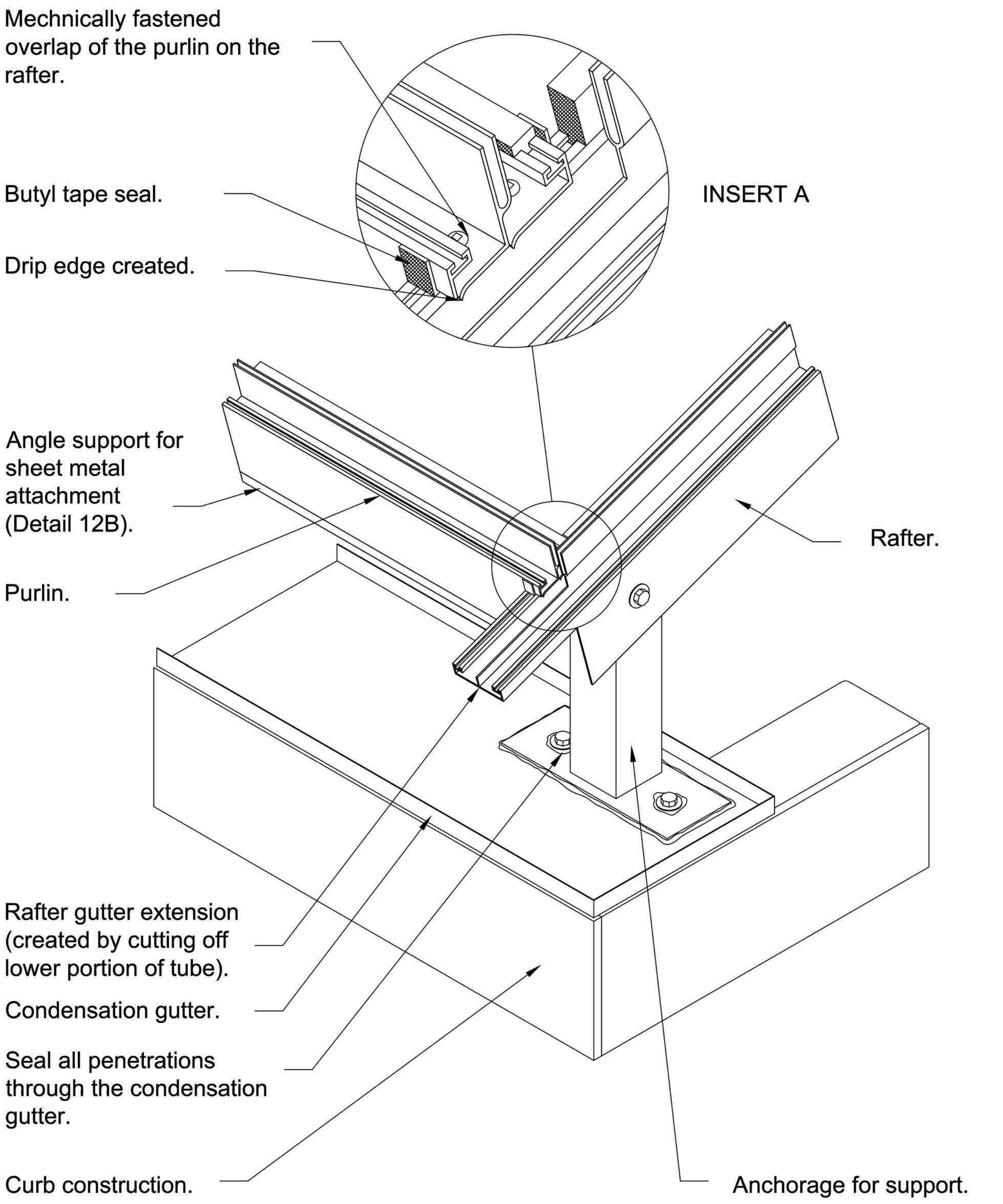
Smaller pieces of a torchable peel and stick membrane are used to facilitate the complex details at the rafters. Larger pieces are far too cumbersome and may lead to poor edge sealing at these critical locations. Larger pieces can be used



DETAIL 11: SKYLIGHT SILL TO ROOF

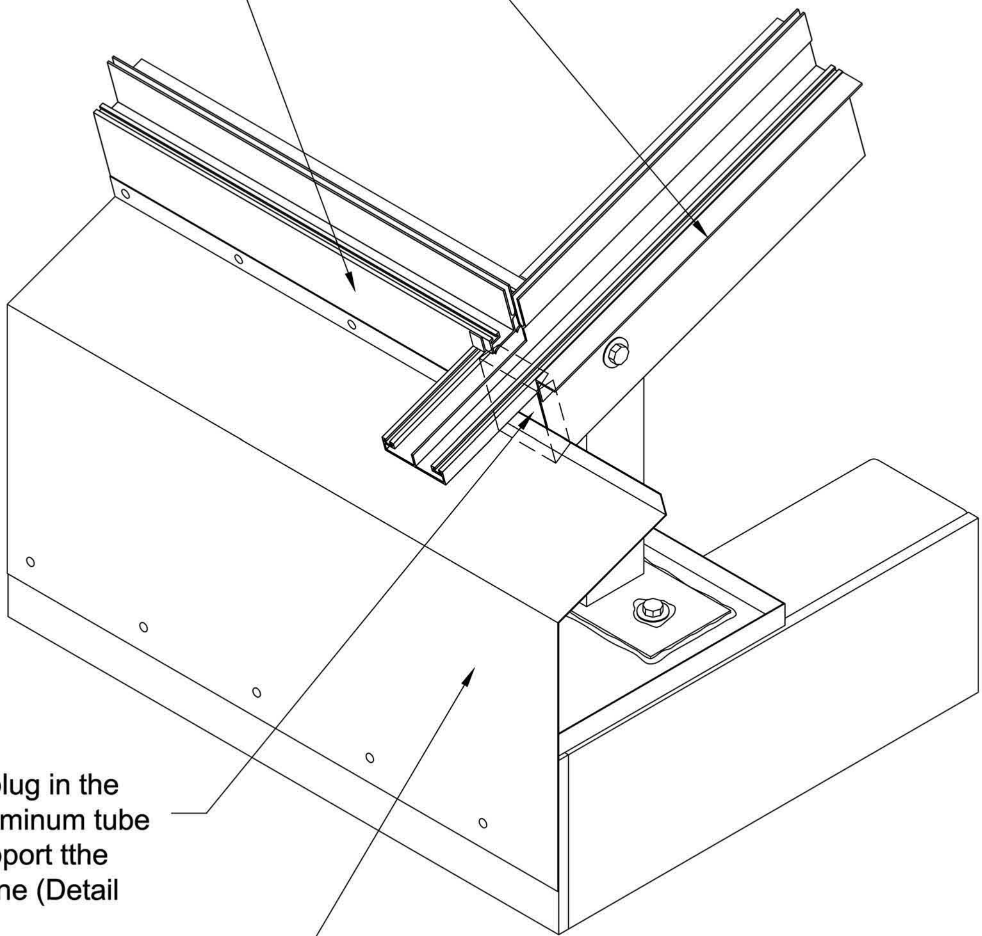
SECTION

11



DETAIL 12: SKYLIGHT SILL
ISOMETRIC CONSTRUCTION SEQUENCE

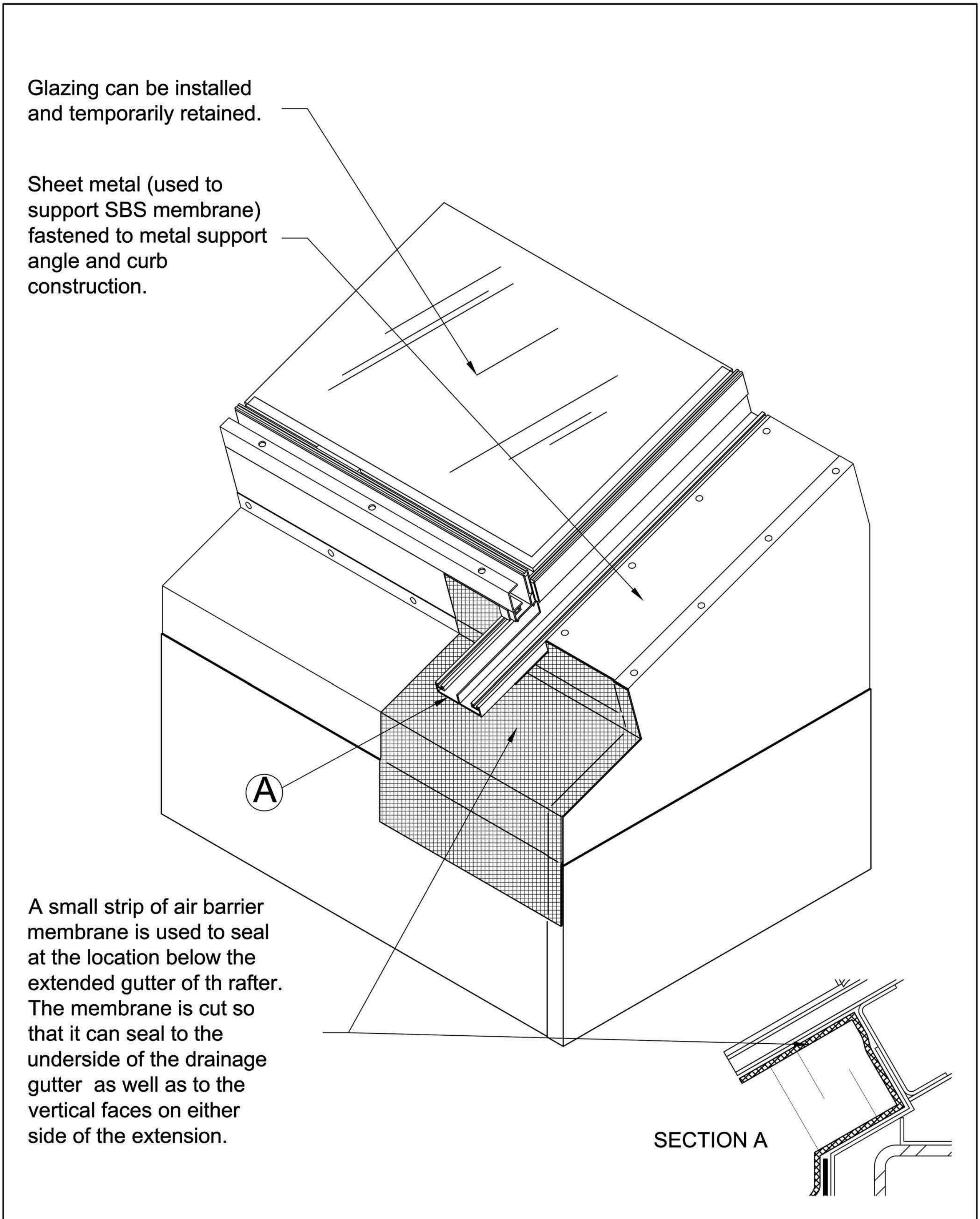
12A



DETAIL 12: SKYLIGHT SILL

ISOMETRIC CONSTRUCTION SEQUENCE

12B



DETAIL 12: SKYLIGHT SILL
ISOMETRIC CONSTRUCTION SEQUENCE

12C

between the detail membranes at the rafters. A small strip of SBS membrane is folded to create an edge that can beinstalled tight into the interior corner of the detail after removal of the release backing. This leaves two sections of unadhered membrane above and below the corner. By doing this the installer can adhere each section of membrane independently of the corner. The installer can now seal these sections tightly to the sheet metal and aluminum sections and minimize the voids that are often found at interior corner installations. Some heat may be applied to the membrane to ensure adhesion but open flame torches should only be used by an experienced installer. Commercial hot air heat guns usually can provide enough heat to weld the SBS seams.

The membrane brought up from the corner is installed tightly to the interior corner created by the extended section of drainage gutter of the rafter (Section A). The membrane is adhered to the underside of the extended gutter of the rafter and a small block of extruded polystyrene is installed to provide a wedge to maintain contact of the membrane. The membrane is cut on either side of the extension and then adhered to the surfaces in the plane of the horizontal mutin. These joints should be heated and tooled with a trowel to ensure adhesion and sealing.

Detail 12D

The remaining surfaces of sheet metal between the rafters and at the end gable have SBS membrane installed to them. The profiles and membrane now provide a water tight and air tight plane continuously from curb to aluminum framing. Overlaps of membrane should be shingled where possible with all joints heated and tooled to ensure adhesion and seal.

The sealed unit can be installed in the frame at any time after alignment and securing of the framing. To prevent damage to the sealed unit it may be advantageous to leave the units out until after the membrane sealing is complete, especially if torches are to be used to seal the membrane edges. Torch application may be necessary to assist the adhesion of the membranes in colder applications.

Anti-rotation channels or angles are installed to the raised leg sections around the perimeter. These provide a surface for fastening of finish flashings and minimize rotation of the pressure plates for the sloped glazing system.

Detail 12E

Extruded polystyrene insulation can now be installed to the exterior of the SBS membrane. A 4 in. channel of insulation is created below the extensions of the rafter gutters by not installing insulation at those locations. This will allow water draining from the gutter to drain onto the membrane and flow to the roofing below. If the water drained onto insulation there would not be sufficient heat (in colder climate zones) to ensure the draining water would not freeze. The resulting ice dam could damage the construction of the curb. Skylights often leak more during the winter when the snow and ice build up on the exterior surfaces providing significant amounts of water which melts and finds the holes in the exterior seals.

Detail 13

This detail is a section through the ridge of a sloped glazed system. The tie-ins of the various planes of water and air seals are critical in this location to ensure drainage of water that may drain through the exterior joints of flashings and pressure plates while at the same time ensuring continuity of the air seal. Moisture in escaping air passing through imperfections in the plane of air and water seal can condense on the underside of the exterior flashings and then find those same imperfections to drain through when it eventually melts. All the levels should follow the same principle of overlapping the materials while at the same time minimizing the ability of water to come into contact with the sealing joints.

In this detail the rafters are supported by a structural steel frame, but in small sloped glazing installations the framing could be self-supporting. In either case the rafter aluminum profile should extend on each slope to meet at the peak where the frame sections are cut on the appropriate angle to meet. Depending on the installation there may be the need for a gap to allow for movement. While some manufacturers may have a single mutin horizontal, their design is often difficult to achieve an air and water seal with. In this detail two standard horizontal mutin sections are used to create the junction detail and allow for movement.

The nosing of the rafter is removed to the height just below the raised leg key-ways for the glazing gaskets of the mutins. The rafter gutter is sealed to the height of the raised leg with neoprene plugs and butyl sealant. A continuous galvanized sheet metal transition support flashing between the two horizontal mutins is fastened to bent angles which have been secured to the upper rafter tube face of the mutin. The raised legs of these sections are retained to allow for the collection of water in the gutter. Removal of the raised leg and application of the sealing membrane to the tube face of the gutter would expose this joint to water for periods of time so it does not follow the principles described. The SBS reinforced membrane is adhered to the cleaned and primed sheet metal so that the membrane seals from the raised leg key-way of each section. The membrane is extended over the edge to promote the drainage of water into the gutter. The system at this point should be air and water tight.

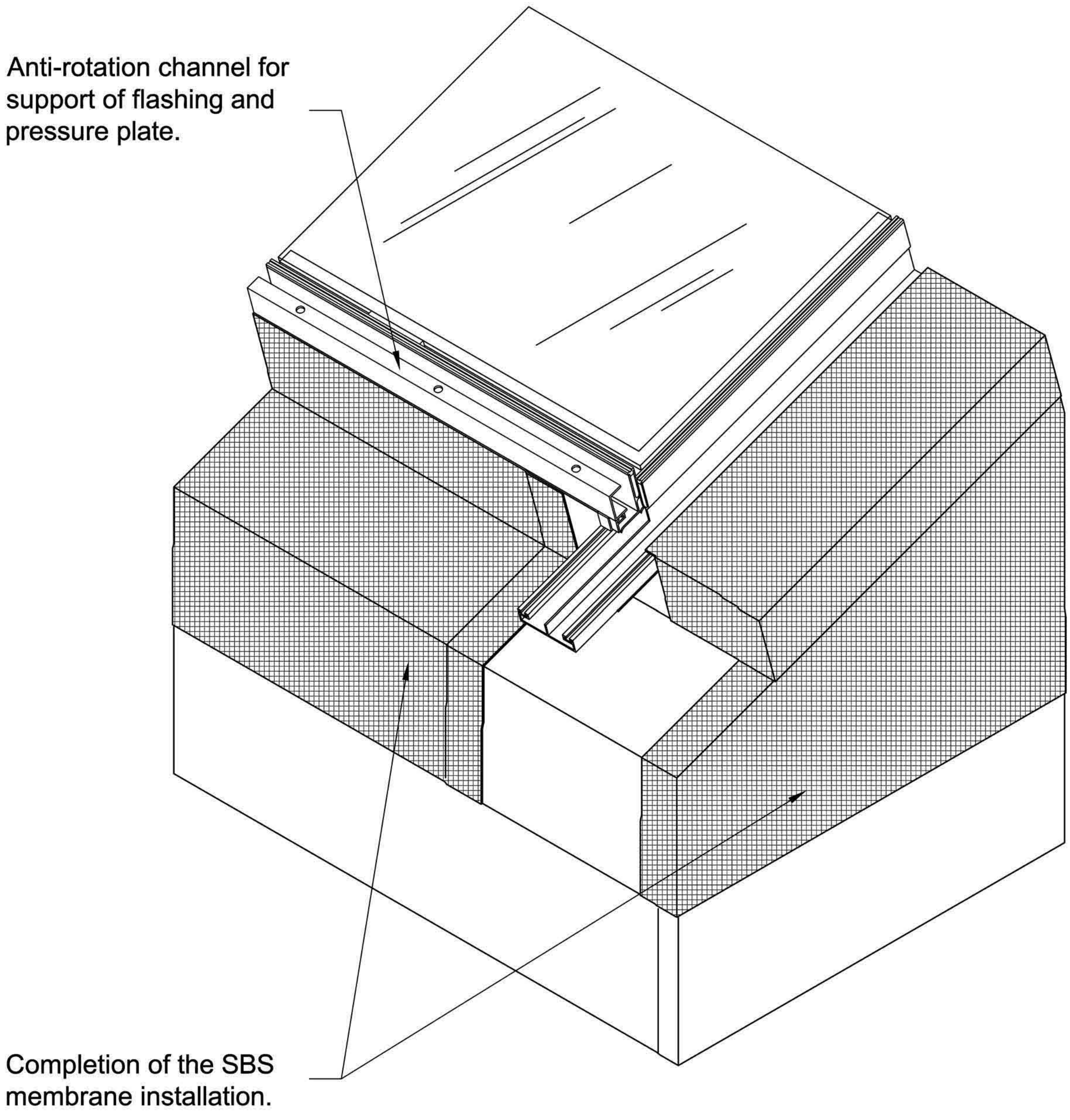
The anti-rotation aluminum channel (or angles) are installed to retain the membrane mechanically while at the same time providing the surface for fastening the ridge exterior flashing. Extruded polystyrene insulation is installed between the anti-rotation channels exterior of the membrane. No insulation is installed interior of this membrane as this could result in condensation on the metal surface in colder climates.

The exterior pressure plates and cover caps are installed to provide the finished exterior aesthetics and to divert most of the water from entering the system, but it is not relied upon to be 100 % perfect. The water that does drain past the exterior seals is contained and redirected through the mutin and rafter glazing rabbet system back to the exterior at the sill.

Detail 14

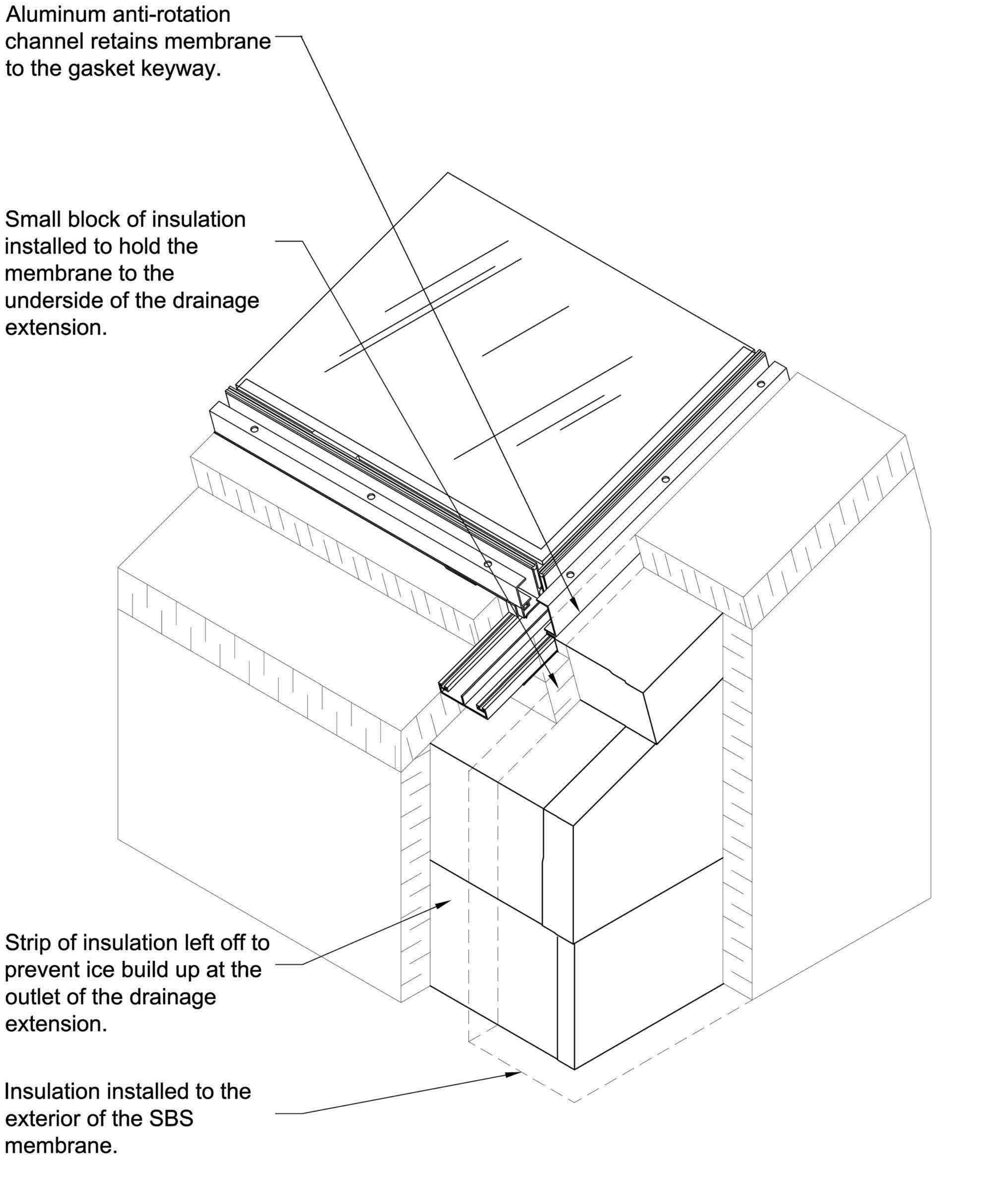
Sloped glazing often terminates at a vertical wall. A minimum of three trades must be coordinated to provide a water tight construction. Sufficient height must be given for these trades to perform their work independently of each other and to allow for future maintenance.

The rafter section is extended beyond the horizontal



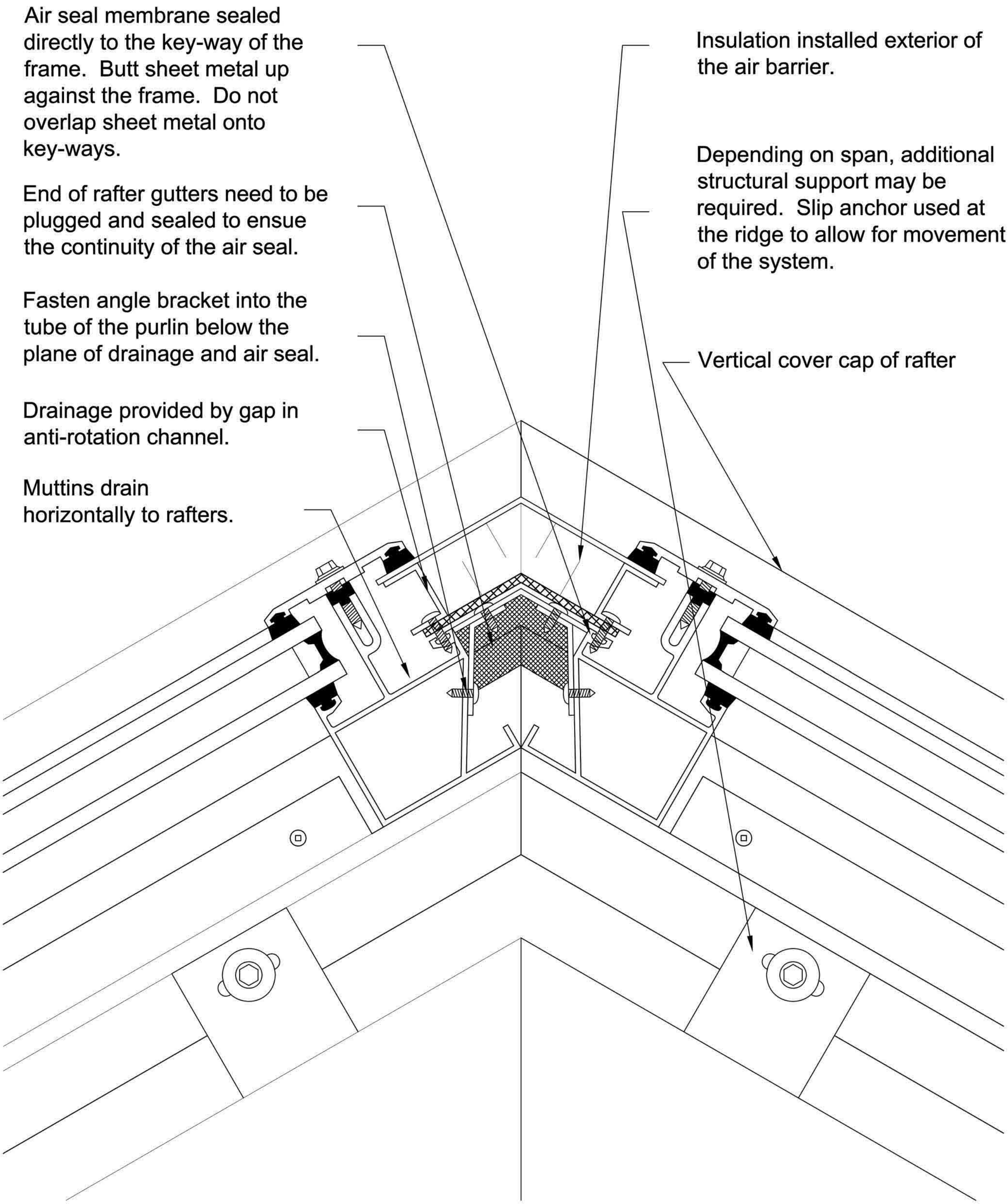
DETAIL 12: SKYLIGHT SILL
ISOMETRIC CONSTRUCTION SEQUENCE

12D



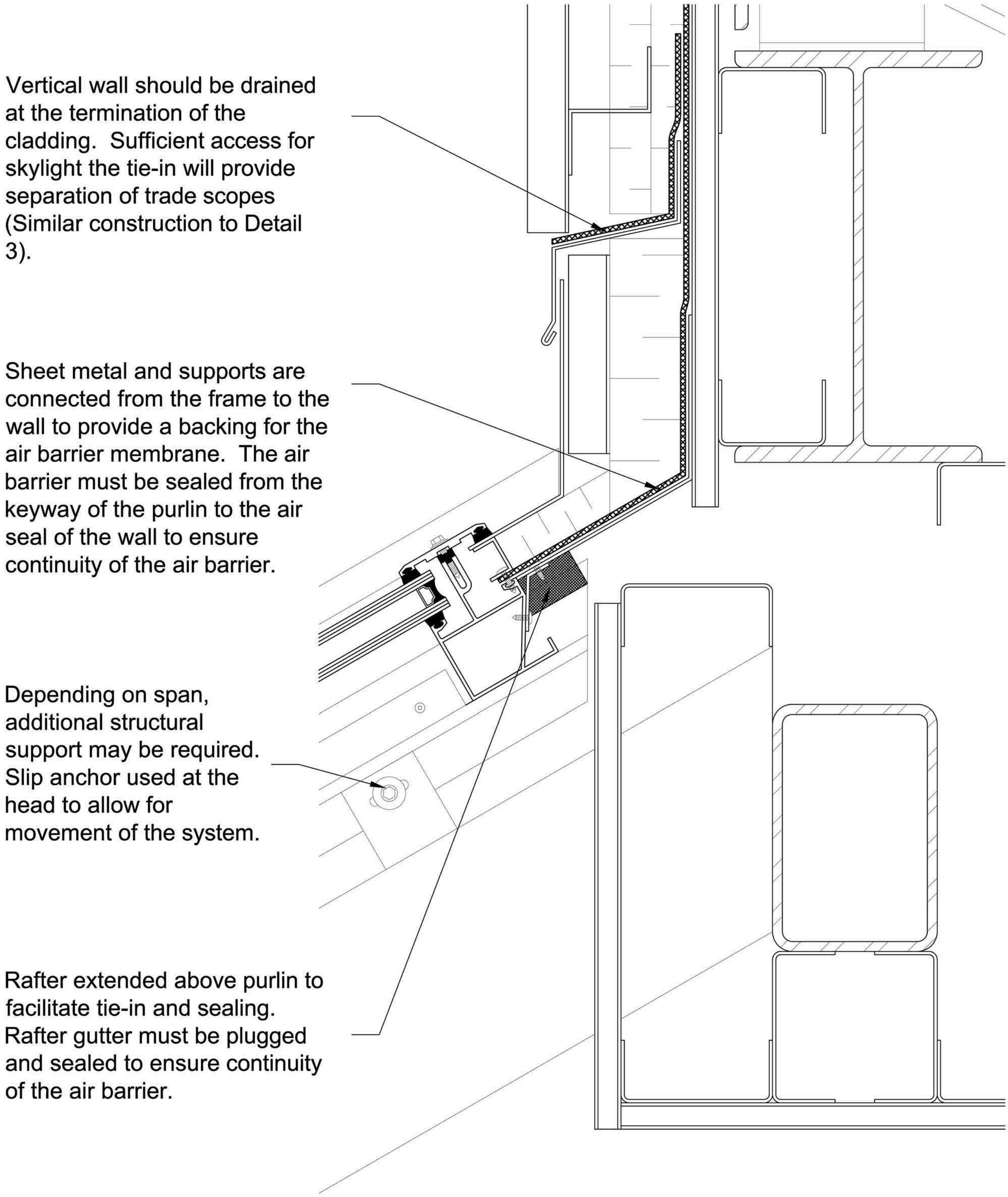
DETAIL 12: SKYLIGHT SILL
ISOMETRIC CONSTRUCTION SEQUENCE

12E



DETAIL 13: SKYLIGHT RIDGE
SECTION

13



DETAIL 14: SKYLIGHT HEAD AT WALL

SECTION

14

mutin to allow for fastening of the anchors and sealing of the rafter gutter with a neoprene plug and butyl sealantcaulking. The nosing of the rafter is removed from the plane of the horizontal mutin nosing to the termination of the rafter to allow for the application of a continuous galvanized sheet metal flashing from the framing to the wall. At the mutin the sheet metal is fastened to an aluminum bent angle which has been prefastened to the mutin tube face. The raised key-way of the mutin is retained to maintain the gutter and allow the seal of the SBS membrane installed over the sheet metal to seal to the key-way. This maintains the SBS membrane above the gutter so it drains down and into the gutter. The SBS membrane, supported by the sheet metal, provides continuity of the air seal and waterproof plane from the aluminum framing of the sloped glazing system to the air seal of the wall above. The sheet metal and membrane should not be installed in a fashion where they create a gutter. If movement is a concern then the sheet metal should be bent to maintain slope to the sloped glazing gutter and in a fashion that will allow for the adhesion of the SBS to it.

The vertical termination of the glazing flashing and air seal of the detail should be made at a sufficient height above the top edge of the sloped glazing to first install the overlapping membranes and to also maintain this critical joint with out removal of the cladding above. The remainder of the detail is as per Detail 13 and Detail 3.

Detail 15: Curtain Wall Details

The termination of curtain wall to a slab or grade beam should acknowledge that concrete is rarely flat and may be at its allowable tolerance according to the standards and specifications. Anchors inserted in the vertical mullions can be hidden while still providing adjustment for variances in concrete finish. The anchor can either be bolted through the side or screwed through the face of the vertical into the hidden anchor. The horizontal rail can be back cut to fit over the spigot and anchors, depending on the configuration and desired aesthetics.

In this detail a light angle anchor is installed to the concrete. The frame would be hoisted over the anchor and leveled before the fastening of the frame to the anchor through the front face of the tube with two countersunk screws. These screw heads will be covered once the SBS membrane is installed. The vertical nosing of the vertical section will be removed similar to those in Detail 7A. This will allow for the application of the SBS membrane from the exterior concrete surface to the tube face of the aluminum section. The membrane will be retained mechanically to the tube face by an anti-rotation channel (or angle) which also provides a face for the fastening of flashings.

Insulation is installed exterior of the waterproofing membrane and protected by parging or a protection board. The glazing is installed with pressure plates and cover caps to complete the detail. The glazing rabbet of the curtain wall is drained to the exterior through slots located in the pressure plates (see Detail 7I) and cover caps. The joint between the cover cap and the flashing is not caulked, as this will impede drainage and is not necessary. Caulking of this joint will lead to additional aesthetic costs when it fails and additional costs for window maintenance.

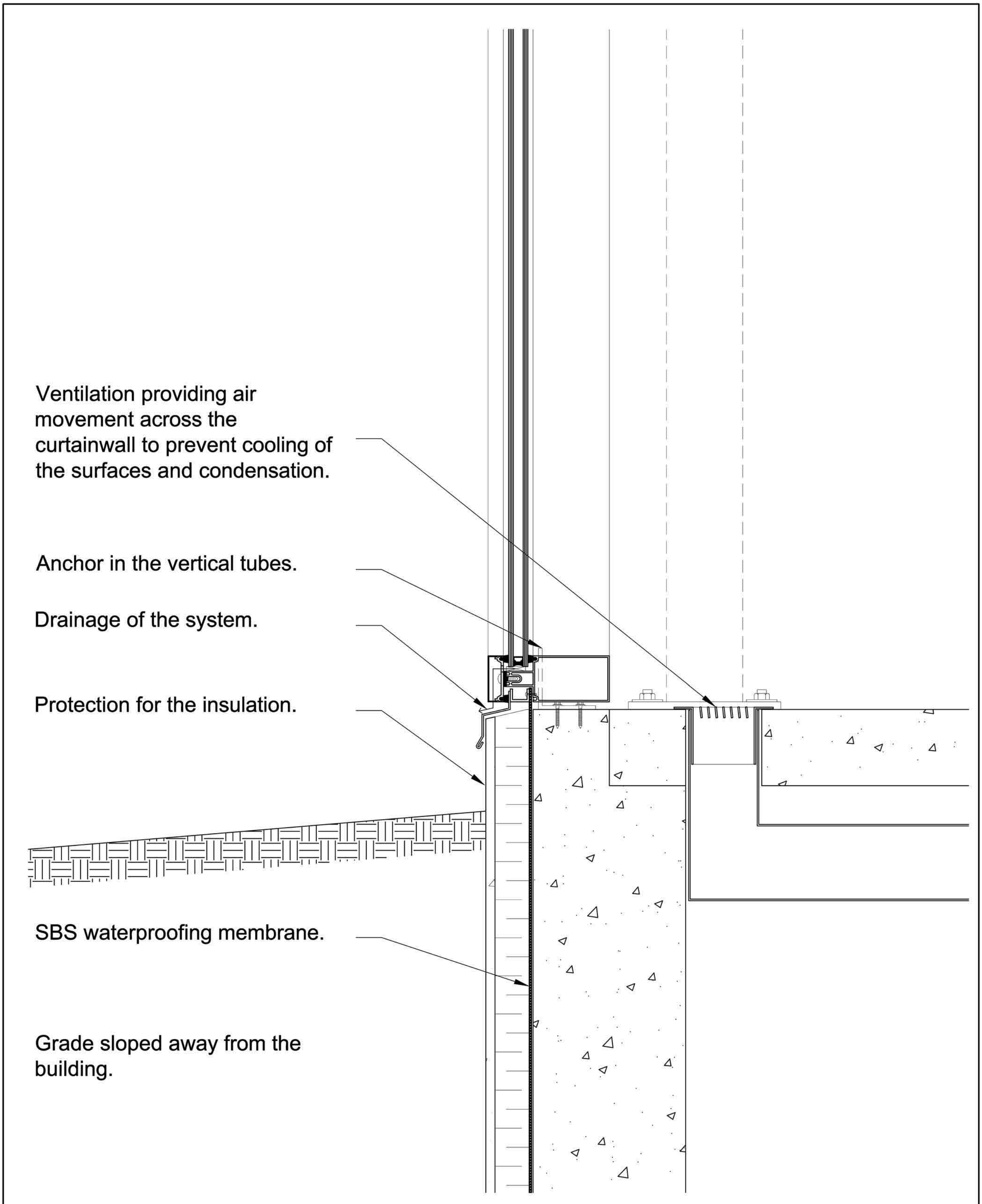
Curtain wall requires heat and air movement to minimize condensation in cold climates. The air should not be directed at the glazing but rather washed near the glass to create air flow over the glass surface. This disruption of dead air at the surface of the glass minimizes the potential for condensation and does not subject the glass to thermal shock.

Detail 16

Glass and aluminum curtain wall is hung from the slab edge of a structure in a multi-story building to provide a continuous building envelope and provide an aesthetic of continuity of the cladding. Tolerance between the slab edge and the back of the aluminum sections is nominally noted in drawings and specifications as 50 mm (2 in.) to accommodate for the tolerances of the structure. Firestop insulation (mineral wool) is installed between the backside of the curtain wall and the slab edge. Some jurisdictions may also require the installation of a smoke barrier sealant at the slab edge. These requirements will require the design team to clearly understand, detail, and specify all potential pathways in the system used. Because glass and aluminum curtain wall moves with loads (horizontally and vertically) imposed on it, the sealants must be flexible and the insulation must be compressed to be retained in the void. The insulation may require mechanical anchors or flashings to retain it for the life of the building. Edge clip fasteners are often dislodged during the installation of mechanical radiation and floor finishes, so a more long lasting solution such as an under slab flashing or galvanized angle strip fastened to the back of the back pan should be considered.

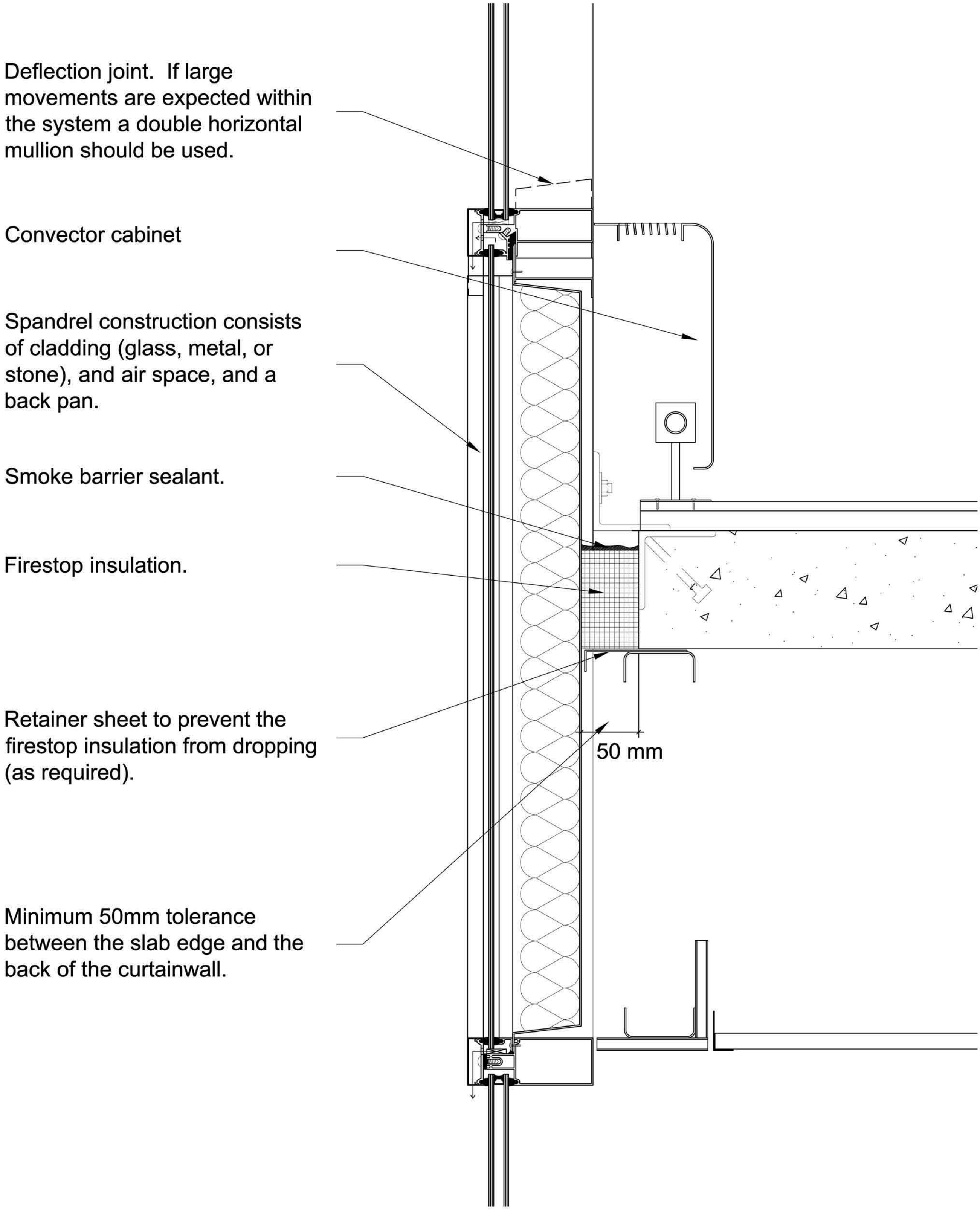
Curtain wall usually has portions of the wall where opaque panels are used either for aesthetics or to hide slab edges or structure behind the wall. These spandrel locations should be installed with an insulated galvanized back pan that is sealed to the aluminum framing of the curtain wall. This back pan provides continuity of the air seal and must be designed to withstand the imposed loads of wind without rupture or leakage. The back pan should also be designed to minimize flexing of the metal as this will affect the cavity space to pressure equalize and may result in unacceptable noise. Thermal resistance in these opaque locations is provided by fibrous insulation held tight to the sheet metal by fused clips. Water that enters past the exterior glazing gaskets is drained to the exterior through the slots in the horizontal rail pressure plates and cover caps. Glass metal or stone can be used to provide an exterior finish and protection for the insulation in these spandrel areas.

The expansion joint for a curtain wall is often hidden visually below the horizontal rail of the vision unit. This is one of the weaker points of the any curtain wall as the seals must withstand all the movements occurring in the system between panels in a very small area. They must also provide ongoing air and water tightness for the system for many years. Each manufacturer has his own approach to sealing this joint, but the designer must be assured that the approach will function long term. Convector cabinets located around the perimeter of curtain walls in cold climates often have provided enough heat necessary to make minor leakage of air and condensation conditions tolerable by occupants. With the advent of radiant panels and reduced air movement at perimeters of buildings, noticeable problems of air leak-



DETAIL 16: CURTAIN WALL FOUNDATION
SECTION

15



DETAIL 17: CURTAIN WALL SPANDREL

SECTION

16

age, condensation, and even minor water leakage have become more common.

Detail 17

The parapet condition terminating the curtain wall at the roof is detailed in this section drawing. In this case there is only a short parapet. The space created between the parapet structure for the termination of the roof and the extension of the curtain wall may be supplied with sufficient heat and air movement to maintain a temperature above the dew point of the air. If the air were to reach the dew point there is the potential for moisture to condense on the surfaces of the construction. When the frost melts it might be absorbed by the components of the construction, but if sufficient frost accumulates and is heated quickly it might appear below as a significant amount of water. This might lead to costly removal from the exterior only to find little or no evidence of the cause.

Glass and aluminum curtain wall is hung from the slab edge in a multi-story building. A tolerance of 50 mm (2 in.) is noted in the details and specifications between the back of the aluminum sections and the slab edge to accommodate tolerances of the structure. Firestop insulation would be installed between the slab edge and the curtain wall at floor slab but may not be required at the roof depending on the jurisdiction and code requirements. If it is required it could restrict heat flow to the cavity and result in condensation in the parapet. Some jurisdictions may also require a smoke barrier sealant at the slab edge. Because the curtain wall will move (horizontally and vertically) with the loads imposed on it, the sealants used must remain flexible during their service life and the insulation must be compressed in the joint and may require mechanical means to retain the insulation. This detail does not show a firestop or smoke seal.

Curtain wall at the parapet usually has an opaque finish at the parapet to hide the structure and slab edge construction. In this detail a heat strengthened glass is shown as an exterior finish. The air seal continuity is provided by a formed galvanized sheet metal back pan which is sealed to the tube face of the horizontal rails and vertical mullions of the framing. It is critical that the corners of the back pan are sealed, especially at the lip flange where it is sealed to the tube face. The back pan will be subjected to the wind loads and may need to be reinforced to minimize how much it will flex. If this movement is not limited the flexing of the sheet metal may create annoying noise problems for the occupants and will affect the pressure equalization of the cavity of the spandrel. An anti rotation angle is installed with a keyway for a gasket. This provides a similar glazing approach to that of the vision sealed units.

The back pan has fibrous mineral insulation mechanically secured with welded stick clips to provide a level of thermal resistance to these opaque portions of the assembly. During the construction the insulation may be wet for periods of time so a mold resistant insulation should be used.

In this detail glass is used as the exterior finish, but metal or stone could also be used to provide an exterior finish and to protect the insulation.

Detail 18

An alternative detail for the termination of a curtain wall at the parapet where there is either a high humidity environment in the building or the parapet is very tall is shown in this detail.

Buildings in cold climates may experience problems of condensation if a cavity is created between the curtain wall and the parapet construction. Even though there is insulation and air seal continuity there may be insufficient heat for periods of time where the surfaces could reach the dew point temperature of the air. Water will condense on the surfaces of the construction and moisture will build up. When the temperature does increase the melting ice and frost may be sufficient to create the impression to the occupants that the roof or parapet is leaking. Ceiling tiles may be stained and damage may be done to other materials in close proximity of the wall.

In this detail the curtain wall is terminated at the roof slab edge to provide continuity of the air seal at the roof plane. The air seal is achieved by the use of sheet metal and SBS membrane from the tube face of the curtain wall termination to the roofing air seal membrane. The membrane would be insulated with a fibrous insulation which would be mechanically secured tightly to the membrane.

An insert sleeve in the location of the vertical mullions allows the placement of a vertical mullion extension above to create the visual appearance that the vertical mullion is continuous. The construction above would have to be structurally held back to the parapet construction depending on the design height. If the design does not allow for the visual horizontal pressure plate and cover cap at the air seal joint, the nosing of the section can be removed and the exterior finish can be continued over the joint.

To better illustrate this detail as to how the continuity of the air seal would be achieved please refer to isometric series Details 19.

Detail 19: Curtain Wall Parapet Isometric

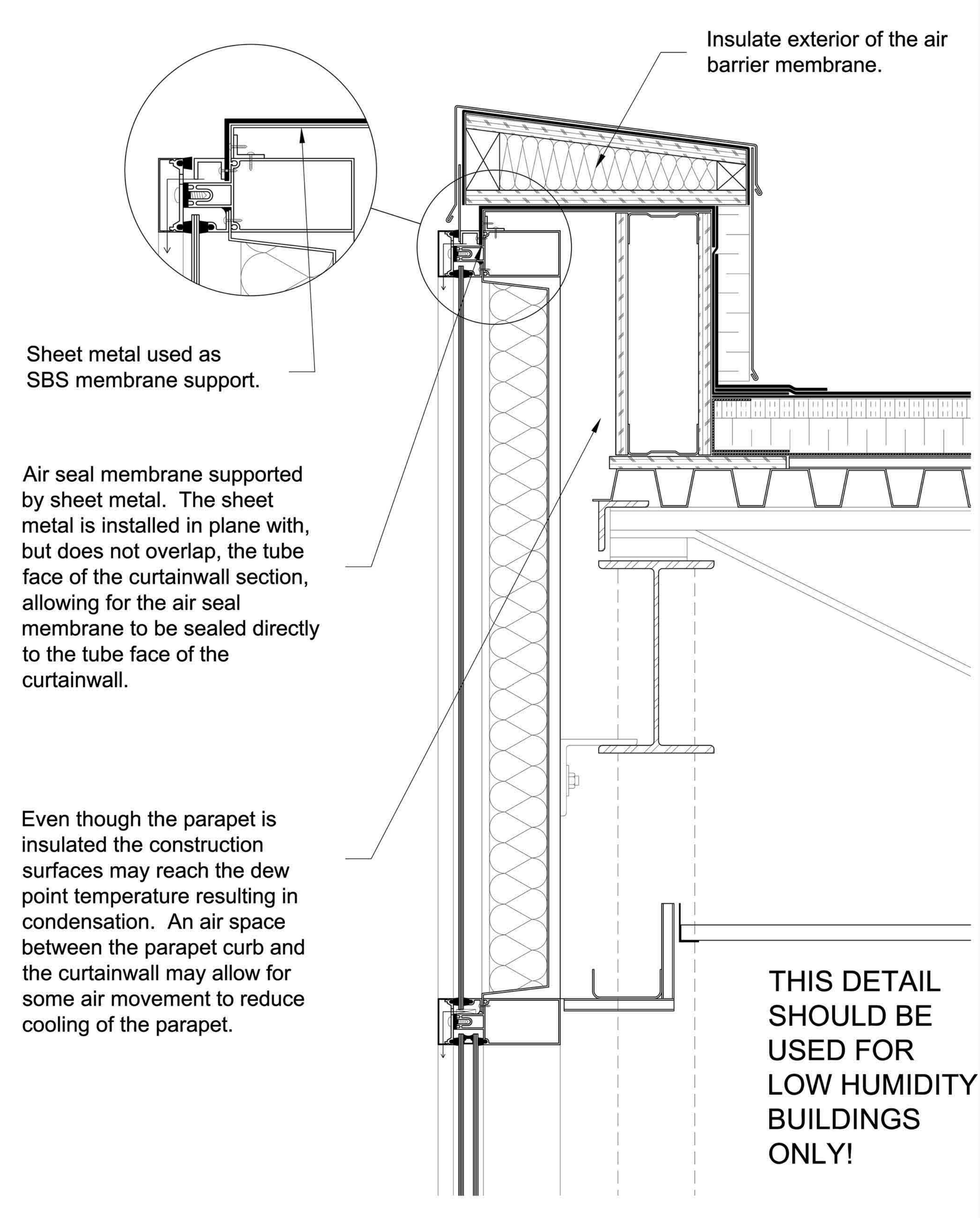
This sequence of details is meant to show how the continuity of the air seal would be achieved for Detail 18. As in most cases an isometric tends to add the other dimension that the two dimensional detail is not able to convey.

Detail 19A

This shows the framing of horizontal rails butting to the vertical mullion of a curtain wall. The nosing of the vertical section has been removed to allow for the continuous sealing of an SBS membrane to the tube face.

Detail 19B

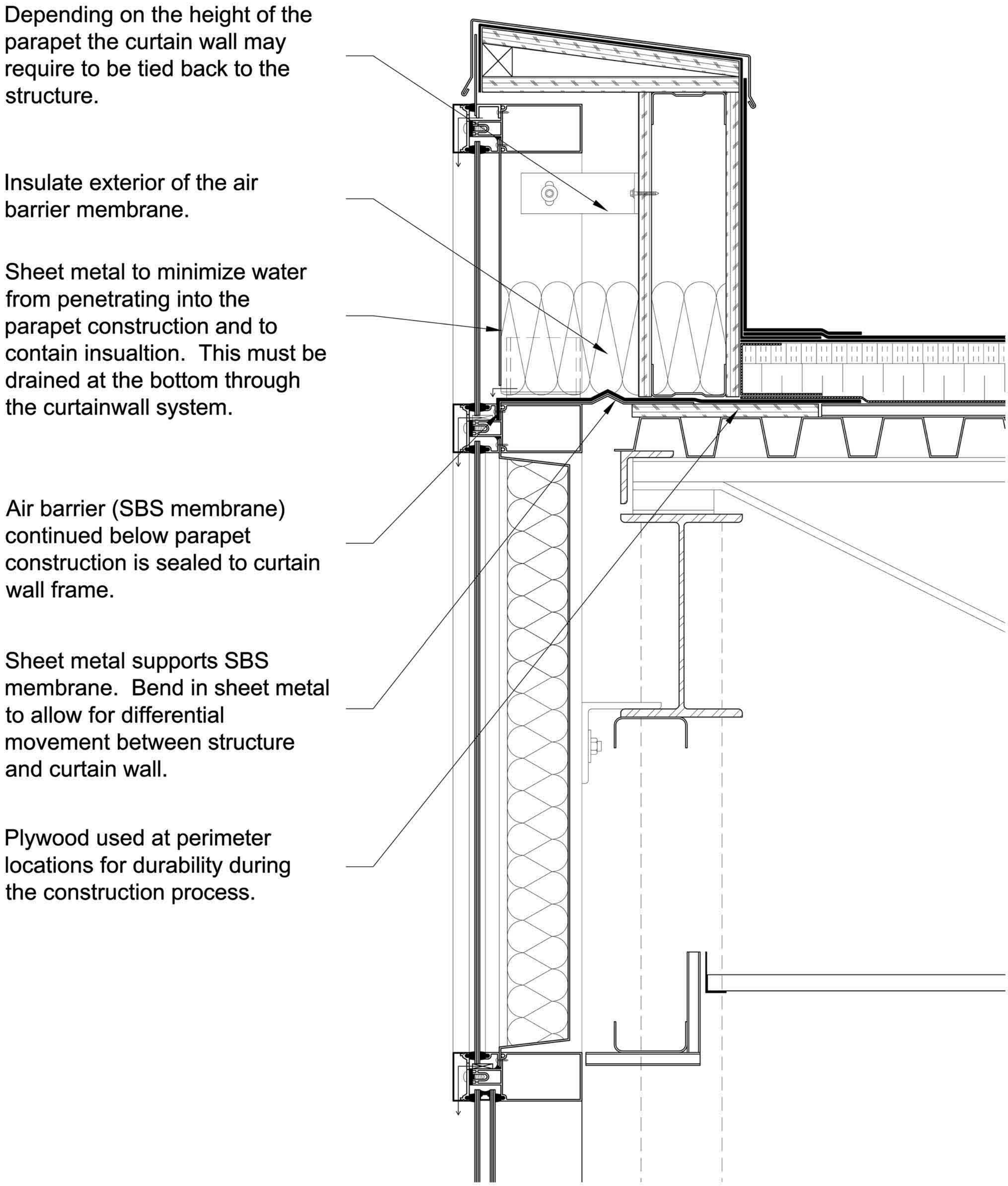
This indicates the placement of the galvanized sheet metal with a slight tent bend in the middle of the gap, from the top face of the curtain wall sections over to the perimeter construction of the roofing. The sheet metal provides support for the SBS membrane over the gap between the curtain wall and the roof perimeter and the void of the vertical mullion. The tent bend will provide support for the membrane if the curtain wall moves relative to the structure while at the same time ensuring that should water enter the parapet construction it would not be trapped in a gutter where-it may-eventually deteriorate the SBS membrane to a point where it might leak.



DETAIL 18: CURTAIN WALL PARAPET 1

SECTION

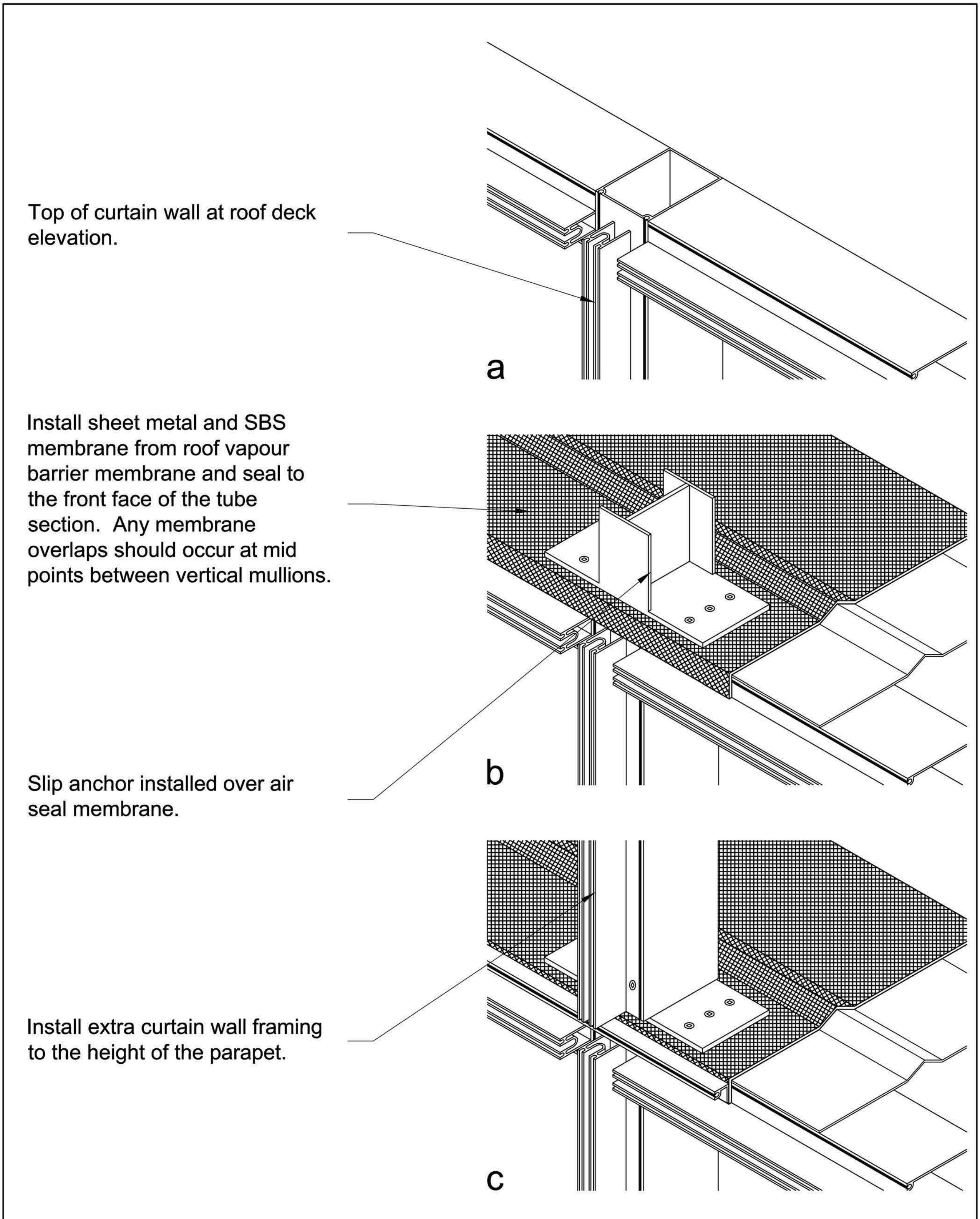
17



DETAIL 19: CURTAIN WALL PARAPET 2

SECTION

18



DETAIL 20: CURTAIN WALL PARAPET 2

ISOMETRIC CONTRUCTION SEQUENCE

19

The purpose made sleeve is fastened to the horizontal rails of the framing below.

Detail 19C

The sleeve anchor allows for the placement and fastening of the vertical extension in line with the mullion below. The SBS membrane requires mechanical fastening on the face of the tube section to retain the seal. As stated before, the horizontal nosing of the rail could be removed to allow the installation of a continuous finish panel across this joint. No pressure plate or cover cap would be visible on the exterior.

16

Roofs

Wayne Tobiasson[1]

Preface

THIS CHAPTER HAS BEEN EXPANDED BY ITS FIRST-edition author to include additional information on:

- Building codes
- Climate zones
- Metal roofing
- Steep roofing
- Structural insulated panels
- Freeze-thaw damage to insulations
- Ventilation of attics and cathedral ceilings
- Ice dam protection underlayments
- Vapor retarders for compact roofs
- Self-drying roofs and downward drying of wet roofs
- Sliding snow hazards and solutions
- Finding leaks and wet insulation
- Air barriers and the necessity of controlling air leakage

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, usually about 14 degrees (3 in./ft) (see Note at end of text) or more, 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 and sidelap must exist to prevent water penetration by wind and rain forces, by air pressure, and by capillary suction [1].

Underlayments are installed under *water-shedding* systems to separate the roofing from the deck, help shed water, and provide weather protection during construction and thereafter (e.g., to resist leakage of water that ponds behind ice dams) [2,3]. Full underlayment (i.e., underlayment that covers the entire roof) is an essential part of all sorts of tile roofs. In the United States, full underlayment is considered an essential part of asphalt shingle roofs [4] but in Canada, codes [5] and other guidelines do not mandate full underlayment under asphalt shingles except at lower slopes (often, below 18 degrees (4 in./ft)) and where water may pond behind ice dams. In parts of Canada full underlayment is not used much on slopes of 23 degrees (5 in./ft) or more. An underlayment's ability to shed water when punctured by the numerous nails driven through it is disputed.

Water-shedding systems work well on relatively steep slopes, but the consequences of melting snow must be considered in cold regions where icicles and ice dams may form at roof eaves (Fig. 1). Water that ponds behind ice dams can rise above the headlap of the water-shedding elements and cause leaks. The underlayment below those portions of water-shedding systems that might be subjected to ponding behind ice dams should be a fully-adhered waterproof membrane such as a self-adhered (i.e., peel and stick) modified bitumen. Such membranes are also useful in roof valleys where snow may retard the flow of converging water causing that water to rise in the snow above the headlap. A compilation of materials used in steep-slope roofing is available [6].

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 [7]. 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 [1,4,8–11] and some excellent systems are available. Since lesser systems are also marketed, the phrase *caveat emptor* (let the buyer beware) is appropriate.

Waterproof membranes and their flashings need to be totally sealed against water penetration up to the top of their base flashings. Cap and counter flashings overlap base flashings so as to provide a water-shedding joint there. Even waterproof membranes should be provided with slope to preclude ponding of water on them [1,8,12,13] since a total seal against water penetration is almost impossible to achieve. A "dead flat" waterproof membrane is a design mistake (Fig. 2). Fortunately, in most instances, a slope of about 1.2 degrees ($\frac{1}{4}$ in./ft) is sufficient. Improvements in performance by increasing the slope above 1.2 degrees ($\frac{1}{4}$ in./ft) are, at best, minimal and at slopes of about 2.4 degrees ($\frac{1}{2}$ in./ft), membrane slippage and other problems as well as costs increase noticeably. It is usually best to create slope by sloping the roof deck rather than using tapered insulation: When the deck is sloped and the membrane and any wet insulation must be replaced, the expense of replacing slope is avoided.

[1] *Civil Engineer/Moisture Consultant, 5 Woods End Road, Etna, New Hampshire 03750; e-mail: weworkshop@aol.com formerly, Senior Research Civil Engineer, Cold Regions Research and Engineering Laboratory* (*CRREL*), *72 Lyme Road, Hanover, NH 03755-1290*)

Fig. 1—Steeply sloped metal roof with severe icings along its eaves.

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 (Fig. 3), 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 that lead to dry wells or storm drains. Scuppers located a few inches above the membrane as shown in Fig. 4 can be used for secondary (i.e., emergency) drainage in the event that the primary drains become blocked. It is unlikely that such scuppers will be blocked by ice on those few occasions when they are needed.

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

Fig. 2—Water remains on a "dead flat" membrane. Slope to drain is essential.

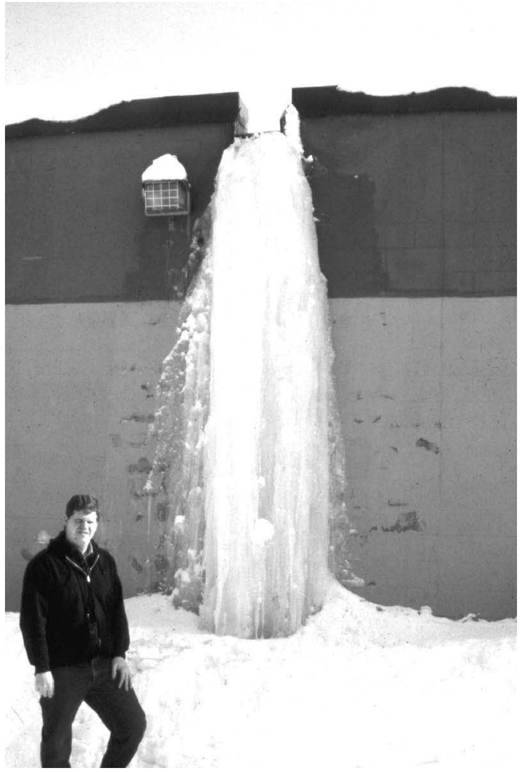


Fig. 3—Membrane roof with drainage through scuppers that have iced up.

the roof [14,15] or added to a roof during construction of the rest of the building by subsequent moisture-generating steps such as pouring concrete slabs, installing gypsum wall board and setting tile and stone [4,16]. Chapter 7 of this manual discusses moisture sources in some detail.

A relatively small number of moisture problems in membrane roofs are related to condensation [17]. Nonetheless, serious condensation problems do occur in some membrane roofs, and it is important to understand how to avoid them.

When referring to metal roofing, "hydro-kinetic" is synonymous with *water-shedding* and "hydrostatic," with *waterproof*. *Waterproof* metal roofing can be used on low slopes and does not require underlayment. Like asphalt shingles and other *water-shedding* systems, *water-shedding* metal systems should be used on slopes of about 14 degrees (3 in./ft) or more [4,8,10,11,18]. They require underlayment and a slip sheet to keep the metal from sticking to and tearing the underlayment as the metal expands and contracts thermally.

In cold regions where snow and ice can retard the flow of water, there is merit in increasing the minimum slope on which *water-shedding* metal systems are used to greater than 14 degrees (3 in./ft) and requiring that their seams contain a factory-applied sealant.

Old style *water-shedding* metal panels with low, lapped side seams and gasketed fasteners that penetrate the metal along its drainage plane are prone to leak over time due to thermal movement of the panels. Such "through-fastened" metal roofing should only be used on roofs of agricultural, industrial, warehouse and other utility buildings without conditioned spaces below. Underlayment is essential. For

Fig. 4—Overflow, *emergency*, scuppers are appropriate, even in cold regions.

"through-fastened" systems used on such utility buildings, the Corps of Engineers recommends a minimum slope of 9.5 degrees (2 in./ft) except in cold regions where the minimum is increased to 14 degrees (3 in./ft) [19].

The development of standing seams and hidden clip fasteners has significantly improved the water-shedding ability of metal roofing systems [20].

Standing seam metal roofing is commonly classified as either "architectural" or "structural" with "architectural" intending to refer to *water-shedding* and "structural" intending to refer to *waterproof* systems. The Metal Building Manufacturers Association (MBMA) [18] indicates that this classification is "simply not correct."

"Architectural" metal systems are those used where aesthetics is a primary consideration. Obviously, their primary use is on roofs that can be seen (i.e., steeply-sloped roofs). Thus, most "architectural" metal roofing systems need only be *water-shedding*. Some "architectural" systems contain sealants in their seams but that does not necessarily make them *waterproof* systems. However, some "architectural" systems are designed to be *waterproof*, so that they can also be used on low slope roofs. Thus, not all "architectural" systems are *water-shedding* systems.

"Architectural" metal systems require the support of continuous or closely-spaced decking since their low standing seams (only 22 to 38 mm [$\frac{7}{8}$ to $1\frac{1}{2}$ in.] above the flood plane of the metal panel) provide only a limited amount of beam action.

"Structural" standing seam metal roofing systems were developed for use on low-slope roofs where aesthetics is of little concern. Since low-slope systems must have *waterproof* capabilities, *structural* standing seam metal systems are thought of as *waterproof* systems that can span between structural supports (purlins usually) spaced some distance apart. However, since the ability to span such distances can be advantageous on some steeply-sloped roofs and aesthetics is not a major issue for some steeply-sloped roofs, "structural" systems are also used on steeply-sloped roofs. Such "structural" systems do not need to be *waterproof* (i.e., their seams do not need to be capable of withstanding "hydrostatic" conditions). Thus not all "structural" standing seam metal systems are *waterproof*.

Aesthetics and structural support issues are of secondary importance to this discussion of moisture. Of greater concern is the system's ability to either shed water or, on occasion, withstand hydrostatic pressure from ponded water. Thus, metal systems are described primarily as either *water-shedding* or *waterproof*.

Because the standing seams impede drainage, and watertightness is rather difficult to achieve and maintain at penetrations wider than the distance between seams and at valleys, eaves, ridges, and rakes, *waterproof* metal systems are not the same as *waterproof* membranes.

Most of the support for *structural* standing seam metal roofing systems is provided by hidden clips, which are usually designed to accommodate thermal movements. The metal panels slide back and forth (i.e., "float") on the clips. Some support is also provided by the compressed fibrous glass insulation placed between them and their structural supports. Manufacturers of *waterproof* metal roofing systems promote their use on slopes down to about 1.2 degrees ($\frac{1}{4}$ in./ft) [18]. However, the National Roofing Contractors Association (NRCA) recommends a minimum slope of about 2.4 degrees ($\frac{1}{2}$ in./ft) [4]. The Corps of Engineers also recommends a minimum slope of 2.4 degrees ($\frac{1}{2}$ in./ft) but increases that to 4.8 degrees (1 in./ft) in highly corrosive environments and to 7.1 degrees ($1\frac{1}{2}$ in./ft) in cold regions [19].

When people say that "metal roofs attract condensation", what is being referred to is the tendency of the thin metal to be cooled well below the outdoor air temperature by radiational cooling on clear nights. The underside of the cold metal is then a surface on which condensation is more likely to form than on other, warmer surfaces [18].

Standing-seam metal roofing systems perform very well in many areas, but they have some limitations for buildings with high indoor relative humidities and 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 [21].

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 preventative 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. 5. The insulation is placed above the roof deck. There is little opportunity for air movement within a compact sys-

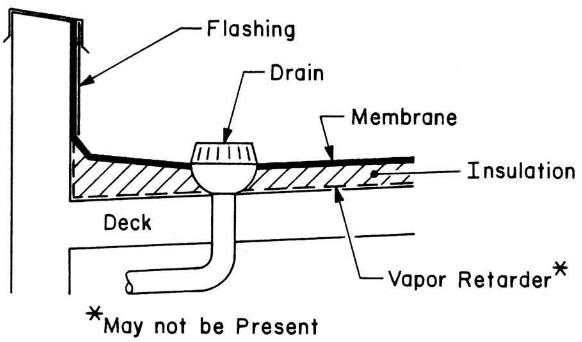


Fig. 5—Typical compact roof.

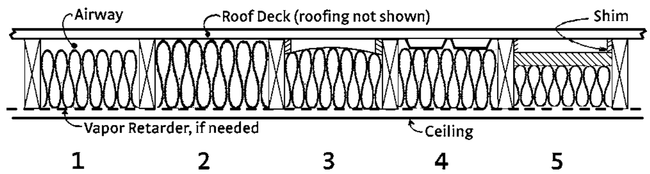


Fig. 7—A variety of airways for ventilated, framed roofs. (1) "Design" position of batt insulation with airway above. (2) Actual position of batt insulation that expands to fill the space. (3) "Housewrap" tightly installed before batt insulation which bows it upward. (4) Continuous chutes installed before batt insulation. (5) Shims and rigid board insulation installed before batt insulation. Recommended way.

tem 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. Mechanically-attached membranes are not as resistant to air leakage but are, nonetheless, relatively tight.

A *framed* roof is shown in Fig. 6. 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 potential 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. 5 and 6. Some roofs are part *compact* and part *framed*. As will be discussed, it can be advantageous to have the *compact* portion of a "hybrid" roof above the *framed* portion.

Metal roofing is used on both *compact* and *framed* roofs. Most water-shedding standing seam metal roofing is on framed roofs. Waterproof standing seam metal roofing is often used on compact roofs that have some of the limitations

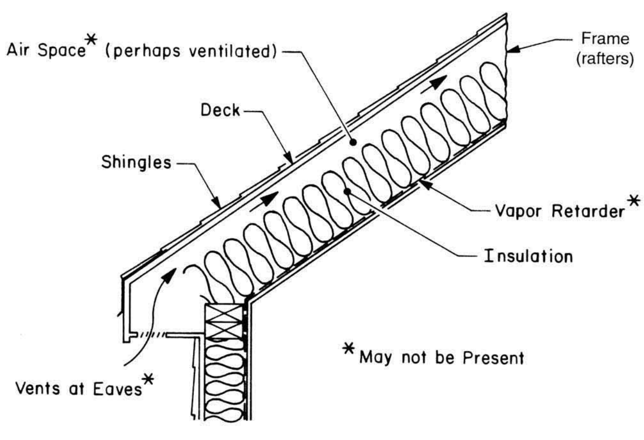


Fig. 6—Typical framed roof.

of framed roofs relative to air leakage because they contain permeable batt insulation and they do not contain a structural deck below.

To Ventilate or Not to Ventilate, That is the Question

Low-slope, compact membrane roofing systems should not be ventilated. Edge venting and the addition of various breather vents to such roofs have been shown to be ineffective [22]. Such roofs do not need to be ventilated and the penetrations of their waterproofing membranes needed to install such vents often do more harm than good.

For decades, ventilation of attics has been promoted as an acknowledgment that some moist indoor air enters them by vapor diffusion and air leakage and it should not be trapped there.

Many attics designed to be ventilated are not, due to blockage of air at their eaves by batt or loose-fill fibrous glass, rockwool, or cellulose insulation. Baffles and chutes are available to avoid such blockages. They also prevent wind from reducing the effectiveness of that insulation by displacing it or by blowing through it. By affording such protection the ceiling is warmer which reduces the risk of condensation and mold growth at a location where framing members create a thermal weak link in the building envelope.

Some cathedral ceilings are ventilated as shown in Fig. 6 for the same reason. The airway 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.

Figure 7 shows (1) a cathedral ceiling designed to have an airway above batt insulation but (2) without an airway due to upward expansion of that insulation and three ways of creating "guaranteed" airways using (3) a vapor-permeable air barrier, (4) chutes, and (5) rigid board insulation [23]. Even when installed "drum-tight," the air barrier will bow upward as shown. The three viable alternatives shown also reduce air leakage up into the roof. All things considered, the use of rigid board insulation is recommended.

Vapor retarders, air barriers, tapes, foam sealants, and such have led to tighter building envelopes and, thus, the amount of moist, exfiltrating air that needs to be ventilated away has diminished. If framed walls built tight do not need to be ventilated, why ventilate framed roofs? One argument is that the forces that promote air exfiltration are greatest at the top of buildings. Thus, large portions of walls may be subjected to air *infiltration*, which, in cold regions, is unlikely to create condensation problems.

Ventilation is also promoted to lower the temperature of attics, reducing summer cooling loads [24–26]. Some studies support this benefit, but others do not.

By ventilating between the insulation and a roofing material such as asphalt shingles, the shingles remain cooler and their useful life may be prolonged. Even though evidence is accumulating that the expected benefits are minimal, most manufacturers of asphalt shingles continue to require ventilation below their products [24] and NRCA continues to recommend attic ventilation [25]. Problems such as shingle splitting are often blamed on missing or inadequate ventilation but, again, little evidence is available to support this contention.

The various reasons for and against ventilation of attics and cathedral ceilings have been summarized, comprehensive references have been provided on the subject [27], and the conclusion reached that ventilation may be beneficial as "an additional safeguard" in some circumstances and climates but certainly not all.

Ventilation is "a double-edged sword" since it can also promote flow of moist indoor air up into a roof. Occasionally, this can increase, 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 can be beneficial especially in cold regions where it can minimize icings at eaves by removing building heat rather than letting it warm the underside of the roof. Such heat can create meltwater that flows downslope then freezes at cold eaves. Building heat, not the sun, is usually the primary cause of ice dams. Heat from the sun may generate meltwater, but that heat usually also warms the eaves, reducing the tendency for growth of icings there. Periods during which building heat creates meltwater can be reduced significantly by using *cold* ventilated roofing systems [23,28–30].

In cold, but not severely cold, snowy regions, unventilated, very-heavily-insulated roofs can work provided that ceiling air leakage is essentially eliminated [28]. If the responsibility for achieving such air tightness is not acceptable, a safer way to build framed roofs that slope to cold eaves is to make them cold, ventilated systems.

The International Building Code-2003 [31] and the International Residential Code-2000 [32] require that attic spaces be ventilated. The International Energy Conservation Code-2000 [33] does not mandate ventilation. Instead, the mandate is "to avoid condensation" within the building envelope by sealing all sources of air leakage and, in some regions, installing a vapor retarder on the warm-in-winter side of the insulation.

Because of the problems roof ventilation can introduce (e.g., ingestion of driving rain and blowing snow, bringing in outdoor moisture, promoting exfiltration of indoor air and reducing the thermal resistance of the roof) proponents of unventilated roofs have changed some local building codes and are working to change the IBC and the IRC to allow the option of unventilated attics and cathedral ceilings. Many such roofs have been designed and built in Canada and America. They are performing well provided that they and the building they cover are properly designed and built (e.g., the roofing and its appurtenances are able to resist rain penetration, the relative humidity indoors is controlled, air leakage into and through the building envelope is minimal, and any small amounts of moisture that get into the roof in time can escape as the seasons change). As long as the critical nature of these issues is understood and appreciated by designers, builders, and the building's occupants and owners, unventilated attics and cathedral ceilings can be expected to perform well in many situations.

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.

Excess moisture in a roofing system can weaken and eventually rot wood, corrode metal (Fig. 8), cause leaching, efflorescence, and spalling of concrete and masonry and, by freeze-thaw action, delaminate or disintegrate roofing components (Fig. 9) [1,8,34].

Each 100 mm thickness of wet insulation can contain up to 96 kg of water per square meter (i.e., 5 lb of water per

Fig. 8—Architectural metal panel lifted to show corrosion on its underside.

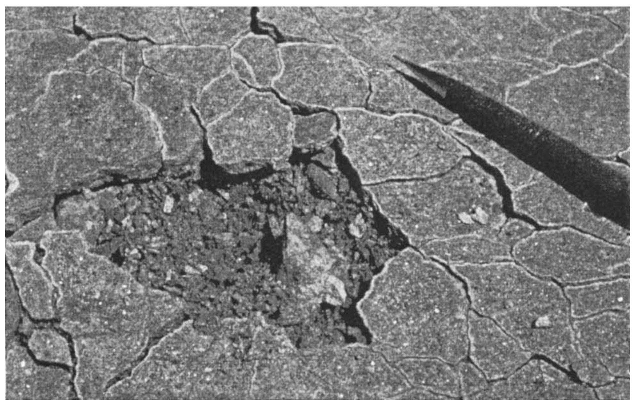


Fig. 9—Concrete paver destroyed by frost action.

square foot for each inch of wet insulation) [13]. This undetected, unwanted extra load can be enough to overstress or fail the roof structure in combination with snow or wind loads.

Membrane Roofing

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 [1,8,35]. 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" organic felts with water contents in excess of 60 % by weight have been measured [36]. The fibers in asbestos and organic felts are weakened significantly if they get wet [37]. The wet strength of such a felt and membranes containing wet felts may be less than 20 % of their dry strength [38,39]. 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 [36]. 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 [40,41]. To perform successfully, such 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.

Today, saturated glass felts are used for all plies. Such felts, when properly installed, have eliminated almost all the moisture problems associated with the other kinds of felts.

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. 10) [8]. 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 [42]. Moisture is not necessary for blister growth, but when moisture is present, the pressure within the void can increase significantly, 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 bituminous 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. 11) such that each felt traverses the membrane from top to bottom (Fig. 12). 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, 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. 13). These cracks can be deep enough to allow moisture to gain access to the felts, and thus the air and water necessary for blister

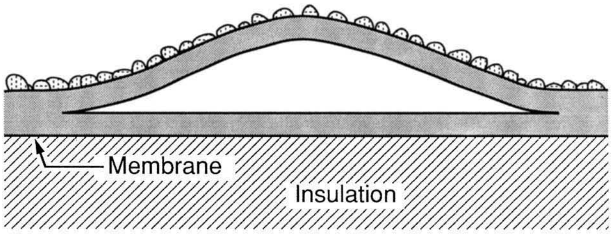


Fig. 10—Interply blister. Most blisters are interply blisters.

Fig. 11—Felts are laid shingle fashion.

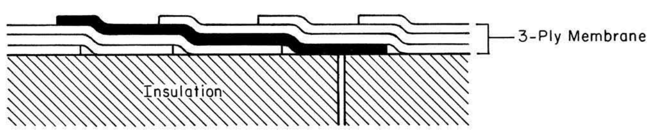


Fig. 12—Three-ply membrane. Each felt traverses the membrane from top to bottom.

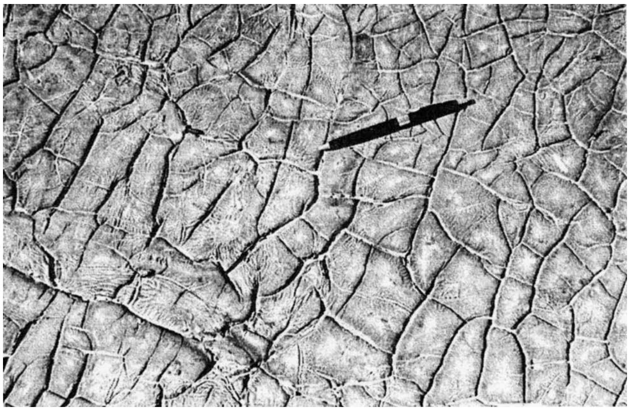


Fig. 13—Bitumen shrinkage. Photo-oxidation causes shrinkage, which produces "alligatoring."

growth can come from above as well as below. When the bitumen is protected by imbedded aggregate or loose stone ballast, its rate of aging slows way down.

Because of the moisture sensitivity of organic felts and the health hazard associated with asbestos, almost all bituminous built-up membranes are now made with felts having glass fibers. Glass felts are not much affected by moisture. The use of glass felts in such membranes has greatly improved their resistance to blistering and moisture provided that these porous felts are laid properly [43]. Membranes constructed with glass felts may not require an immediate flood coat of bitumen on top. However, delayed completion of a built-up membrane is generally not recommended.

Most of the rubber, plastic, and modified bitumen membranes are much less affected by moisture than bituminous built-up membranes made with moisture-sensitive felts. That is a major reason why they have become so popular. However, most of 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. To combat shrinkage, reinforcing mats are now built into PVC membranes, but most other "single-ply" membranes are not reinforced.

Comprehensive overviews of various low-slope membrane materials and systems are available [4,8], including newer materials such as polyester reinforcements and thermoplastic polyolefin (TPO) membranes. A current trend is toward self-adhering single-ply membranes, TPO membranes in particular. Self-adhering can ease installation and reduce environmental issues associated with adhesives applied on site. Provided that surfaces are properly cleaned and primed, strong attachments and seams can be created.

Sprayed-in-place polyurethane foam (SPF) surfaced with a liquid-applied membrane such as urethane, acrylic, or silicone is popular. The SPF adds thermal resistance and the system is lightweight, seamless, and self-flashing. On dry substrates a tenacious bond is achieved by the foam [4,8]. Proper application requires skill due to constraints created by winds and moisture. The need for periodic recoating of the membrane is to be expected.

Other Roofing

Wood shingles and shakes are made from durable, moisture-resistant woods such as cedar. Sometimes they are also protected with a preservative to increase their durability. To remain serviceable, they need to dry after becoming wet. When drainage and drying are provided, they last for many years.

Slates used in roofing are virtually nonabsorbent and thus quite resistant to moisture. However, moisture-related weathering progresses at varying rates among the range of slates being quarried. This is not a longevity issue but it is a very important aesthetic issue. When selecting a slate its "unfading" or "weathering" characteristics must be determined.

Clay tiles absorb water at various rates. The rate is slow for dense, well-baked clay but for other clays it can be five times as fast [10]. Water absorption rate determines a tile's resistance to frost action. Tiles that are slow absorbers (i.e., Grade 1 tiles) can survive in cold climates where numerous freeze-thaw cycles occur annually. Grade 2 tiles have only "moderate" resistance and Grade 3 tiles have negligible resistance to frost action. Maps of the USA are available that show regions where each grade can be used successfully [4].

Since concrete tiles are rather absorbent, they are commonly made with air-entrained cements to make them resistant to frost action. Nonetheless, they are not as durable as clay tiles [10]. Sealers are sometimes used to reduce their porosity. After some years of exposure resealing is to be expected.

In the late 50s, asphalt (i.e., "composition") shingles had problems when their asphalt-saturated organic reinforcing felts were not adequately back coated to resist moisture [44]. Moisture under the shingle tabs wicked up into the felt and, when the sun caused drying, the felt shrunk, causing the center of each tab to rise up. This gave the tabs the appearance of "clawing" at the roof. Moisture can also cause upward curling of such shingles. Improved felts and use of more and better asphalt have significantly improved such shingles [45]. Problems still occasionally occur when moisture-weakened shingles spilt due to weaknesses or movements in the deck. In the 70s, newer shingles with fibrous-glass reinforcing were introduced. Fibrous glass mats provide better fire resistance than organic felts and they do not absorb moisture. Unfortunately, early lightweight glass-mat shingles suffered splitting and wind-blow-off problems. The tear resistance of shingles with glass-mat reinforcing can be reduced when they are wet and hot. This explains vertical tearing of dark shingles having hard, inflexible, asphalt wind sealant that tied them all together [46]. Over the years, improvements have been made to both types of asphalt shingles. In cold climates organic-mat shingles are tougher and more pliable than glass-mat shingles. For this reason, organic-mat shingles are more popular in cold climates than they are elsewhere. In warm, humid climates glass-mat shingles are preferred for their moisture resistance with many enhanced with algae and fungus inhibitors [47]. Some shingles are now being made with polymer-modified asphalts to further increase their resistance to weathering and aging. It makes little sense to use inexpensive, "low-end" asphalt shingles; considering life-cycle costs, only a rich man can afford cheap shingles.

Underlayments (or interlayments in the case of wood shakes) are an important part of most *water-shedding* roofing systems. The porous nature of asphalt-saturated felts reinforced with fibrous glass mats makes them unsuited for this purpose. Any asphalt-saturated organic felt that has been perforated to make it more suitable for use in the construction of bituminous built-up membranes is also not acceptable. In some situations #15 asphalt-saturated felts are a suitable underlayment but in others, #30 or even #45 felts are needed. A very durable underlayment should be used under a very long-life roofing, such as slate. Underlayment provides a second line of defense against moisture intrusion but, since the felts used are not completely waterproof, they need to dry out after a bit of wetting, rather than progressively become wetter. A felt underlayment exposed to a light rain or even dew during installation may wrinkle. Such wrinkles should be removed before the shingles are installed since they can cause the shingles to also appear wrinkled.

In the past, at particularly challenging places on roofs such as in valleys and along eaves where all drainage occurs and where ice dams may form, added protection was provided by using two layers of felt with the first nailed to the deck and the second set on it in a continuous layer of roofing cement or moppings of hot asphalt. The attempt was to create a *waterproof* membrane in such places where occasional ponding of water was anticipated. Today, self-adhering polymer-modified bituminous sheet materials (i.e., "peel-and-stick mod-bits") are commonly used in these places. They are a much more moisture-resistant product and by being fully-adhered, not dry nailed to the deck, they are better able to resist lateral movement of water. They also tend to self-seal around nails driven through them into the deck. The use of "peel-and-stick mod-bit" underlayments over entire roofs is acceptable to some groups, provided that the space below is ventilated to avoid condensation problems [18,48]. However, others warn that full coverage has caused some decks to rot, particularly above occupancies having a high relative humidity [30,49]. Since asphalt shingle roofing with #15 felt underlayment on a plywood or OSB deck is a rather air-tight and vapor tight assembly, it is likely that those problems would have occurred even if the underlayment were #15 felt. Excessive ceiling air leakage, not the underlayment, is probably the root cause of such problems.

Decks

Wooden roof decks such as plywood and oriented strand board (OSB) expand when their moisture content increases. To prevent buckling and movement of such decks, they are required to be installed with 3 mm (1/8 in.) gaps along their edges. Deck movements may telegraph up through the roofing above causing aesthetic problems or damage. The pull-out resistance of fasteners in wet decks is decreased significantly. When wet plywood dries, it tends to return to its original size but OSB may not.

Problems have been encountered when fire retardant treated (FRT) plywood is used for roof decks. Combinations of moisture and heat have resulted in chemical reactions that corrode fasteners and weaken the plywood [50].

Metal Decks and Roofing

Metal decks and roofing are subject to corrosion in the presence of moisture. Steel, the most widely used metal for roof decks and roofing, requires a metallic coating for corrosion protection. By hot-dipping steel into zinc it becomes galvanized steel. Most roof decks are galvanized steel. However, for roofing, "galvanized steel, by itself, is not considered to provide adequate corrosion protection for long life" [18].

Various trade names are used for steel that has been hot-dipped in an aluminum-zinc alloy, which, today, is the standard of the metal roofing industry. Most metallic coated steel is also painted for additional protection. Since the durable, siliconized polyester and fluoropolymer paints used on the exposed side of the metal panel are rather expensive, the underside often only receives a primer which affords much less protection. When condensation occurs, it is commonly on the underside of the panel, thus it is quite important to prevent condensation in metal roofing systems.

Many metal panels are roll formed on site by the installer. That operation lacks the "close predictable control over quality" available in a factory [20]. When the panel is bent too sharply, the paint cracks making the panel susceptible to rusting both from above and below.

Insulations

Moisture also causes numerous problems with roof insulations. A few key issues are mentioned below.

Most insulations used in roofs can become wet, and when wet, they become heavy, lose strength, swell, and deteriorate, especially during freeze-thaw [1,51]. 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 as shown in Fig. 14. Extruded polystyrene insulation is quite resistant to moisture even in the presence of freeze-thaw [51–55], but there are situations where even extruded polystyrene insulation can slowly become wet [55,56]. The other cellular plastic insulations used in roofs (expanded bead polystyrene, polyurethane, polyisocyanurate, and phenolic) take on moisture in the presence of temperature and vapor pressure gradients [57–62]. Wet phenolic insulation is highly corrosive to steel decks. As a consequence of many documented instances of severely damaged steel decks below phenolic insulations, that material is no longer being used in the United States [63].

Insulation boards of fibrous glass, wood fiber, and perlite take on moisture rapidly [58,59,61]. When wet, the insulating ability of roof insulations is significantly reduced

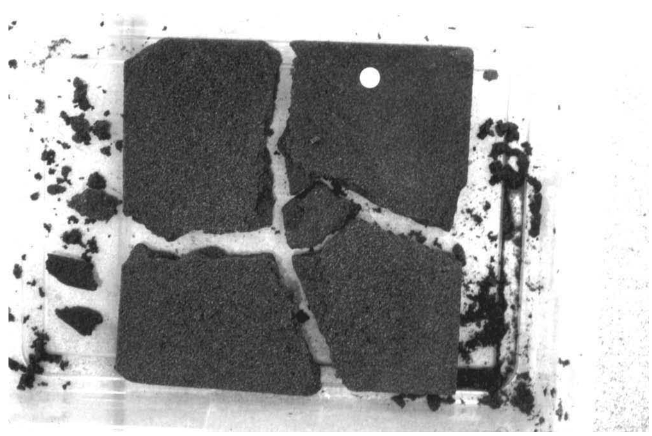


Fig. 14—Cellular glass insulation, 0.3 m (12 in.) square, broken down by freeze-thaw.

[52–62]. Additional information on the effects of moisture is presented later in this chapter and in Chapter 3. Since *essentially all insulations are adversely affected by moisture*, the normal goal is 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

Roof Leaks or Condensation?

If you are betting on where problematic moisture is getting into a roof, bet that it is coming from the exterior due to flaws in the roofing. Even when it only leaks once the sun hits the roof in the morning or after a cold snap, which, to some people, are guarantees that condensation of indoor moisture is the villain, it is still too soon to dismiss external sources.

It is understandable that roofing contractors have a strong vested interest in blaming condensation, especially after having unsuccessfully responded to complaints, which they can often resolve. Even after hearing their savvy opinions, it is still too soon to dismiss external sources.

On the other hand, the possibility that problems *are* related to condensation should not be dismissed too soon either, even when most leaks occur after a heavy rain.

If condensation is found to be the cause, the smart money is then on *air leakage* not diffusion as the means of entry.

Of course, rather than betting on any of this, it is far better to examine the building in some detail while keeping an open mind about all possibilities. Often as an investigation proceeds, the complexity of the situation becomes apparent and simplistic initial thoughts must be reformulated. It often takes a fair amount of ripping and tearing to get to the heart of moisture problems.

Chapter 12 discusses troubleshooting moisture problems in buildings. Guidance is available elsewhere on how to visually inspect and maintain roofs [8,64–74]. Unfortunately, the presence of wet insulation in a roof can seldom be detected visually. Fortunately, special tools and services are available that can find wet insulation rather well. Information on roof moisture surveys is presented at the end of this chapter.

Diffusion or Air Leakage?

Chapter 1 describes various moisture movement merhanisms 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 [75].

The following quotes from the *ASHRAE 2001 Fundamentals Handbook* [76] are worth remembering:

1. "Even small airflows can carry large amounts of water vapor when compared to vapor diffusion."
2. …"an effort should be made to provide as tight an enclosure as possible."
3. …"the exterior envelope of a building should be constructed to minimize airflow into or through the building envelope."
4. "Airtight construction is recommended in all climates."

The *NRCA Roofing and Waterproofing Manual* [4] contains similar guidance.

Once air leakage is acknowledged as the big issue that must be addressed to avoid condensation problems, it is clear why some types of roofs suffer condensation problems while others do not.

Vapor Retarders and Air Barriers

In the first edition of this manual, I stressed the importance of vapor retarder continuity, indicating that if continuity was lacking, air leakage could defeat the vapor retarder. That was one way of stressing the importance of focusing attention on control of air leakage. Today, focusing on airtight construction is still appropriate but it is now considered more appropriate to think about vapor control and control of air leakage separately. Separate vapor retarders and air barrier systems, located at different places in the building envelope, are at times appropriate. However, convection of moist air within some roofs is possible if the air barrier system and the vapor retarder are separated. If a separate system provides air leakage control the vapor retarder may not need to be sealed at penetrations and such. If it only covers 99.9 % of the roof, it can still be well over 90 % effective in stopping the slow movement of diffusing vapor.

Since, to be effective, barriers to air movement must be tightly sealed, it is appropriate to think of air barrier *systems* not just air barrier *materials*. To create an effective plane of air tightness in a roof, air barrier materials must also be capable of being (and staying) sealed together and to other components of the building envelope.

An air barrier system that only covers 99.9 % of the roof is not acceptable since a massive amount of moist air can move by the remaining 0.1 %. In a 5 m by 5 m (16.4 ft by 16.4 ft) roof, an opening 0.18 m (7 in.) in diameter is 0.1 % of the area.

Only if a vapor retarder is well sealed, can it also serve as an air barrier. Using a well sealed vapor retarder as an air barrier can be a valid design option but there are others.

Figure 15 shows a hole in a polyethylene vapor retarder in a ceiling viewed from above with fibrous glass insulation moved aside. The hole in the vapor retarder is much bigger than the pipe penetration. Since a gap also exists between the pipe and the ceiling, indoor air has direct access to the attic here. Some would call this an inadequate vapor retarder since it lacks continuity at penetrations such as this one. Others, in increasing numbers as of late, would say that this *may* be an acceptable vapor retarder but what this ceiling lacks, is an effective air barrier system. Since this ceiling is in Alaska, it would have been appropriate to seal this vapor retarder so that it could also serve as air barrier material in a system capable of controlling air leakage.

To serve as a *vapor retarder* (*vapour barrier* in Canada), a material must have a high resistance to the passage of water vapor (i.e., a low permeance). ASTM Standard Test Methods for Water Vapor Transmission of Materials (E96) is used to

Fig. 15—Polyethylene vapor retarder cut back around a pipe penetration in a ceiling. There is no air barrier here.

determine the water vapor permeance of materials. The water vapor permeances of many building materials are given in Table 7 of Chapter 2 and in Table 9 of Chapter 25 in the *ASHRAE 2001 Fundamentals Handbook* [76]. Wet cup and dry cup values are presented for hygroscopic materials since their permeance increases as they absorb water. Table 1 presents the permeances (in both SI and IP units) of most of the materials mentioned in this chapter. In a general way, doubling the thickness of a material such as an insulation halves its permeance.

A common definition of a *vapor retarder* for use in roofs is a material with a permeance of 28 $ng/s \cdot m^2 \cdot Pa$ (0.5 perms) or less [4]. However, roofing literature contains recommendations that range from 6 to 57 $ng/(s \cdot m^2 \cdot Pa)$ (0.1 to 1.0 perms) or less [8]. Other guidance defines specific permeances for various climatic zones and occupancies [76,77]. To avoid creating vapor traps in building envelopes, some people recommend that the permeance of components on the cold side of the vapor retarder should be no less than that of the vapor retarder [78] or, no less than five times that of the vapor retarder [16]. Table 1 indicates that the very low permeance of most roof membranes makes it very difficult to follow such recommendations in compact membrane roofs. They are seldom followed, fortunately without ill effects.

In the late 1980s, an air barrier *material* had to be capable of being sealed to itself and to other components of the building envelope and have an air permeability of about 0.1 $L/s \cdot m^2$ at 75 Pa (0.02 cfm/ft^2 at 0.3 in. water) or less [79]. Specific recommendations for various applications ranged from 0.02 to 0.2 $L/s \cdot m^2$ at 75 Pa (0.004 to 0.04 cfm/ft^2 at 0.3 in. water) or less [80]. More recently, the National Building Code of Canada [5] has been amended to require that air barrier *materials* have an air permeance less than 0.02 $L/s \cdot m^2$ at 75 Pa (0.004 cfm/ft^2 at 0.3 in. water).

TABLE 1—Vapor permeance of some roofing components. Most values are averages from Ref. [76]. (D)=dry **cup test value** (W)=wet **cup test value.**

Material	**SI Units** $ng/(s \cdot m^2 \cdot Pa)$	**IP Units Perm**[a]
ROOFING		
Bituminous built-up membrane	0.0	0.0
Roll roofing (asphalt shingles similar)	3 (D) 14 (W)	0.05 (D) 0.2 (W)
1 mm (45 mil) EPDM	2.4	0.04
1.5 mm (60 mil) EPDM	1.8	0.03
VAPOR RETARDERS, AIR BARRIERS, AND UNDERLAYMENTS		
Aluminum foil (no holes, no laps)	0.0	0.0
0.1 mm (4 mil) polyethylene	4.6	0.08
0.15 mm (6 mil) polyethylene	3.4	0.06
0.1 mm (4 mil) poly vinyl chloride (PVC)	about 63	about 1.1
Kraft paper laminates with asphalt	17 (D) 103 (W)	0.3 (D) 1.8 (W)
Asphalt-kraft paper on batt insulation	23 (D) 137 (W)	0.4 (D) 2.4 (W)
No. 15 asphalt-saturated felt	57 (D) 320 (W)	1 (D) 5 (W)
No. 30 asphalt-saturated felt	34 (D) 192 (W)	0.6 (D) 3 (W)
Housewraps	3000 to 6000	50 to 100
DECKS AND CEILINGS		
Steel decks	0.0	0.0
Uncracked concrete, 150 mm (6 in.) thick	about 30	about 0.5
Plywood, 6 mm (1/4 in.) thick, exterior glue	40	0.7
Gypsum wall board, 10 mm (3/8 in.) thick	about 3000	about 50
25 mm (1 in.) wood, pine	about 170	about 3
INSULATIONS 25 mm (1 in.) thick		
Cellular glass	0.0	0.0
Polyurethane/isocyanurate	about 60	about 1
Polystyrene, extruded	about 70	about 1.2
Polystyrene, expanded	about 230	about 4
Rigid fibrous glass	about 3400	about 60
Mineral wool batts	about 9000	about 160

[a] A perm has units of grains/$(h \cdot ft^2 \cdot in.\ Hg)$. A grain is equal to 6.48×10^{-5} kg. One perm is equal to 57.2 $ng/(s \cdot m^2 \cdot Pa)$. The "old metric perm," which is not used herein, has units of $g/(24\ h \cdot m^2 \cdot mm\ Hg)$. One perm is equal to 0.66 "old metric perm."

Fig. 16—Spray foam used to seal the ends of a steel deck so it can serve as an air barrier. (Courtesy of Canam Building Envelope Specialists, Inc. and the Roof Consultants Institute.)

Using that value, the following qualify as air barrier *materials* [81]: polyethylene films, roofing membranes, self-adhering modified bituminous sheets, plywood, oriented strand board (OSB), particleboard, extruded polystyrene insulation, foil backed polyurethane/polyisocyanurate insulation, cement boards, gypsum wall board, and some, but not all, "housewraps." However, these materials will only create effective air barrier *systems* when all their seams and gaps are tightly sealed against air leakage. Plywood, for example, is deliberately installed with gaps, which, if not sealed, prevent a plywood roof deck from being an air barrier system. The flutes of a steel deck create additional complexities since their ends provide entrances for air and the flutes are pathways allowing it to disperse laterally above the deck. This not only facilitates air leakage but also short circuits about a quarter of the vapor retarding ability of the steel deck. By sealing (1) the ends of a steel deck as shown in Fig. 16 and (2) any penetrations made in the deck, an effective air barrier can be created, provided that the deck is well nested. In this way a steel deck can be both a vapor retarder and an air barrier. Without seals, it is neither.[2]

The sprayed-in-place polyurethane foam (SPF) shown in Fig. 16 is a valuable air barrier *material* since it sticks to most everything, but, unfortunately, not to polyethylene sheets. Usually it is very effective at creating the seals all air barrier *systems* require.

The following do *not* qualify as air barrier *materials* [81]: concrete block, fiberboard, expanded polystyrene insulation, fibrous glass insulation batts and boards, some "housewraps," #15 and #30 asphalt-saturated roofing felts, tongue and groove wood planks and boards, vermiculate insulation and cellulose spray-on insulation.

When a plywood roof deck is installed with 3 mm (1/8 in.) gaps, 0.26 % of the deck area is open to air leakage. With a #15 felt over the plywood, the effective air leakage rate of the composite, based on area, is $0.40 \times 0.0026 = 0.001$ L/s·m^2 at 75 Pa (0.0002 cfm/ft^2 at 0.3 in. water). Since this is far less than the above limit of 0.02 L/s·m^2 at 75 Pa (0.004 cfm/ft^2 at 0.3 in. water) this combination qualifies as an air barrier provided that the #15 felt is held in place, which it would be by asphalt shingles. For other kinds of water-shedding roofing (e.g., metal and tiles) it probably would not be secured well enough to resist air exfiltration and thus, in combination, plywood and #15 felt would not be able to serve as an air barrier *system*.

Climate

The need for *vapor retarders* and *air barrier systems* and their position in roofs are strongly related to climate. The predominant direction moisture moves through roofs in *cold* climates is upward and outward. The reverse is usually true in *hot* climates where the predominant direction is downward and inward. In each place there are seasonal reversals of direction (which sometimes can be used to advantage to remove moisture) but over the life of the building, the winter (upward) direction prevails in *cold* climates and the summer (downward) direction usually prevails in *hot* climates. Between *hot* and *cold* climates, in what is sometimes called the temperate region or the *mixed* climate, the summer-winter unbalance is smaller with summer somewhat stronger in some places and winter somewhat stronger in others.

Climatic information and climate zones are discussed in Chapters 6 and 18. Information on the need to relate condensation control measures to climate can also be found elsewhere [4,16,82]. In a series of guides for builders, North America has been divided into five hydro-thermal regions: Severe cold, cold, mixed-humid, hot-humid, and hot-dry/mixed-dry. Four guides, one for each region except severe cold, are available. The text explains design principles and numerous drawings illustrate how buildings should be built in each region [83–86].

In this chapter, North American climate is discussed as cold, mixed, and hot. *Cold* refers to Alaska, most of Canada (except the Pacific Coast and Nova Scotia), and the northern "half" of the contiguous United States (except the Pacific Coast and the Atlantic Coast south of New Jersey). *Hot* refers to the dry Southwest, the humid Gulf Coast, and the humid Atlantic Coast north to Virginia. *Mixed* refers to the area between the *cold* and *hot* climates. Some *mixed* climates are dry and some are humid.

In *hot* climates, the primary vapor drive in roofs is downward because many buildings are air-conditioned. In compact membrane roofs the waterproofing membrane also serves as the vapor retarder and the air barrier. Since most waterproof membranes must have their edges and any penetrations well sealed to be waterproof, they are also well equipped to resist both vapor diffusion and air leakage. By not sealing the underside of the roof, small amounts of outdoor moisture that get by the membrane and its flashings may be able to continue downward into the building rather than be trapped in the roof. With the roof membrane provid-

[2] It can be argued that the air spaces created above the flutes of a steel deck should disqualify it as a component of a "compact" roofing system. I choose to think of steel decks as "compact" since, overall, they are more akin to "compact" than to "framed" systems. However, it is worth remembering that the air spaces the flutes create can reduce the moisture resistance of a roofing system with a steel deck, below that of other "compact" roofing systems.

ing all of these functions at once, there are very few condensation problems in compact membrane roofs in *hot* climates.

Most condensation problems in *mixed* and *cold* climates are generated in cold weather when the warm air in buildings usually has a higher vapor pressure than the cold outside air. This plus (1) wind effects, (2) the buoyant nature of warm indoor air, and (3) positive pressures created indoors by mechanical heating and ventilating systems, all tend to force indoor moisture up into roofs. If an essentially impermeable roof membrane caps the roof, any moisture in the roof is prevented from leaving. The dew point of the indoor air is often reached within the roof during cold periods and thus condensation may occur there. It is highly unlikely that a little condensation on the coldest days of the winter will do any harm, but when condensation occurs for many days, weeks, or months, the amount of moisture deposited can create major problems [87]. In *cold* climates, moisture barriers may be needed within roofs to reduce the flow of moisture to an acceptable level.

To prevent moisture from getting to cold portions of a roof, moisture barriers (i.e., vapor retarders and air barrier systems) may be needed within the warmer portion (but not necessarily the warm side) of the roof.[3] In *mixed* and *cold* climates, if a vapor retarder is present, it is often appropriate to tightly seal it so it can also serve as the air barrier system.

A potential moisture trap is created when a vapor retarder, such as polyethylene, is used as an air barrier material within the colder portions of a framed roof in *mixed* and *cold* climates. An air barrier material that stops air but, by some "magic," allows moisture vapor in that air to pass, can be placed most any place within the roof. Of the air barrier materials listed above, only interior gypsum wall board and vapor-permeable (i.e., "breathable") "housewraps" meet these requirements. They have water vapor permeances above about 458 ng/(s·m^2·Pa) (8 perms). By placing such a vapor-permeable air barrier material above permeable batt insulation in a ventilated framed roof, a potential moisture trap is not created and less of the insulation's thermal resistance is lost to wind washing by the ventilating air. Also, convection cells that form in the insulation are weaker which makes that insulation even more effective. However, if instead the air barrier system is located on the warm side of the insulation, moist indoor air is prevented from gaining access to the insulation and that is also rather important. Thus there are good reasons to place air barrier systems at various locations in roofs. In fact, in all climate zones it is beneficial to provide air leakage resistance on both sides of permeable insulation [16]. "Breathable" air barrier materials can be placed in locations where vapor-tight (i.e., low perm) air barrier materials cannot.

Air barrier materials must be capable of withstanding stack-, wind- and fan-induced air pressures across them in either direction without displacement or damage. To achieve this, it may be necessary to fasten them securely along each rafter, joist, or stud with special fasteners as close as 150 mm (6 in.) on center or sandwich them between rigid materials.

In most climates, vapor drive reverses during part of the year. The presence of a nonhygroscopic vapor retarder, such as polyethylene, with very low permeance, prevents the drying out of moisture that has gotten into the roof when moisture was flowing in the opposite (i.e., predominant) direction. By using vapor retarders that have much higher wet cup permeances than dry cup permeances, some drying can be achieved. When the temperature of such a vapor retarder is below the dew point temperature of the trapped air, condensation forms on its backside and, being wet, it is able to pass moisture at its faster "wet cup" rate. As shown in Table 1, the asphalt-coated kraft papers used as vapor retarders on batts of fibrous glass insulation have a wet cup permeance several times that of their dry cup permeance. However, the "wet" rate of vapor diffusion is still rather slow and, thus, this "smart" feature of some vapor retarder materials cannot be expected to remove large quantities of water that accumulate in winter in roofs with inadequate air barriers or from roof leaks. Other "smart" vapor retarders are discussed later in this chapter.

Valuable guidance on vapor retarders, air barriers, and ventilation is presented in Chapters 23, 24, and 25 of the *ASHRAE 2001 Fundamentals Handbook* [76].

Building Codes

The National Building Code of Canada [5] 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 vapour barriers are well established, as is the need to support them properly [88].

Until recently, American building codes said little or nothing about condensation control. Neither the International Building Code 2003 (IBC-2003) [31] nor the International Residential Code 2000 (IRC-2000) [32] contains any requirement for control of roof or ceiling air leakage. That is an unfortunate weakness in these documents.

To control condensation, the IBC-2003 requires that attics and cathedral ceilings be ventilated with inlet areas near the eaves and outlet areas in the upper portion of the attic equal in size. The outlets must also be at least 0.9 m (3 ft) higher than the inlets. When a vapor retarder with a permeance of 57 ng/(s·m^2·Pa) (1 perm) or less is present, the required amount of ventilation is cut in half (from 1/150th of the area to be ventilated to 1/300th of that area).[4]

The IRC-2000 also requires that attics and cathedral ceilings be ventilated. However, if the ventilating area is 1/150th of the area to be ventilated, there are no requirements (1) for balancing inlet and outlet areas, (2) for minimum heights between inlets and outlets, *or* (3) for a vapor retarder. Surprisingly, if inlet and outlet openings are close to balanced and the minimum height difference of 0.9 m (3 ft) between inlets and outlets is met, the ventilating area can be reduced to 1/300th of the area to be ventilated, without the need to have a vapor retarder. Thus, in residences, ventilated attics without vapor retarders (or air barriers) but with reasonably-well-balanced inlet and outlet areas and

[3] It is conventional to think about the winter-warm-side in *cold* and *mixed* climates but there can be merit in placing the vapor retarder, at least in compact roofs, in as *cold* a location as possible where it can still do its job. More on this later.

[4] The ratios 1/150th and 1/300th mean that the net free openings at the eaves and the ridge, which should be about equal in size to "balance" the system, should sum to 1/150th (i.e., 0.67 %) and 1/300th (i.e., 0.33 %) of the area of the ceiling of the space that is the source of moisture.

common slopes can be designed and built with reduced ventilation. In the IBC-2003 such roofs would require vapor retarders. This inconsistency is unfortunate. The allowed reductions in ventilation in the International Residential Code are questioned; those in the International Building Code are somewhat more reasonable. Both codes are unreasonable in that they fail to address air leakage. When air leakage is controlled, much less ventilation should suffice.

As counterpoint, the International Energy Conservation Code 2000 (IECC-2000) [33] does not require attics to be ventilated. Instead, it requires that means to avoid condensation be provided (e.g., use of a vapor retarder on the warm-in-winter side of the insulation in cold regions) *and* that *all sources of air leakage in the building envelope be sealed*. While IECC-2000 does not mandate attic and cathedral ceiling ventilation, it should, but does not, provide guidance for such ventilation, which is a reasonable design option in many situations. The next edition of the International Residential Code (IRC-2006) will introduce the option of unventilated attics and provide design guidelines for them.

In inconsistent bits and pieces, it is taking American building codes (and others in the building industry) a very long time to recognize that controlling air leakage in building envelopes is critical if condensation problems are to be avoided. As more attention is paid to air leakage, the need to ventilate roofs diminishes and, in some climates and situations, disappears. This is not to say that ventilation is wrong or unnecessary; rather, it is to stress that ventilation of attics and cathedral ceilings is not a *prerequisite* for thermal and moisture control in many buildings but control of air leakage *is*.

The current situation creates serious inconsistencies and liabilities for designers and builders. If a code or the requirements of manufacturers is not followed and something goes wrong, fingers point, even if lots of studies and research support a different approach. In this way, codes, while improving, are still creating situations that promote moisture problems in buildings.

Condensation Control Guidelines

General

This section provides specific guidance, in sequence, for the following kinds of roofs:

- Compact membrane roofing systems
- Compact water-shedding roofing systems
- Framed water-shedding roofing systems
- Framed membrane roofing systems

Compact Membrane Roofing Systems

Description

A tightly sandwiched compact roofing system is shown in Fig. 17. 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. Compact roofing systems with their membrane fully adhered to insulation are remarkably resistant to air leakage. Loose-laid membranes secured with ballast and mechanically-attached membranes are not quite as resistant to air leakage. Nonetheless, they are usually good air barriers. The primary reason compact membrane roofing systems suffer few condensation problems is that most are quite resistant to air leakage.

Vapor Retarders

In *hot* climates, the low vapor permeability, as shown in Table 1, and air tightness of waterproofing membranes prevents outdoor moisture from entering the roofing system. In other words, the membrane also serves as a vapor retarder and an air barrier. Adding another vapor retarder would create a potential vapor trap and prevent any downward drying into the occupied space below. Thus, in *hot* climates, where many buildings are cooled by air conditioners much of the year, most compact membrane roofs do not need, and are better off without, a separate vapor retarder. However, if the building has a high indoor relative humidity, a vapor retarder may be needed even in *hot* climates.

In *cold* and *mixed* climates, where the predominate direction of moisture movement is upward and outward, the low vapor permeability and air tightness of waterproofing membranes creates a potential moisture trap in the roof in winter. Almost all buildings occupied by people have an indoor design temperature of 20°C (68°F) in winter and almost all have, for human comfort, an indoor relative humidity of 30 % or more. The dew point temperature of such indoor air is 2°C (35°F) or warmer. Figure 18 shows the distribution of outdoor winter design temperature over North America. Thus, for essentially all buildings in North America the dew point temperature occurs within the roof during winter (i.e., a portion of the roof is colder than the dew point temperature during the winter design condition). If the design objective is to avoid condensation within the roof at any time, an essentially perfect vapor retarder and air barrier system must be provided in a portion of the roof that is warmer than the dew point temperature. The "Dew Point Method" described in Chapter 10 can be used to determine

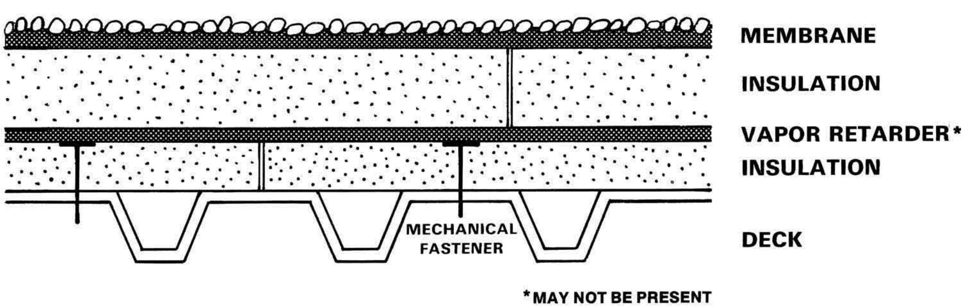


Fig. 17—Cross section of a compact membrane roofing system with a vapor retarder installed between insulation layers.

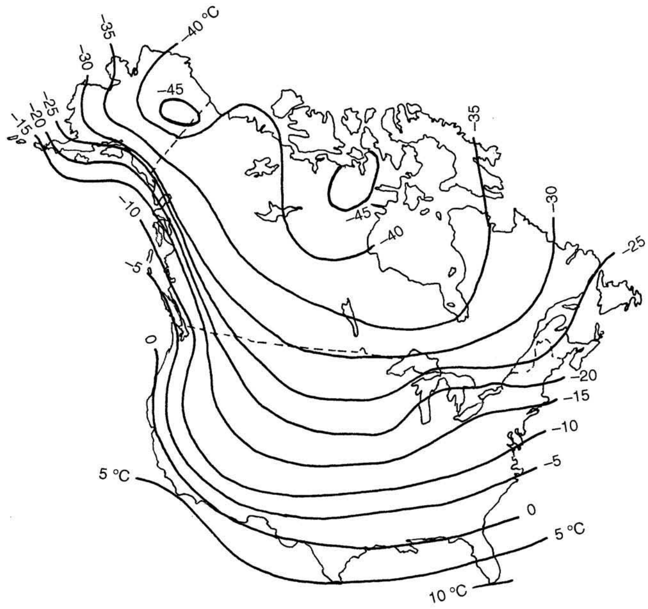


Fig. 18—Distribution of winter design temperatures over North America [82].

where in the roof condensation will form. However, it is not necessary to go through all those calculations to determine if a vapor retarder is needed since the answer is always, "yes."

Most compact membrane roofs are built without vapor retarders. They have not suffered as a result and, thus, it is clear that the design approach of *avoiding* condensation is overly conservative. It results in the provision of vapor retarders in essentially all membrane roofs, many of which are far better off without them, as will be discussed.

Various "relaxed" guidelines on when to use vapor retarders in compact membrane roofing systems have been summarized [4,77,89]. Philosophical guidance ranges from "When in doubt, leave it out" [8] to "When in doubt, think it out" [1]. The broad differences that exist among vapor retarder guidelines for compact roofs and the relatively small number of condensation problems in such roofs suggest that the more stringent guidelines are excessive. Guidelines range from the need for vapor retarders for the entire United States to only where the average January temperature is less than 2°C (35°F) or 4°C (40°F) or 7°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."

For many years, NRCA has recommended installing a vapor retarder with a permeance of 28 ng/(s·m^2·Pa) (0.5 perm) or less, only when the average January temperature is below 4°C (40°F) (Fig. 19) *and* the indoor relative humidity in winter equals or exceeds 45 % [4]. These *NRCA Guidelines* have advocates, but that guidance 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 [90]. Weather records were analyzed such that the entire winter was examined, not just the coldest portion. Seasonal wetting and drying potentials were determined. Figure 20 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. 20(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 dry-

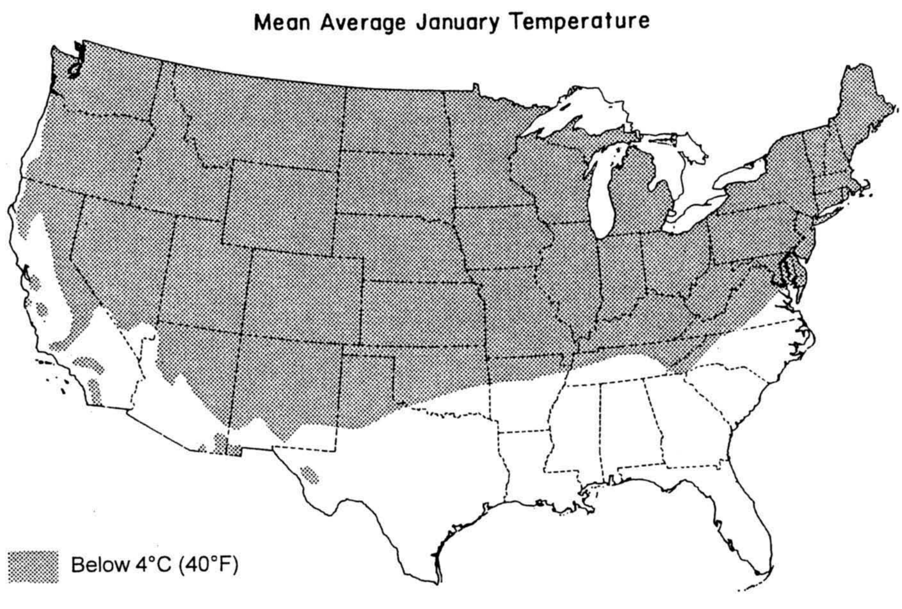


Fig. 19—Area of the United States that has a mean average January temperature below 4°C (40°F).

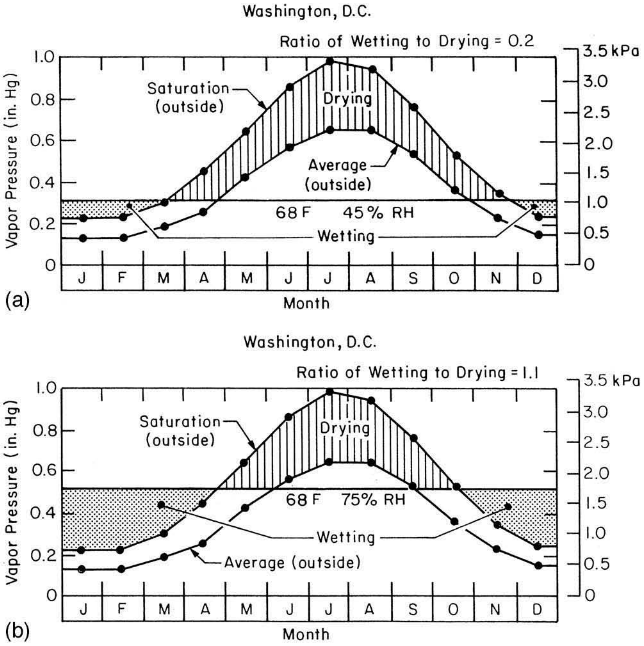


Fig. 20—Wetting and drying potentials for roofs in Washington, DC, with indoor relative humidities of 45 and 75 %: (a) Indoor relative humidity 45 %; (b) indoor relative humidity 75 %.

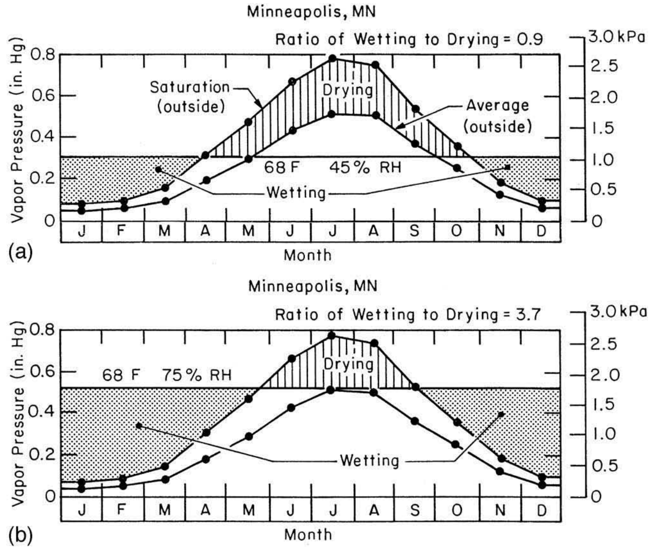


Fig. 21—Wetting and drying potentials for roofs in Minneapolis, Minnesota, with indoor relative humidities of 45 and 75 %: (a) Indoor relative humidity 45 %; (b) indoor relative humidity 75 %.

ing areas) is 0.2. When the relative humidity below the roof increases to 75 % [Fig. 20(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.

Figure 21 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.

Figures 20 and 21 show 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 [82]. That map is presented in Fig. 22.

Using this map, designers can see that compact membrane roofs of 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. For example, in Tennessee the indoor RH needs to be about 60 % before a vapor retarder is needed.

The Fig. 22 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. 22 should be corrected using Fig. 23. For example, in New York City the Fig. 22 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. 23 show how this was determined. If Figs. 22 and 23 indicate that a vapor retarder is needed, Fig. 24 can be used to determine how close to the cold side of the roof it can be placed and still serve its intended purpose. For example, if Figs. 22 and 23 indicate that the maximum indoor relative humidity (RH) without a vapor retarder at the geographical location in question is 30 %, and the indoor RH of the building in question must be 45 % due to the presence of computers and other equipment therein, Fig. 24 indicates that no more than 62 % of the thermal resistance (R-value) of the roof can be below the vapor retarder; that is, at least 38 % of the R-value of the roof must be above the vapor retarder. If the total thermal resistance (R-value) of the roof is 4.4 m^2K/W (25 F°·h·ft^2/Btu), up to 2.6 m^2K/W (15 F°·h·ft^2/Btu) of that can be below the vapor retarder. Figs. 22–24 are known as the *CRREL Guidelines*.

There are numerous reasons for using two or more layers of insulation with their joints staggered in compact membrane roofs [91]. In most roofs that need a vapor retarder according to the *CRREL Guidelines*, the vapor retarder does not need to be placed directly on the deck but can go in between the layers of insulation. It is advantageous to place the vapor retarder *not* on the warm side of the roof where it is vulnerable and hard to build but in as *cold* a place in the roof as the guidelines allow since, there, it allows a larger portion of the roof to be "self-drying." It also reduces the amount of insulation that is apt to become wet if the waterproofing ability of the roof membrane is compromised.

In a couple of minutes, Figs. 22–24 can be used to determine if a vapor retarder is needed and where in a compact membrane roof it can be located. Using that guidance many

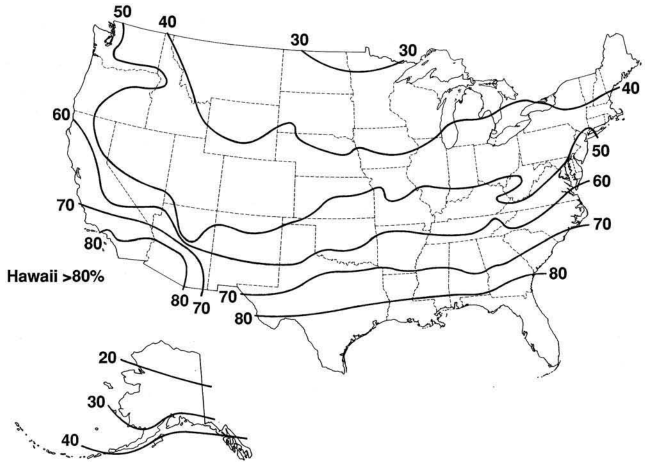


Fig. 22—Indoor relative humidities at 20°C (68°F), above which a vapor retarder is needed in membrane roofing systems. If the indoor temperature is not 20°C (68°F), use Fig. 23 to modify these values.

roofs do not need vapor retarders and for those that do, considerable flexibility is provided as to where in the roof the vapor retarder can be placed.

Oak Ridge National Laboratory (ORNL) has also developed a diffusion-based method for determining if vapor retarders are needed in compact membrane roofs [89,92]. The *ORNL Guidelines* also consider seasonal wetting and drying cycles but use hourly data rather than the monthly averages used in the *CRREL Guidelines*. In addition, the *ORNL Guidelines* consider the specific moisture-storing ability of each component of the roof while the *CRREL Guidelines* assume the same moisture-storing ability for all roofs.

The *ORNL Guidelines* can be utilized by going to

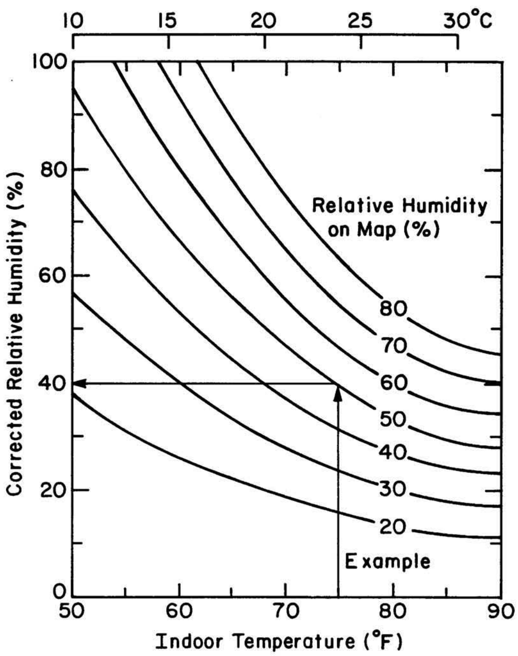


Fig. 23—Graph for correcting the mapped values in Fig. 22 for indoor air temperatures other than 20°C (68°F).

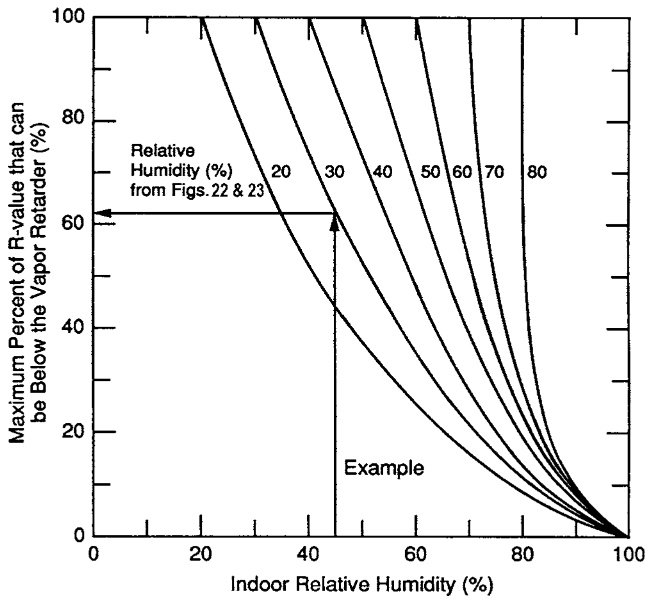


Fig. 24—Graph used with Figs. 22 and 23 to determine the maximum percent of the thermal resistance of the roof that can be on the warm side of the vapor retarder.

www.ornl.gov/roofs+walls. Using them, various designs can be tried with the possibility that certain combinations of materials can preclude the need for a vapor retarder. ORNL is a strong proponent of self-drying roofs [93,94] which cannot contain vapor retarders since they thwart downward drying into the building during the summer. The ability of the *ORNL Guidelines* to further reduce the number of roofs that need vapor retarders makes those guidelines of particular value to individuals interested in self-drying roofs.

NRCA [4] overviews the four methods mentioned in this chapter for determining if a vapor retarder is needed in a compact roof. NRCA calls the Dew Point Method the *ASHRAE Guidelines*. Of the four methods, NRCA promotes use of its guidance but indicates that it is "not supported by a great deal of scientifically-developed data." NRCA suggests that their guidelines be "further confirmed" using the *CRREL Guidelines* or the *ASHRAE Guidelines*. NRCA also indicates that the *ASHRAE Guidelines* are "extremely conservative."

NRCA acknowledges that the *ORNL Guidelines*, which are based on mathematical modeling and computer simulations, consider more variables than the other methods. However, because the number of choices is limited and the answer is not clear, NRCA does *not* recommend using the *ORNL Guidelines*.

ORNL, on the other hand, feels that its guidance should replace all other existing guidelines.

Thus there is general agreement that the Dew Point Method (i.e., the *ASHRAE Guidelines*) is far too conservative (i.e., its zero tolerance for moisture within a compact membrane roof is an impractical and unnecessary design constraint). The majority believe that the *CRREL Guidelines* are better supported and better calibrated to the collective judgment of the roofing industry than the *NRCA Guidelines* are and, thus, should replace them. There is significant disagreement about use of the *ORNL Guidelines*. They are the most controversial but they may be the most accurate.

All things considered, I recommend the following: Use the *CRREL Guidelines* to quickly determine if a vapor retarder is needed and, if so, where it can be located within the roof. With the location of the site and the indoor temperature and relative humidity in winter established, this will take only a few minutes. *If* the finding is that a vapor retarder is *not* needed, there is some, but not much, incentive to go to the time and effort of checking that finding by using the *ORNL Guidelines* since they are even more strongly focused on eliminating vapor retarders than the *CRREL Guidelines* are. However, *if* the *CRREL Guidelines* indicate that a vapor retarder *is* needed and the disadvantages of including it are thought to be significant, alternative roofing configurations should be studied using the *ORNL Guidelines*. By doing that, it *may* be possible to find a way to eliminate the vapor retarder.

The *CRREL and ORNL Guidelines* each have strengths and weaknesses. When both methods give the same answer, that is nice to know. When they give different answers, that is also valuable since that difference can be considered when deciding which way to proceed. Fortunately, in many situations, the *CRREL* and *ORNL Guidelines* give the same answer and that answer is that many compact membrane roofs do not need vapor retarders.

It is very important to realize that all of the above guidance applies *only* to compact roofing systems where air leakage is well controlled. When these guidelines are used and problems develop, "convective air currents," "many small openings and small voids in which water vapor could easily flow," and "air infiltration" are the common cause [95].

When they are not needed, vapor retarders should not be used since they are expensive to install properly and they allow "cancers" of wet insulation to grow within roofs having membrane or flashing flaws. Flawed roofs without vapor retarders *may* leak water into the building sooner, limiting the lateral extent of wet insulation. However, large areas of wet insulation do form within some roofs without vapor retarders. Thus, there is no guarantee that, by eliminating a vapor retarder, wet insulation will be prevented from forming in a roof.

A flawed compact membrane roof without a vapor retarder *may* be able to dry out downward in warmer weather. However, the flaw, not the vapor retarder, is the root cause of this problem and there is merit in focusing attention on finding such flaws and eliminating them rather than expecting a vapor-retarderless roof to survive for long periods without the need to inspect, maintain and repair its waterproofing. Several methods are available for finding wet roof insulation and membrane flaws. They are discussed at the end of this chapter.

Since most moisture problems in compact membrane roofing systems are from external sources, not condensation of indoor moisture, the highest priority is to build the waterproofing membrane as resistant as possible. A proven way to do this is to provide it with a strong, stable substrate. When bituminous membranes are used, an excellent way to achieve stability is to mechanically attach the lower layer of insulation to the deck, which is commonly steel, then adhere the upper layers of insulation with hot asphalt. Figure 17 shows this configuration and Fig. 25 shows insulation being installed this way. In the past, a solid mopping of hot asphalt between layers of insulation, without the addition of at least one layer of felt, has not been considered to be a vapor retarder since it may lack continuity at board edges. However, in a compact membrane roof such a solid mopping of hot asphalt can be a very effective moisture barrier. As such it prevents the upper portion of the roofing system from self-drying but, by improving the membrane's longevity, it reduces the *greater* risk of this becoming a "self-wetting" roof. Eliminating such beneficial, impermeable layers because they prevent self-drying is not recommended. If a self-drying roof is required, other systems, such as mechanically attached single ply membranes, should be considered.

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 compact membrane roof needs a vapor retarder it *may* not be essential to seal the vapor retarder at flashings and penetrations so that it can resist air leakage if the membrane and its flashings act as an air barrier system. However, sealing the vapor retarder is not a bad idea and may be quite beneficial if the membrane is mechanically-attached rather than fully-adhered since a membrane that is not fully-adhered may billow in the wind. 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.

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 50 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

Fig. 25—Using hot asphalt to adhere a layer of insulation to mechanically attached insulation below. (Courtesy of Dick Fricklas who advises that safety issues such as the unguarded perimeter and unprotected forearms are present.)

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

By definition, a compact membrane roofing system contains no air spaces and is thus very difficult to ventilate. If it has no vapor retarder, it should not be ventilated since ventilation may cause more harm than good by promoting air leakage [96].

The incorporation of a vapor retarder in a compact roofing system (Fig. 17) creates a potential trap for vapor between the waterproofing membrane and the vapor retarder. In the past, the need to vent potential vapor traps in roofs to prevent the accumulation of moisture within them and avoid the possibility of pressurization was considered essential by NRCA and others [1,8].

Attempts to provide ventilation include the use of kerfed wood nailers 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 have been promoted (Fig. 26). 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 were 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.

It is argued that the installation of breather vents or other venting features in compact roofing systems makes little sense [97].

Until the mid-1990s the National Roofing Contractors Association (NRCA) recommended use of one breather vent for every 93 m^2 (1000 ft^2) of roof surface for roofs with vapor retarders, but this practice was seldom followed. Thousands of compact membrane roofs with vapor retarders exist without venting features at their perimeter or breather vents. There is no evidence that these roofs perform any worse than others with vents. If anything, just the opposite is true since a membrane perforated with a field of breather vents contains many penetrations that may be flawed, allowing external moisture to enter the system. NRCA no longer recommends such vents, indicating instead that research has shown that they are "not as effective as the roofing industry previously believed" [4].

It is not a problem if flaws in an imperfect vapor retarder allow *small* quantities of moisture to enter a compact roofing system in cold weather since those flaws do not close once the moisture has entered. When vapor drive reverses in warmer weather, the system can dry out downward through the same flaws [90].

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 [98]. Figure 27 shows that the pressure in a blister is essentially unrelated to that in the insulation below. The nearby breather vent prevented pressurization of the insulation but the blister formed and grew nonetheless.

As shown in Table 1, the permeance of a bituminous built-up membrane is essentially zero [8,76], but that of rubber and plastic single-ply membranes is somewhat higher [7]. 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 by upward migration of the moisture in it, through the "breathable" membrane. However, calculations [99], tests [22], and experience by the roofing industry [100] 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 [101,102]. Years ago it was speculated that this was 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, further study concluded that "moisture can accumulate, but not a significant amount" [101].

Compact membrane roofing systems, even those containing potential vapor traps, should *not* be vented. Nothing should be done that reduces their resistance to air leakage.

Improvements

Insulation is best attached to steel decks by mechanical fasteners. If a vapor retarder is placed between the deck and the insulation, it will be penetrated by the 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. 22 and 23, 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. 17, the vapor retarder is not violated by mechanical fasteners. This approach (with or

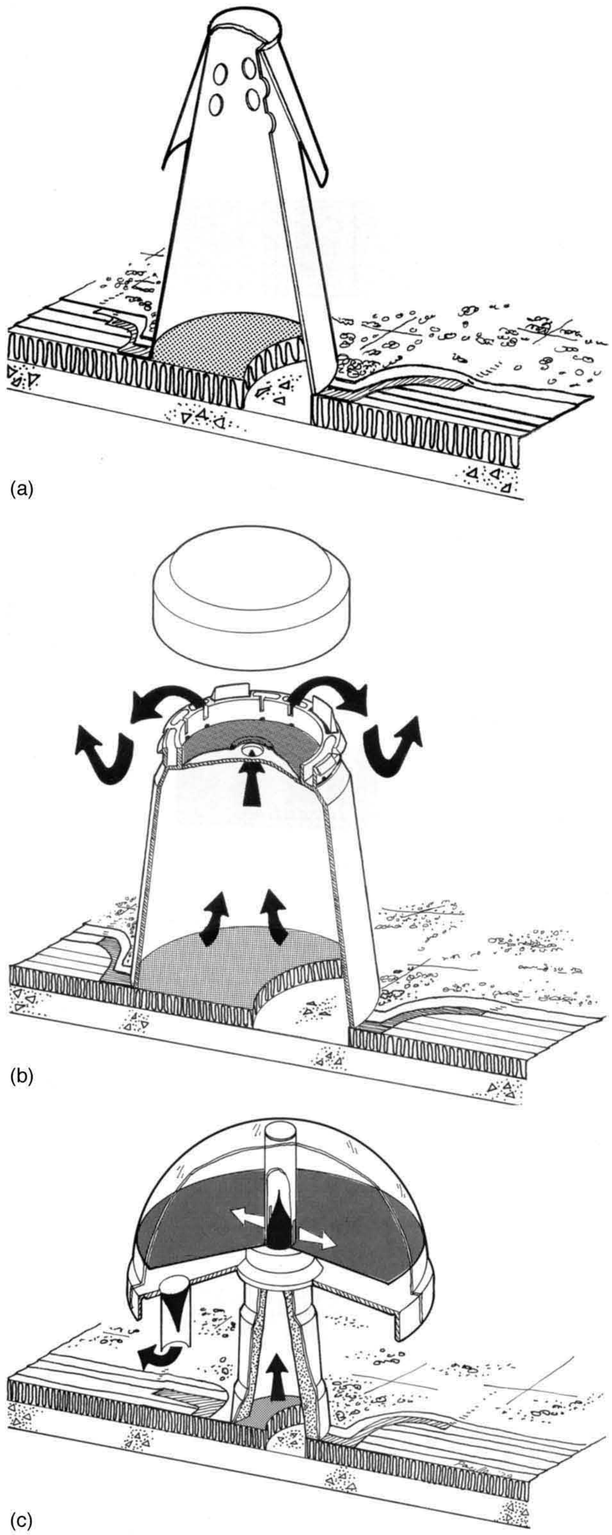


Fig. 26—Two-way, one-way, and solar-powered roof breather vents: (a) Two-way vent; (b) one-way vent; (c) solar-powered vent.

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

Fig. 27—Breather vents do not prevent membrane blistering.

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, strengthens the roof and improves its resistance to moisture migration. Whenever possible, the nail-one, mop-one method of construction should be used.

If Figs. 22 and 23 indicate that a vapor retarder is barely needed, Fig. 24 will indicate that 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. 22 and 23, the vapor retarder must be placed closer to the warm side of the roof in winter. By placing a vapor retarder as close to the cold side as Fig. 24 allows, any flaws in the waterproofing can wet the least amount of insulation and the greatest portion of the roof will be "self-drying."

A protected membrane roofing system is shown in Fig. 28. 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, facilitating drainage. The waterproofing membrane is below at least some of its insulation. There, 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 is not exposed to deleterious solar effects or subjected to the mechanical abuse that exposed membranes suffer. A protected membrane should be fully adhered and sloped to drain to reduce the adverse effects of any flaws in it and its flashings. Since it is more often in a damp environment, it should *not* be made of moisture sensitive components. Flashing materials and seam sealants should be carefully chosen since they are not commonly called upon to survive in such an environment. Rather than find out that a protected membrane leaks after the insulation, filter fabric and ballast have been installed, flood testing or electronic leak detection testing should be considered before placing all those materials above it. 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. 22–24.

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 [1,53–55,103–106] 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 [107]. However, in most circumstances, only 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 [104]. 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. Over much of North America, pavers must be able to resist deterioration by freeze-thaw (see Fig. 9).

The rain and meltwater that may wet the insulation above a protected membrane also may short-circuit some of its insulating ability [54,108]. A reduction in thermal resistance of 20 % has been measured during a moderate rain [108]. 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 [54,107]. Design guidelines for protected membrane roofing systems have been developed in Norway [103].

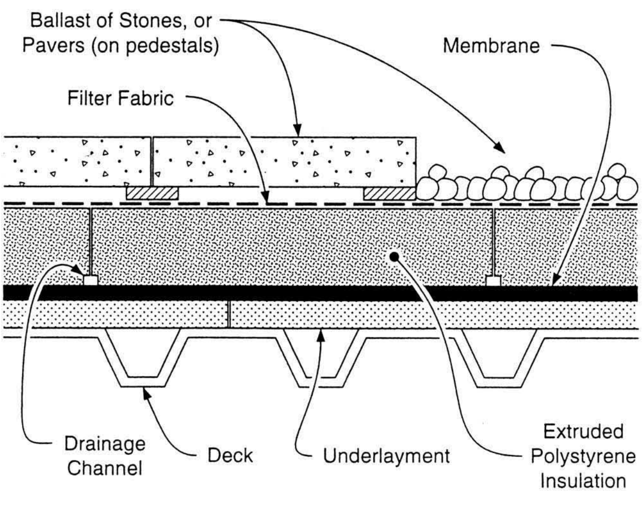


Fig. 28—Protected membrane roofing system.

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 [109]. 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

Exposed, loose-laid, and mechanically attached single-ply roof membranes also have some advantages because they are not as sensitive to substrate movements as are fully-adhered membranes. However, their lack of complete attachment somewhat increases the potential for air leakage and condensation problems.

Winds cause portions of mechanically-attached membranes to flutter and lift on occasion. This can draw moist indoor air up into the roof and move it laterally under the membrane. Condensation on the underside of the membrane can result. When a membrane can billow, its ability to serve as an air barrier is diminished [81]. The same is said for ballasted membranes but this is expected to be far less of an issue for them since it takes much stronger winds to initiate lifting of a ballasted membrane.

Beads of water have been found on the underside of a 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 [101,102]. Probably leakage of indoor air, not diffusion of outdoor water vapor, has brought moisture to the underside of the EPDM. Air leakage is often present when condensation problems occur. Control of air leakage into loose-laid and mechanically attached membrane roofing systems can be achieved by constructing their perimeters air tight and by using two layers of insulation with seams staggered with, perhaps, an air barrier in between them. It is somewhat easier to apply self-drying principles to these kinds of membranes than to fully-adhered membranes. However, fully-adhered membranes are better able to resist lateral movement of moisture that enters at membrane and flashing flaws.

Metal Roofing

Structural standing seam metal roofing is commonly used without a deck under the fibrous glass batt insulation below the metal. That insulation comes with a low-permeability vapor retarder whose joints are sealed during installation since it must also serve as an air barrier. Such metal roofs have some of the features of *compact* membrane roofs, but not all since (1) a roof deck is not present; (2) permeable, batt insulation is used; and (3) some air spaces are probably present directly under the metal (e.g., under the standing seams when they are of trapezoidal configuration). When the vapor retarders of such roofs are not well sealed (i.e., when they are not also air barriers due to openings at seams and around penetrations), condensation problems are likely since indoor air can leak by them. To enhance the insulating ability of such roofs, additional batt insulation and large sheet vapor retarders can be added below. When they are properly installed, they improve the thermal and moisture resistance of many buildings. However, such systems are risky where indoor humidities are high (e.g., swimming pools), especially in *cold* climates.

Most *structural* standing seam metal roofing, by virtue of the way it is installed directly on unrolled batts of fibrous glass insulation on low slopes, is not ventilated. Natural ventilation is slight on such slopes. Thus it is likely that ventilation will do little more than create moisture problems by promoting air exfiltration. When small, inadvertent air passages exist between the metal and the top of the insulation and the continuity of the vapor retarder is poor (i.e., it is not also an air barrier), the potential for moisture problems is high when the indoor relative humidity is high. Since low slope, *structural* metal roofing drains over cold eaves, large icings are likely in snow country as shown in Fig. 29. Water accumulates behind such icings. Due to the low slope, this water may overtop the standing seams near the eaves, subjecting them to hydrostatic pressure for long periods. Often this portion of the seam has to be hand sealed which does not produce as reliable a seam as mechanical seamers do. It is reasonable to expect that these *hydrostatic* metal systems can cope with standing water, now and then, just as *waterproof* membranes are asked to. But it is wishful thinking to expect that either of these systems, membrane or metal, can successfully sustain such forces for weeks at a time, winter after winter without developing leaks.

Fig. 29—Structural standing seam metal roof with severe icings along its eaves.

Compact Water-Shedding Roofing Systems

Description

A compact water-shedding roofing system such as that shown in Fig. 30 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.

Vapor Retarders and Air Barriers

Many water-shedding roofing systems have a higher vapor permeance and a higher air leakage rate than do membrane roofing systems. Much of their increased ability to pass moisture (i.e., to avoid trapping it) is due to the way they are assembled, which, for some, facilitates air leakage. A tile roof on battens and a wood shake roof with interlays of #30 felt is not an air barrier system. However, an asphalt shingled roof underlain with #15 felt and architectural standing seam metal panels on a slip sheet and #30 felt are vapor retarders and, acknowledging the contribution of their underlayment and deck, are reasonable air barrier systems as well. Thus, as a group, compact, water-shedding roofing systems have a wide range of air leakage and vapor retarding properties relative to the consistent air and vapor tightness of compact membrane roofing systems. As a group, water-shedding systems have a greater need for separate air barrier systems, since they are not as air tight as waterproof membranes. Like compact waterproof membrane roofing systems, some compact, water-shedding roofing systems need vapor retarders but some do not. The conservative design approach is to provide *all* compact water-shedding roofing systems with air barrier systems but provide them with vapor retarders only if they would need them using the *CRREL* or *ORNL Guidelines*, which assume that the roofing acts as a vapor retarder.

Figure 30 shows a tongue and groove wood deck. Such decking should not be considered to be an air barrier since seasonal and long-term shrinkage create gaps between the wood planks.

Ventilation

When air leakage and vapor diffusion are adequately handled, which is not difficult, it is not necessary to ventilate compact water-shedding roofing systems to avoid condensation problems. However, other reasons such as code requirements, manufacturer's warranty requirements, or the need to avoid ice damming along eaves, may justify ventilation.

When compact water-shedding roofing systems are ventilated, they are, strictly speaking, no longer "compact." Where ventilation is desired, a framed roofing system is usually more economical than a compact roofing system.

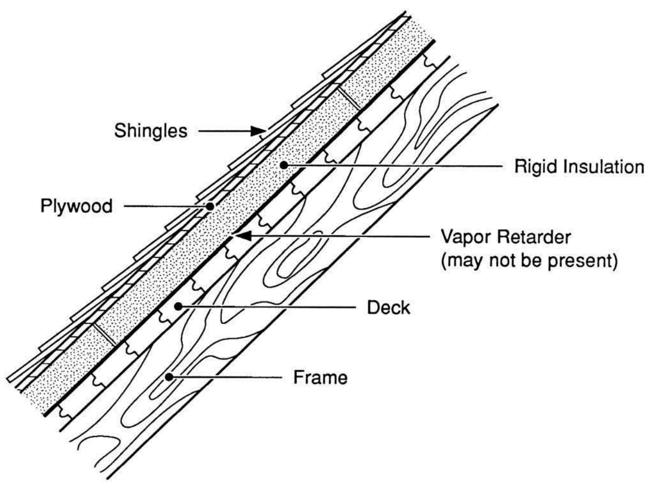


Fig. 30—Compact water-shedding roofing system.

Insulation boards are available with a wavy upper surface that creates airways below the roof deck placed on them. Other venting composite insulation boards have wood spacers and OSB or plywood attached to their top side for the same purpose. These specialty products reduce the time devoted to "stick-building" airways using expensive on-site labor. However, they have some moisture-related limitations; underlayment cannot be installed at the base of such pre-built airways and the straight-through nature of all seams from the interior up through the airway and, for the latter product, the roof deck, invites air leakage problems.

Ventilation guidelines (e.g., sizing inlet, exhaust openings, and airway heights) are presented in a subsequent section of this chapter dealing with framed roofing systems.

Structural Insulated Panels

Rather than use separate decking and insulation as shown in Fig. 30, the roof can consist of structural insulated panels (SIPs) supported on purlins or beams. The panels usually have top and bottom OSB surfaces adhered to a core of expanded polystyrene, extruded polystyrene, polyurethane, or polyisocyanurate insulation. Each panel has a low vapor permeance and a very high resistance to air leakage. However, some SIP assemblies have experienced serious condensation problems as a result of air leakage where the panels are joined together. A variety of joints are being used, some of which work better than others.

Often SIPs are used on residential timber frame construction. It may take some years for such timber frames to stop shrinking as they slowly dry out. This can gradually open up air leakage paths in tight, well-built SIP systems supported on large timbers.

A few years ago in Juneau, Alaska over 60 buildings, mostly homes less than seven years old, built with SIP roofs, suffered moisture problems ("roof rot") to the degree that most of the weak wet panels had to be removed. Juneau, Alaska's capital in its southern "panhandle," has a cold, snowy, very wet maritime environment. The panels were from different manufacturers but most had 0.25 m (10 in.) thick expanded bead polystyrene cores and OSB surfaces. Roof slopes were commonly 18 degrees (4 in./ft) with asphalt-saturated felt and asphalt shingles nailed directly to the top surface of the panel (i.e., the roofs were not ventilated). Many of the buildings had a rather high indoor relative humidity with clothes driers in some vented directly indoors.

While improper protection of some of the Juneau panels occurred before they were installed and prior to the installation of the roof coverings, the primary cause of failure was air leakage at panel joints. Some panel edges were found to have been improperly trimmed at the factory for the splines, dimension lumber or wooden I-beams used to join them. However, the principle cause of problems was shoddy installation. Where splines or seals were loose, missing or discontinuous, there was damage. Where joints were well fitted, well sealed, and located in the lower (i.e., warmer) half of the panel, no moisture damage occurred. The inability of even trained, conscientious individuals to install SIP systems air tight in this wet environment was offered as an explanation, but the existence of other SIP buildings in Juneau free of problems contradicts this. Nonetheless, many of the owners chose not to replace their roofs with SIP systems.

Most problems were concentrated near the ridge so they were thought *not* to be related to waterproofing issues or ice damming. However, many roofs were replaced with ventilated systems to minimize icings, remove indoor moisture that might get into the roof, and meet shingle manufacturers warranty requirements. Joints of replacement SIPs were carefully sealed and a polyethylene vapor retarder was installed under them, in spite of concerns by some that it would prevent downward drying in warm weather.

Clearly, SIP systems must be carefully built and installed so that the assembly can resist air leakage.

SIP systems have been used for buildings at the summit of the Greenland Ice Cap and at the South Pole in Antarctica, where some panels arrived by parachute.

Metal

Most *water-shedding* metal roofing systems are placed on *framed* roofs. However, they are also used above steel decks, rigid board insulation and underlayment in *compact* roofs. Because (1) some narrow air spaces commonly exist below the metal roofing, (2) roof edges are not as resistant to air movement as those of most *waterproof* membrane roofing systems, and (3) at night, the metal roofing often cools to temperatures well below outdoor ambient temperatures, they have a somewhat higher risk of incurring condensation problems than do most other *compact* membrane roofs with the same level of air leakage resistance below. Moisture that reaches the underside of metal panels can corrode them rapidly as shown in Fig. 8. When moisture is controlled, such problems can be avoided.

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. 6 or an attic with the insulation between ceiling joists as shown in Fig. 31. The space between the roof deck and the insulation may be ventilated as shown in those two figures, or it may not be ventilated.

Air Leakage

It is difficult to control air leakage in framed water-shedding roofing systems since many air leakage paths are created in them 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.

Places where warm moist air within a building can enter its attic are shown in Fig. 31. 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. Holes cut for 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 ceiling but by air leakage [110–112]. 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 *mixed* climates, attic ventilation may be able to remove all the moisture from exfiltrating air. However, in cold

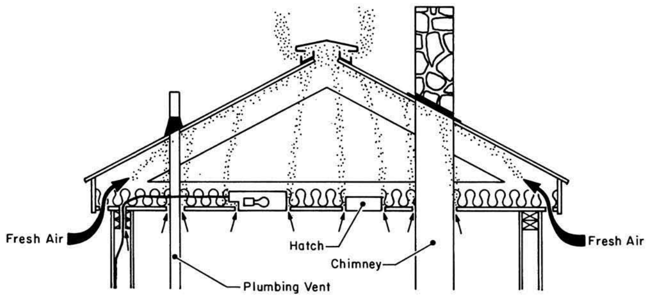


Fig. 31—Air leakage paths into an attic.

regions large quantities of frost can grow even in well-ventilated attics when hatches, electrical fixtures, and pipes are not well sealed. Figure 32 shows an example. In warmer weather the frost melts, the insulation is soaked, the ceiling is damaged, mold grows, 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.

Current design and construction practices for sealing penetrations are improving but gaps still exist in new ceilings through which indoor moisture enters the roof. Figure 15 shows a typical unsealed pipe penetration. Seals against air leakage are needed at these locations. Guidelines are available on how to achieve this by creating air barriers out of the polyethylene vapor retarders used in wood-frame construction [113,114]. However, in some *cold* and most *mixed* climates the use of polyethylene as a roof/ceiling vapor retarder may be inappropriate since it prevents downward drying in warm weather. "Smart" vapor retarders, i.e., materials with higher wet than dry permeances, such as the asphalt-kraft papers on batt insulation, may be more appropriate since they allow some downward drying in warm weather. However, if they increase air leakage by having more seams and otherwise lacking continuity, they well may do more harm than good. The "bottom line" is, once again, the necessity of controlling air leakage.

Vapor Retarders

In *hot-humid* climates, moist summer air should be prevented access to cool portions of roofs above air conditioned spaces. If a framed, water-shedding roofing system is not ventilated, some but not all kinds of roofing provide both the vapor retarder and, when penetrations and such are sealed on the warm (i.e., top) side of the insulation, the air barrier system.

Past guidelines that did not call for a vapor retarder in *hot-humid* climates have been mistakenly construed by some designers and builders to mean that no provisions need to be taken to control air leakage. In such cases some moisture problems have developed. When such roofs are ventilated, the roofing's ability to serve as a vapor retarder or an air barrier is short-circuited and moisture barriers are needed below the ventilated space (i.e., above the insulation) to prevent condensation in the insulation if the building is air-conditioned. Use of insulations, such as extruded poly-

Fig. 32—Attic frost caused by leakage of indoor air by a ceiling with a vapor retarder but not an air barrier.

styrene, with low air and vapor permeances should be considered in the lower portion of the ceiling. It may be that a vapor retarder is not needed but an air barrier is. If so, a breathable air barrier allows upward drying when the air is cooler outside.

For framed water-shedding roofing systems in *cold* and *mixed* climates, a vapor retarder having a permeance of 28 $ng/(s \cdot m^2 \cdot Pa)$(0.5 perm) or less has usually been required along with ventilation. However, the technical need to ventilate many such roofs is now questioned as discussed earlier in this chapter. If such roofs are not ventilated, it is harder to remove any indoor moisture that gains access to them and thus the "as built" quality of the vapor retarder and, in particular, the air barrier system becomes a critical issue as does the ability of the roof to remove, in warm weather, any indoor moisture that enters it in winter. Thus there is incentive to use "smart" vapor retarders in such roofs instead of vapor-trapping polyethylene.

In *very cold* climates (e.g., the colder portions of Alaska and Canada), sustained periods of cold create the potential for a significant upward flow of indoor moisture into roofs. There, diffusion alone may introduce enough moisture to create problems. Past guidance has focused on the need for vapor retarders with a permeance as low as 6 $ng/(s \cdot m^2 \cdot Pa)$ $\times$(0.1 perm). This precludes the use of most any material but polyethylene and foil-backed kraft paper. Such tight vapor retarders are not "smart" and thus have no ability to remove moisture from the roof in summer. If the very low permeance values some people recommend in *very cold* climates are accepted, it is hopelessly inconsistent to not also tighten up air leakage by a factor of ten. Since "off-season" moisture removal is always a worthy design objective, there is extra incentive to ventilate such roofs. Another reason to ventilate roofs in such places is to control icings at their eaves.

Ventilation

Reasons for and against roof ventilation are summarized in the "To Ventilate or *not* to Ventilate, That is the Question" section earlier in this chapter. The "Building Codes" section shortly thereafter, presents various requirements for ventilation of attics and cathedral ceilings when vapor retarders are absent or present. As stated therein, there are a number of inconsistencies among these requirements. Considering the relatively small amounts of moisture that enter roofs by diffusing through the elements of a roof, the need to vary the size of ventilation systems based on the absence or presence of a vapor retarder is questioned except, perhaps, in *very cold* climates. The quality of the roof's *air barrier system* is an order of magnitude more important issue that should determine the amount of ventilation needed. For an attic lacking reasonable control of air leakage, the ratio of 1/150th may not provide enough ventilation to avoid moisture problems. However, the solution is not to provide more ventilation but to provide a better (i.e., tighter) air barrier system. Conversely, for a roof with a well-sealed air barrier, halving the ventilation area from 1/150th to 1/300th may still result in much *more* ventilation than is needed to control moisture.

Most of the ventilating area requirements of codes and of manufacturers of roofing products will provide more than enough ventilation to prevent moisture problems when reasonable air barrier systems exist.

Ventilation increases as roof slope increases because stack-induced flow (i.e., chimney draft) increases with slope. Chimney draft also increases in cold weather, enhancing ventilation. 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 air intakes all along the eaves and exhaust openings of about the same size all along the ridge are usually the most effective way of ventilating an attic. Of course, if there are two eaves as is common for gable roofs, the openings at the ridge should equal those along both eaves.

For small buildings, louvers having a total open area of 1/300th or 1/150th of the ceiling area, located on opposite ends of the attic near the ridge, may be able to 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 continuous along all eaves and exhausts continuous all along the ridge.

Intakes and exhausts of roof ventilation systems must be designed to resist driving rain and blowing snow. Some continuous ridge vents do not do this well. I have an aversion to low shingle-over ridge vents because of this and tests that show they provide less than half the airflow of higher-aspect-ratio ridge vents with baffles such as the one shown in Fig. 33. The "Boston Cap" (Fig. 34) [115] is a wooden version, popular in the mountains of the West where snow is deep

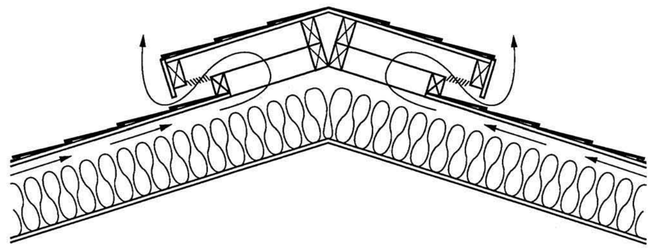


Fig. 34—Wooden "Boston Cap" continuous ridge vent.

and remains on roofs for long periods thus presenting a greater risk of blocking the ventilation system. The well sheltered outlet openings of the "Boston cap" resist blockage by snow.

Winds often keep portions of a continuous ridge vent clear of snow. However, even when a ridge vent is covered by snow, some air can pass out of the vent through the snow. In areas experiencing deep snowfall, roofs sheltered from winds may need some additional provision to ensure adequate ventilation with the ridge buried under deep snow. Secondary exhaust openings can be provided by extending each end of a Boston Cap out beyond the end of the roof and opening its underside there. At very high elevations, such as in the High Sierra, where dramatic diurnal temperature changes occur, "cold," ventilated roofs are promoted as are venting cupolas along the ridge as shown in Fig. 35 to account for deep burial of continuous ridge vents by snow [116]. Plumbing vents, bathroom exhaust fans and gas-fired appliances are also being vented effectively by use of such ridgeline structures.

Cathedral ceilings can be ventilated by creating a continuous air space between the deck and the top of the insulation (Figs. 6 and 7). Some guidelines indicate that a 10-mm (3/8-in.) deep airspace will suffice [117]. However, since such narrow spaces are difficult to achieve, more common minimums are 38 to 50 mm (1.5 to 2 in.). That space must extend *unobstructed* from the eaves to the ridge over the entire roof. Deliberate steps must be taken to ensure that roof insulation does not block the airway. If a chimney, skylight, dormer, or roof hip blocks ventilation, notches or holes

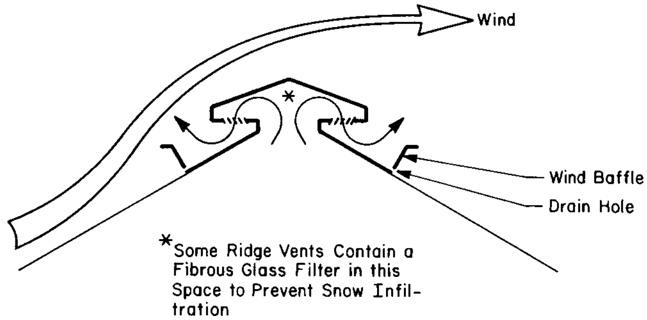


Fig. 33—Baffled ridge vent configured to prevent ingestion of driving rain and blowing snow.

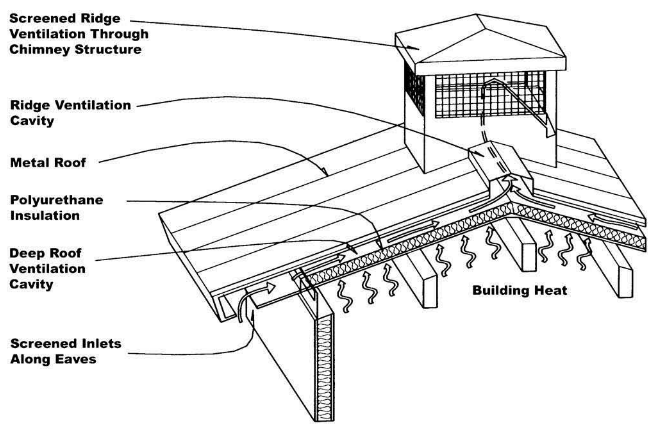


Fig. 35—Vented cupola used in the High Sierra where continuous ridge vents are often deeply buried by snow for long periods of time. (Courtesy of Ian Mackinlay Architecture, Inc.)

should be made in rafters to allow the air to complete its journey to the ridge [118]. The structural implications of such cuts should be considered.

At slopes below 14 degrees (3 in./ft), it is usually appropriate to interconnect all individual rafter spaces by installing purlins on the rafters before the deck is laid (Fig. 36). When valleys are present or where dormers block portions of the eaves, such purlins are needed to bring outdoor air into hard-to-reach portions of the roof (Fig. 37). At slopes less than 9.5 degrees (2 in./ft) it is quite important to interconnect all the enclosed rafter spaces as shown in Figs. 36 and 37. Additional information on ventilation of low-slope framed roofs is presented in the "Framed, Membrane Roofing Systems" section of this chapter.

Ventilating to Avoid Chronic Icings Along Eaves

Since snow is a good insulator, a warm (unventilated) roof tends to melt snow that accumulates on it even in relatively cold weather. Such melting 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 cold eaves, icicles and ice dams will develop (Figs. 1 and 29) that can result in roof leaks. Figure 38 shows how water ponds behind ice dams. 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 [13,115,119–123]. However, ventilation is not needed to control icings in every place where it snows.

Figure 39 shows two photographs taken within minutes of each other, of two identical, nearby buildings. One has large icicles and ice dams along its eaves while the other is ice-free. The chimney shown in the right photograph provides a clue as to why this difference occurred. Snow on that chimney indicates that that building was not being heated while the other one was. Figure 39 illustrates that building heat, not the sun, is the primary cause of such icings. Certainly, icings can form on unheated buildings and from solar heating, but they are usually small and infrequent and do not cause chronic problems. However, if heat-producing equipment is located in a ventilated attic, additional ventilation may be required [13,21].

Fig. 37—Use of purlins to ventilate a valley. Without some form of cross-ventilation, valleys are not ventilated.

The amount of icing can be reduced by improving the insulating ability of the roof, by preventing leakage of warm indoor air into the roof, and by using ventilation to dissipate building heat under the roofing. Icings can also be reduced by (1) making the surface of the roof slippery so that snow slides off, (2) by not installing gutters, and (3) 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. 40). All things considered, a 0.3 m (12 in.) overhang is a good minimum for most steep roofs in cold regions.

Guidelines have been developed for sizing roof ventila-

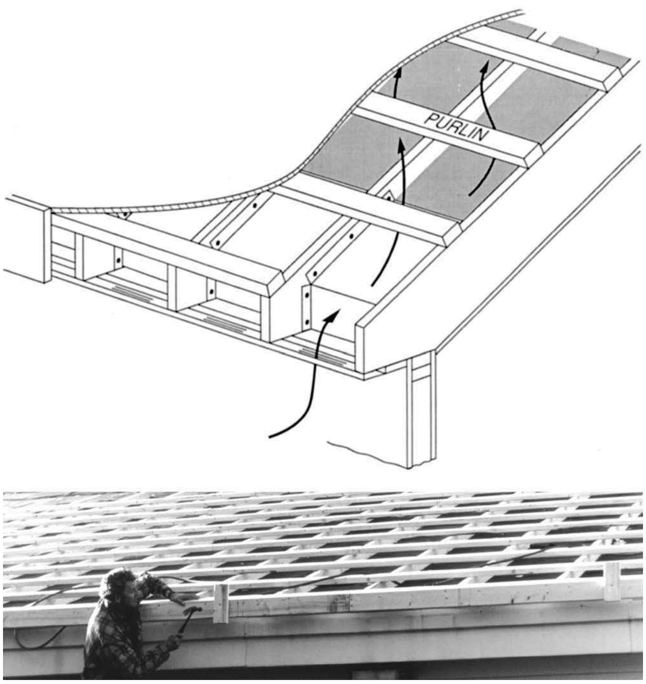


Fig. 36—Use of purlins to interconnect the ventilating airways of a framed roof.

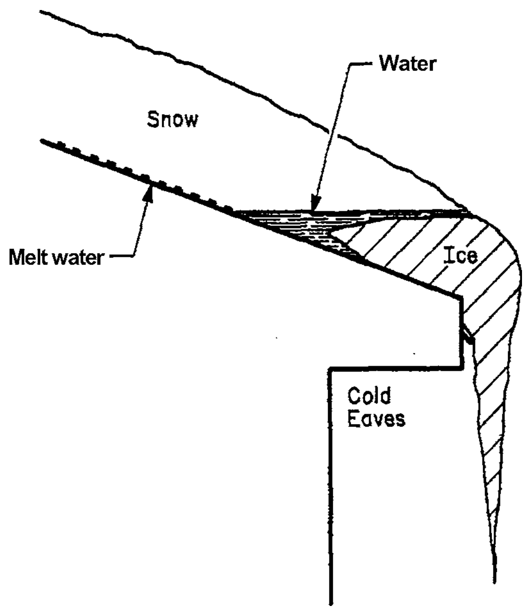


Fig. 38—Ice dam cross section.

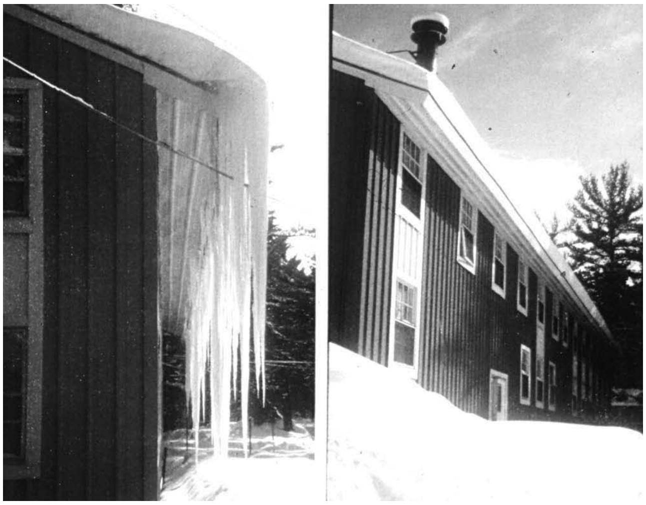


Fig. 39—Two identically constructed, nearby buildings photographed at the same time. The building on the right, with no icings, was unheated.

Fig. 40—Icings can form on walls if the eaves do not overhang far enough.

tion systems to prevent chronic ice damming along roof eaves for attics and cathedral ceilings [28]. They are based on data from instrumented buildings which indicate that such ventilation systems should be sized so that −5.6°C (22°F) outdoor air is warmed only to 0°C (32°F) as it exits the ridge vents. With all of the attic or cathedral ceiling colder than the freezing point, building heat does not melt snow on the roof. When it is colder than −5.6°C (22°F) outside, it is easier to remove heat with outside air since the air is colder. When it is warmer outside, it is unlikely that meltwater will refreeze along the eaves.

Figure 41 shows an attic and a cathedral ceiling at the "design" condition.

For *attics*, the total open area (A) of inlets along both eaves in mm^2/running mm of attic is related to the attic width (w) in meters, the roof slope (ø) in degrees and the thermal resistance of the ceiling (R) in m^2 K/W, as follows [28]:

$$A = 22.18(w/\tan \varnothing)^{0.5}/R \quad (1)$$

[In IP units: $A = 33.28\,(w/\tan \varnothing)^{0.5}/R$ with A in in.^{2}/running ft of attic, w in feet, ø in degrees, and R in F°·h·ft^2/Btu.]

The same net free area should be provided along the ridge to exhaust the air that enters along the eaves.

When "A" is determined as above, and findings are related to the area of the attic, ventilation ratios are found to range from about 1/100th to 1/300th for roofs having ceilings with thermal resistances ranging from 3.5 to 7.0 m^2 K/W (19 to 40 F°·h·ft^2/Btu) and slopes from about 14 degrees (3 in./ft) to about 45 degrees (12 in./ft). Less ventilation is needed for well-insulated ceilings and steep slopes.

For *cathedral ceilings*, the situation is somewhat more complicated since airflow is restricted, not just by the inlets and outlets, but also by the size and length of the airway. Airflow and heat gain equations have been developed and validated by cold room testing of instrumented airways [23]. Figures 42–44 present three of the twelve graphs prepared to facilitate use of this design procedure [23,28]. Both of these references are available at *http://www.crrel.usace.army.mil/techpub*. Once there, click on the "Structures" category.

Figure 42 is for roofs with a relatively low slope of 15 degrees (about 3 in./ft) and limited roof insulation of 2.6 m^2 K/W (15 F°·h·ft^2/Btu). Each curving line in Fig. 42 is for a different length of airway. As the length of an airway increases, the area of inlets (and outlets, which should be the

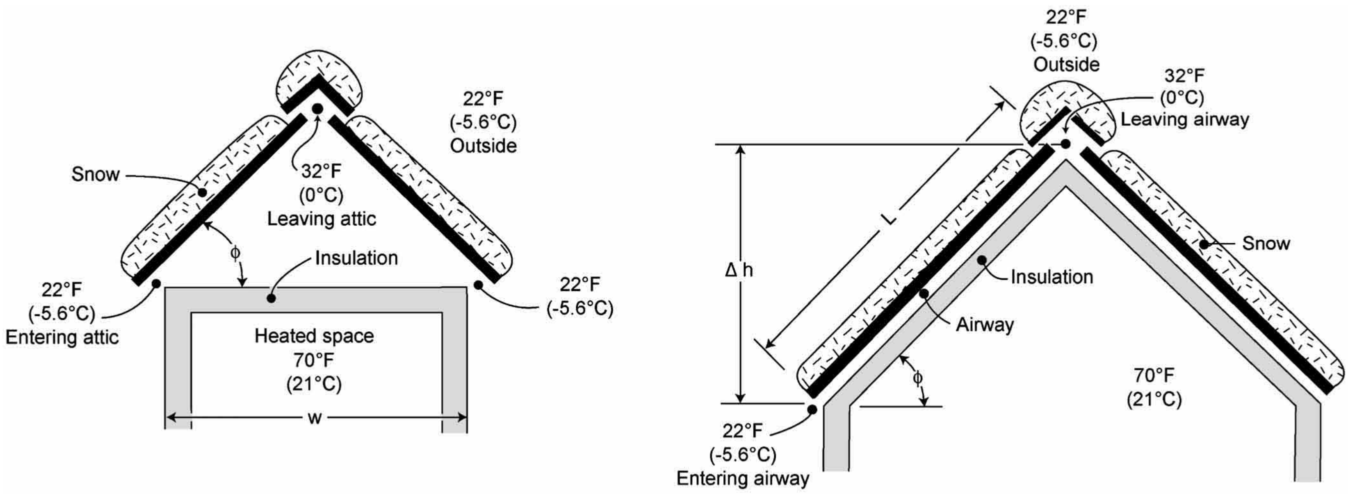


Fig. 41—A ventilated attic and a ventilated cathedral ceiling at the "design" condition.

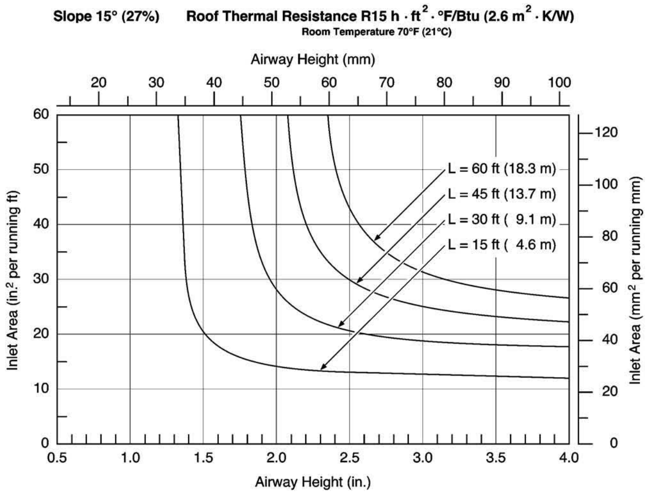


Fig. 42—Airway heights and inlet areas for cathedral ceilings with a slope of 15 degrees (about 3 in./ft) and a thermal resistance of 2.6 m^2 K/W (15°F·h·ft^2/Btu).

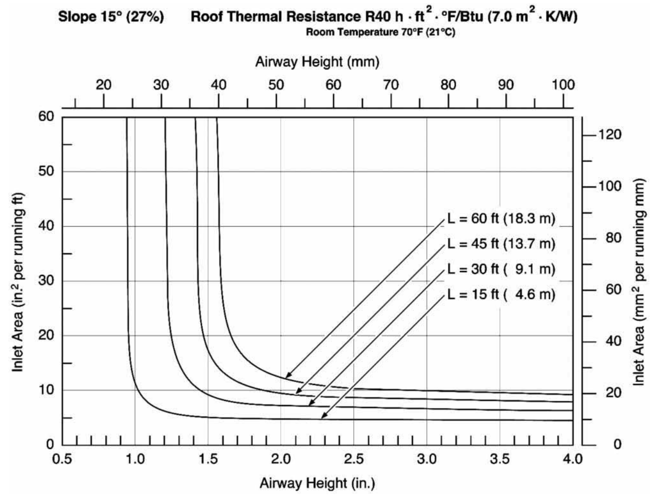


Fig. 43—Airway heights and inlet areas for cathedral ceilings with a slope of 15 degrees (about 3 in./ft) and a thermal resistance of 7.0 m^2 K/W (40°F·h·ft^2/Btu).

same size) and the airway's height must increase. The nearly horizontal portion of each curving line indicates that if the area of inlets is made too small, the height of the airway must increase greatly. Obviously, design should *not* be based on this portion of one of the curving lines. In a similar fashion, the nearly vertical portion of each curving line indicates that if the airway height is made too low, the size of inlet (and outlet) openings must increase greatly. Thus, design should be based on combinations of inlet areas and airway heights in the central *curving* portion of each line.

For example, in Fig. 42 for a 9.1 m (30 ft) long airway, a 38 mm ($1\frac{1}{2}$ in.) high airway will not work but a 51 mm (2 in.) high airway will work if the inlet area is 60 mm^2/mm (28 in.^{2}/ft). That is a large inlet (and outlet) area to provide. An alternate is to increase the airway height to 64 mm ($2\frac{1}{2}$ in.) thereby reducing the inlet area to about 44 mm^2/mm (21 in.^{2}/ft).

It is important to note that these areas are for each airway while the inlet (and exhaust) sizes discussed above for attics are for the entire attic not just "one side."

Figure 42 illustrates how large inlets (and outlets) and airways need to be when cathedral ceiling roofs are not steeply sloped and not well insulated.

Reductions in size when the slope remains at 15 degrees (about 3 in./ft) but the roof is better insulated to 7.0 m^2 K/W (40 F°·h·ft^2/Btu) are shown in Fig. 43. The 9.1 m (30 ft) long airway can be 38 mm ($1\frac{1}{2}$ in.) high, which is far easier to provide than a 64 mm ($2\frac{1}{2}$ in.) high airway and the inlets need only be about 20 mm^2/mm (9 in.^{2}/ft).

When both the thermal resistance and the slope increase, the reductions in size are even greater as shown in Fig. 44, which is for a slope of 45 degrees (12 in./ft) and a thermal resistance of 7.0 m^2 K/W (40 F°·h·ft^2/Btu). In this case, an airway only 25 mm (1 in.) high works with an inlet area of only 13 mm^2/mm (6 in.^{2}/ft).

On the above-mentioned web site, a step-by-step calculation procedure (using IP units) is provided at the end of Ref. [28] for generating a line like those in Figs. 42–44 for a specific cathedral ceiling knowing the roof slope, the rafter spacing, the length of the airway, the temperature within the building and the thermal resistance of the roof.

As stated previously, ventilation for control of icings at eaves is *not* needed every place it snows. The need to ventilate for this purpose is related to the amount of snow a site encounters and the amount of insulation in the roof as shown in Table 2 [28]. The "ground snow load" used in Table 2 is that used by structural engineers in the design of roofs. Alan Greatorex and I developed the ground snow load map in the national design load standard [124]. It is also available in the International Building Code [31], the International Residential Code [32] and on the above-mentioned web site.

In some places where "extreme local variations in ground snow load preclude mapping" on a national scale, ground snow loads are not mapped. For such places, snow load "case studies" are needed. CRREL provided them free, upon request, for many years.

Since small, infrequent icings are still likely, it is appro-

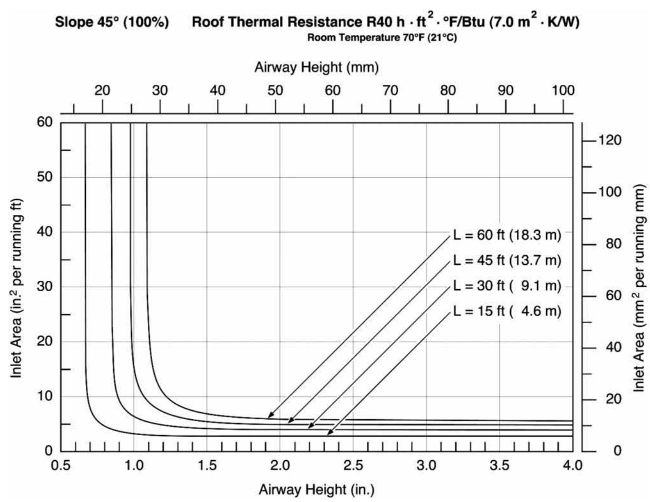


Fig. 44—Airway heights and inlet areas for cathedral ceilings with a slope of 45 degrees (12 in./ft) and a thermal resistance of 7.0 m^2 K/W (40 °F·h·ft^2/Btu).

TABLE 2—To avoid problematic icings, ventilate residential size roofs of heated buildings under the following conditions [28].

Ground Snow Load kN/m^2 (lb/ft^2)	Guidance
Less than 0.48 (10)	No need to ventilate to avoid ice dams.
0.48 to 0.74 (10 to 15)	Ventilate if the thermal resistance of the roof is less than 1.8 (R10)[a].
0.75 to 1.46 (16 to 30)	Ventilate if the thermal resistance of the roof is less than 3.5 (R20).
1.47 to 2.18 (31 to 45)	When the elevation is above 1,830 m (6,000 ft) ventilate all roofs. Below that elevation, ventilate if the thermal resistance of the roof is less than 5.2 (R30).
2.19 to 2.89 (46 to 60)	When the elevation is above 920 m (3,000 ft) ventilate all roofs. Below that elevation, ventilate if the thermal resistance of the roof is less than 7.0 (R40).
2.90 (61) and up	Ventilate all roofs.

[a]SI units are m^2·K/W and IP units are F°·h·ft^2/Btu.

priate to convert the lower portion of a sloped roof from a water-shedding system (that will leak if water ponds on it) to something closer to a membrane system that can better resist ponded water due to ice damming. A good way to accomplish this is to use a self-adhering polymer-modified bituminous sheet material (i.e., a "peel and stick mod. bit.") under the water-shedding system in valleys, around penetrations and along eaves. The International Building Code [31] and the International Residential Code [32] require such protection wherever the average January temperature is −4°C (25°F) or colder. NRCA [4] uses −1°C (30°F) which is supported by severe ice damming problems in New Jersey in 1996 [30]. In fact, the New Jersey problems support an even warmer (i.e., further south) dividing line. Figure 45 shows about where these two isolines are located in the United States. In mountainous areas, local weather data, not this map, should be used to determine the average January temperature. However, I believe that it is better to relate the need for ice dam protection underlayment to "ground snow load" with reasonable limits being areas with a ground snow load equal to or greater than 0.96 or 1.20 kN/m^2 (20 or 25 psf). I recommend installation of ice dam protection underlayment wherever the ground snow load is 1.20 kN/m^2 (25 psf) or more. This calls for their use over somewhat more of the nation than either of the two isolines in Fig. 45 call for.

Figure 46 shows how far upslope from the eaves the ice dam protection underlayment should go. The International Codes [31,32] and NRCA [4] call for the horizontal distance in Fig. 46 to be 0.61 m (24 in.) with NRCA increasing that to 0.91 m (36 in.) if the slope is less than 18 degrees (4 in./ft). MBMA [18] calls for 0.81 m (32 in.) for a slope of 18 degrees (4 in./ft) or more and recommends increasing that for lower slopes. Others feel that such underlayment should be used over the entire deck when water-shedding metal roofing is used in areas with high snow loads [10].

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 limit their size by maintaining drainage holes through whatever ice does form (Fig. 47) [125]. The drains prevent water from ponding on the roof and leaking into the building. Heating cables, laid over existing ice dams that are causing leaks, can melt their way down through the ice, accomplishing the same thing. Installing heating cables on asphalt shingles is a relatively straight-forward task but installing them on metal is more complicated [125]. Hammers, hatchets, chain saws, and salts used to remove ice along eaves usually do more harm than good.

In cold regions, framed water-shedding roofing systems,

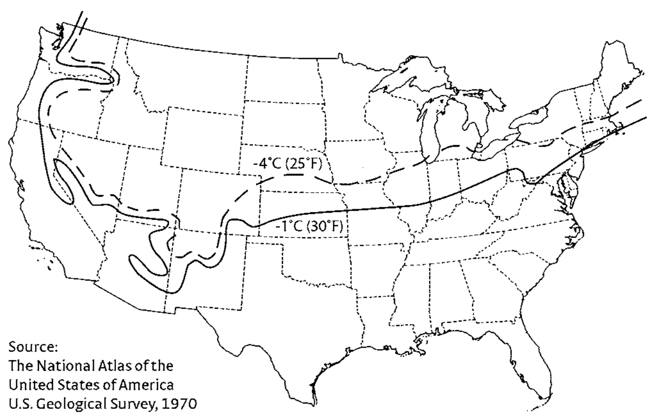


Fig. 45—Generalized location of two isolines of average January temperature across the United States used to define where ice dam protection underlayment is needed.

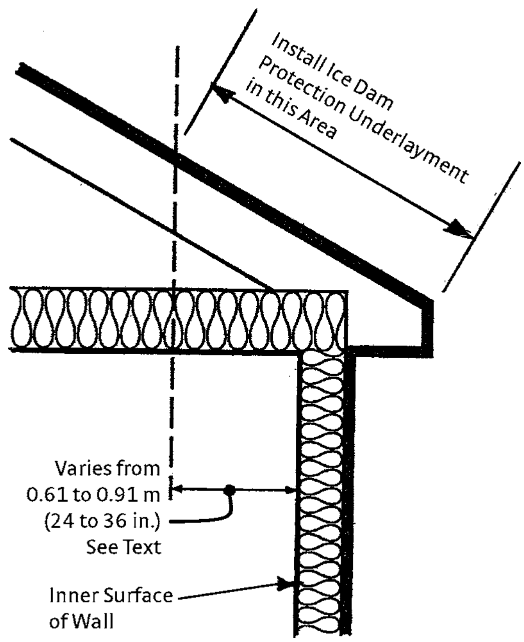


Fig. 46—Portion of steeply-sloped roofs with water-shedding roofing that should have ice dam protection underlayment.

Fig. 47—Holes through an ice dam created by electrical heating cables.

due to the difficulty of providing them with effective air barriers, may encounter condensation 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. 30 may be needed. This is not a ventilated system. A ventilated alternative is shown in Fig. 48. It consists of a hybrid compact-framed ventilated system with far better air leakage resistance than a framed system.

Sliding Snow and Ice

When large ice dams develop on steeply-sloped shingled roofs and cause leaks, some people believe that replacing the shingles with *architectural* metal roofing (or sometimes even less-expensive metal roofing with only lapped seams and exposed fasteners) will solve the problem. On occasion, snow slides off the slippery metal and the problem goes away but, most of the time, icings still form, water still ponds, leaks return with a vengeance, and hazards are created. Reducing heat losses up into the snow by improving insulation, controlling air leakage, and, perhaps, improving or adding ventilation are the directions to take to solve such problems not changing to metal roofing. However, once these steps are taken, there are several reasons that a switch to metal roofing may be appropriate. Aesthetics, long service life, and low maintenance are good reasons to consider re-roofing with metal but eliminating icing problems often is not.

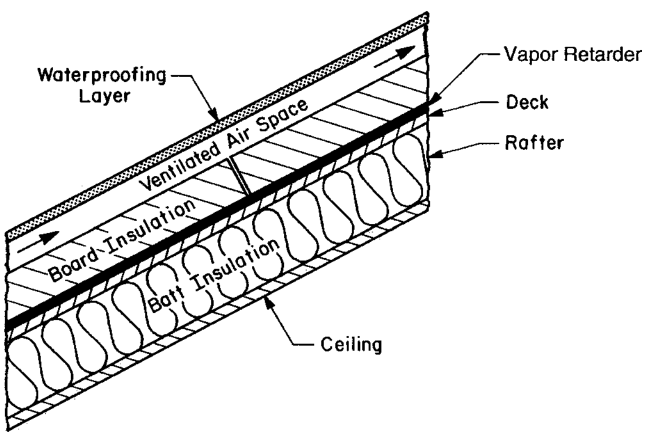


Fig. 48—Hybrid compact-framed, ventilated roof with a portion of its insulation above the deck to better resist air leakage.

Metal is not the only slippery roofing surface. Bituminous membranes with a smooth surface (i.e., without imbedded aggregate or mineral granule surfacing) and most single-ply membranes are also slippery, as is glass and slate. Some tiles are slippery but others contain protrusions that tend to hold snow on the roof. When asphalt shingles or roll roofing with a mineral granule surface have been replaced with single-ply membranes on large arched roofs of hangars and arenas, serious sliding snow problems have occurred. Roof-mounted mechanical equipment has been torn loose and parapet walls on adjoining flat roofs have been pushed over by the sliding snow.

Some *water-shedding* standing seam metal roofing systems are *not* ventilated on the belief that snow will slide off them thereby reducing the risk of ice damming at their eaves. That is risky since even small icings there can, and do, prevent snow from sliding.

The sliding of snow off a roof can be beneficial since it reduces snow loads. However, sliding snow can endanger people and damage property, including the roof as shown in Fig. 49 [126]. Snow accumulating on an ice-dammed slippery metal roof can break away the ice dam and cause considerable damage as shown in Fig. 50

Thus it may be necessary to install obstacles (snow guards) on the roof to prevent sliding. Several types of snow guards are available [127]. They must be robust because snow and ice can exert great forces on them.

Design of snow guards [127] 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 row in the vicinity of the eaves. Snow guards should not be placed out over cold eaves because they tend to facilitate the 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. They are secured

Fig. 49—Snow sliding down a valley does not move parallel to the standing seams of a metal roof but tends to bend them over and push them apart.

Fig. 50—The load of snow held on this metal roof by icings along its eaves peeled it apart.

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 in a nonpenetrating way by clamping onto the standing seam, not through the metal pan on which water flows. When fasteners which hold the metal panels to the frame of the building are not able to resist snow forces, the panels and their snow guards have slid down the roof

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. Also, if the loads for which a roof was designed are based on removal of snow by sliding, which is allowed, subsequent holding of snow on that roof may overload it.

Some metal roofs terminate before they reach the eaves (Fig. 51) so as to create a space on the roof where sliding snow can be retained rather than create hazards several stories below. The trough created at the eaves contains membrane roofing and the upper portion of the building wall is designed to sustain any loads from the sliding snow. Some such troughs contain electrical heaters to melt the collected snow.

Fig. 51—Troughs created at the base of these metal roofs retain sliding snow on the roof. (Courtesy of UNA-CLAD: Firestone Metal Products.)

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 almost no stack effect to cause a draft between the intake and exhaust openings. Thus, ventilation is slight except during windy periods. *Ineffective ventilation of low-sloped roofs, combined with the high air leakage many framed systems allow, explains why such framed membrane roofs suffer so many condensation problems in cold and mixed climates* [128–130].

Air Leakage

Figure 52 shows cold weather air leakage paths in a typical low-slope framed membrane roofing system. The most effective way to solve condensation problems in such roofs in *cold* and *mixed* climates is to eliminate such air leakage paths. If serious attention cannot be given to airtight construction, roofs should not be built this way. Air-tight construction is difficult, especially after the fact, but it is well worth the effort. Two Canadian booklets [113,114] 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, those fans 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 [131]. 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.

For air-conditioned buildings in *hot-humid* climates and some *mixed-humid* climates, air *infiltration* rather than *exfiltration* is the primary concern. Thus, roof ventilation as shown in Fig. 52 may increase, rather than reduce, moisture problems. Moisture barriers are needed in ventilated ceilings in such climates to keep moist *outdoor* air from gaining access to the colder portions of the roof. This can be accomplished by using low permeance rigid insulation boards directly above the ceiling then batts above those boards [86]. The joints in the boards should be taped or sealed to keep

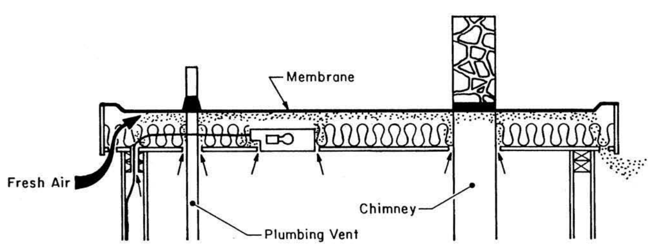


Fig. 52—Air leakage paths into a ventilated flat roof with below-deck insulation.

moist outdoor air out of the colder, lower portions of the roof where condensation could occur. However, a more direct approach would be to *not* ventilate such roofs. By making their exterior as air tight as possible and not having a vapor retarder below their roof insulation, little moisture has access to the roof and any that does arrive is not trapped there. Use of rigid board insulation directly above the ceiling, as was just discussed, can further reduce the potential of condensation in such an unventilated roof.

Vapor Retarders

In *cold* and *mixed* climates, air leakage paths such as those shown in Fig. 52 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 so it also serves as an air barrier system.

In somewhat misdirected attempts to solve condensation problems with "flat" timber framed roofs in *cold* climates, the permeance of their vapor retarders has been lowered over the years to as low as 3 $ng/(s \cdot m^2 \cdot Pa)$ (0.05 perms). However, the need for a permeance below 29 $ng/(s \cdot m^2 \cdot Pa)$ (0.5 perms) is questioned except in *very cold* regions where a value of 6 $ng/(s \cdot m^2 \cdot Pa)$ (0.1 perm) *may* be appropriate. The most effective way to avoid condensation problems for these roofs is to equip them with very tight air barrier systems and, perhaps, also ventilate them since their vapor retarders restrict downward drying.

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 in *cold* and *mixed* climates since there is incentive to not ventilate such roofs in *hot-humid* climates and some *mixed-humid* climates.

Any moisture that moves up through a reasonably airtight ceiling into a big open attic space, such as that shown in Fig. 31, is relatively easy to ventilate away. Decades ago, many low slope roofs contained vented lofts for that purpose (Fig. 53) [1].

When the attic or loft is removed and the deck and waterproofing are placed directly on top of the ceiling joists as in Fig. 52, little or no air space is available for ventilation. If serious attention cannot be given to airtight construction, roofs should not be built this way since ventilation is apt to *cause* moisture problems, not prevent them.

For "flat" roofs with enclosed rafter spaces, guidelines on the net area of openings for natural ventilation range from 1/300th (i.e., 0.33 %) of the area of the space to be ventilated to 1/150th (i.e., 0.67 %) of that area. When the roof slope is less than about 10° (2 in./ft), the air space should be at least 25 mm (1 in.) high and cross-purlins at least 38 mm (1.5 in.) high should be present above the rafters (Figs. 36 and 37). This interconnects all the individual enclosed rafter spaces to avoid dead spots where condensation is likely.

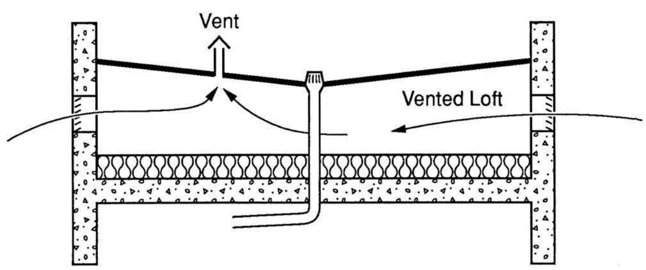


Fig. 53—Vented-loft roofing system.

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 have occurred 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 [132].

Studies in Denmark [133] 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. 52 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. 52 "seems to function satisfactorily for "flat" roofs in the Danish climate [about 3,700 heating degree days Celsius (6,600 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 and also serves as an air barrier, 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 in *cold* and *mixed* climates, condensation risks can be reduced by placing only a portion of the insulation below the deck. With the rest of the insulation above the deck, an unvented compact roof is created above the framed portion. This dual insulation method is shown in Fig. 54. The vapor retarder shown in Fig. 54 may or may not be needed but that location is a very effective place to control air leakage and, if necessary, vapor diffusion. A potential vapor trap is created between the waterproof membrane and the vapor retarder but since this portion of the roof is "compact" it is unlikely that this will result in moisture problems. As the relative humidity in the building increases, the amount of insulation allowed in the wood-frame portion decreases. In Denmark, for houses and

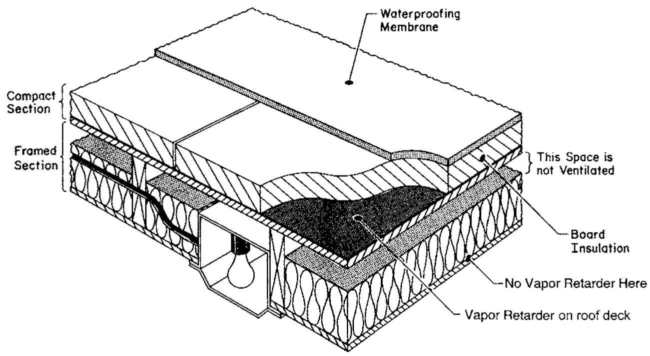


Fig. 54—Unventilated wood-framed roof with insulation in compact and framed portions.

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 Danish guidelines is to keep the dew point temperature of the indoor air above the deck and vapor retarder during most of the winter, thereby eliminating 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 compact portion than would be determined by using Figs. 22–24 (i.e., the *CRREL Guidelines*). Since the *CRREL Guidelines* are for totally compact roofs not such framed-compact hybrids, the more conservative Danish guidelines and the *ASHRAE Guidelines* (i.e., the Dew Point Method) are more appropriate for such roofs.

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 appropriate to add a ventilated space above the insulation as shown in Fig. 48.

If enough insulation is placed above the deck to cause the dew-point temperature of the indoor air to occur in the compact portion of the roof above the deck at the winter design temperature, condensation problems are highly unlikely.

If the framed portion of such a hybrid roof can be made moisture resistant by installing a vapor retarder and an air barrier system that protects it, the *CRREL Guidelines* can be used. Since the dew point temperature would then be below the compact portion of the roof at the winter design temperature, a "smart" vapor retarder should be used so that downward drying is possible in summer. The asphalt-kraft paper on batt insulation would be a suitable material. In this application, in particular, that vapor retarder should be well sealed so it can also function as the air barrier system.

Summer Condensation

Most framed-roof condensation problems occur in *cold* climates and are from indoor moisture. However, outdoor moisture can cause problems for air-conditioned buildings in *hot-humid* and *mixed-humid* climates. Air spaces for roof ventilation allow moist outdoor air direct access to the ceiling. Thus, there is merit in not ventilating framed roofs in such climates. 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 [134]. For this reason, vapor retarders are usually not wanted in framed roofs in these climates. 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 on their underside, they should be well sealed against air leakage. Vapor permeable latex paint on gypsum wall board is an example of a high permeance ceiling. Permeances of many building materials are presented in Table 7 in Chapter 2 and in Table 9 of Chapter 25 in the *ASHRAE Fundamentals Handbook* [76].

Referring to the map in Fig. 22, few membrane roofs in *mixed* and *hot* climates need vapor retarders: Few buildings there have indoor relative humidities in winter above the mapped values. However, all roofs in *all* climates need air barrier systems. In *hot humid* and *mixed-humid* climates, air barrier systems need to prevent hot humid outside air, or such air within the airway or attic of a ventilated roof, from gaining access to cool inner portions of the roof above air-conditioned spaces. In such climates there is also merit in using a vapor-impermeable insulation system directly above the ceiling so outdoor moisture does not have direct access to cold permeable insulation just above the ceiling.

Improvements, Repairs, and Re-Roofing

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 [135,136].

For example, consider the compact roofing system shown in Fig. 55. The roof itself has a low thermal resistance of only 1.75 $K \cdot m^2/W$ (10 $F° \cdot h \cdot ft^2/Btu$) and the air space and suspended ceiling below have a combined thermal resistance of about 0.53 $K \cdot m^2/W$ (3 $F° \cdot h \cdot ft^2/Btu$). 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 11°C (52°F) at the winter design condition. Using the Dew Point Calculation Method (i.e., the *ASHRAE Guidelines*), the relative humidity of the air within the building can be as high as 56 % before condensation will form on the bottom of the deck. However, if insulation with a thermal resistance of 1.25 $K \cdot m^2/W$ (7 $F° \cdot h \cdot ft^2/Btu$) is placed above the suspended ceiling, the temperature of the underside of the deck will drop from 11°C (52°F) to about 1°C (34°F) and condensation will occur there if the relative humidity of the indoor air is above 28 %, which is certainly possible.

If the less-demanding *CRREL Guidelines* are used, problems will not be expected unless the indoor RH is above about 42 %. However, because the *CRREL Guidelines* were developed for compact membrane roofing systems, which

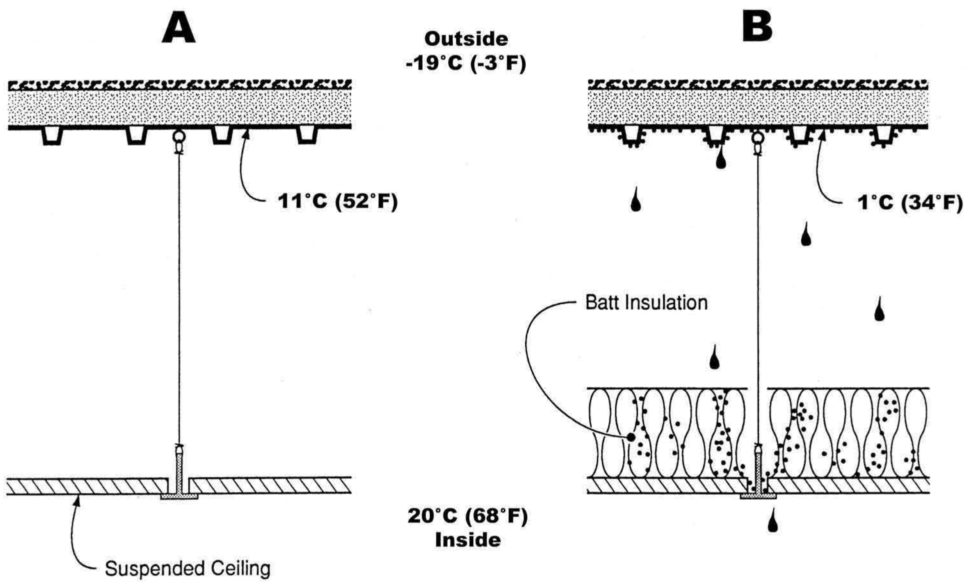


Fig. 55—Adding insulation above a suspended ceiling. This increases the risk of condensation on the underside of the roof deck: (A) existing roof and ceiling; (B) after adding insulation above the suspended ceiling.

this hybrid certainly is not, use of the *CRREL Guidelines* here is inappropriate unless air leakage up through the suspended ceiling can be essentially eliminated. A few suspended-ceiling insulation systems have been designed to reduce both heat and moisture flow [137,138], but most are not able to effectively control air leakage.

From this example it is obvious that before insulation is added below a roofing system, the possibility of introducing condensation problems should be investigated.

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 often 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 re-roof over existing materials whose performance is poor enough to warrant re-roofing. 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. Many codes and standards limit the number of roofing systems a roof can have to two.

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 residual 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 [139]. However, if the existing system is dry or can dry downward into the building, 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

Interest in buildings that contain instrumentation to monitor their performance has lead to the design and testing of a wide range of imbedded sensors for detecting moisture in roofs [140–142] but very few roofs are equipped with them.

On becoming wet, some insulations soften and, even under an aggregate-surfaced bituminous built-up membrane, may be noticed "under foot." Patterns of frost on a roof in the morning can also indicate where insulation is wet [143]. Other than that, it is virtually impossible to determine the extent of wet insulation in roofs visually. However, nuclear meters, capacitance meters, and infrared scanners can locate wet insulation in compact roofing systems [144,145].

Nuclear meters (Fig. 56) and capacitance meters (Fig. 57) 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. 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. 58) 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. 59). 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.

Comparison of nuclear, capacitance, and infrared surveys on a roof [146] indicated that all three techniques can detect wet insulation but each has its own strengths and weaknesses related to false indications, operator skills, regulations and costs. The infrared technique provided the best overview of substrate conditions and the nuclear technique provided the best method of quantifying the amount of moisture in the insulation. There was a much stronger correlation between nuclear readings and core sample moisture contents than there was for capacitance meter readings.

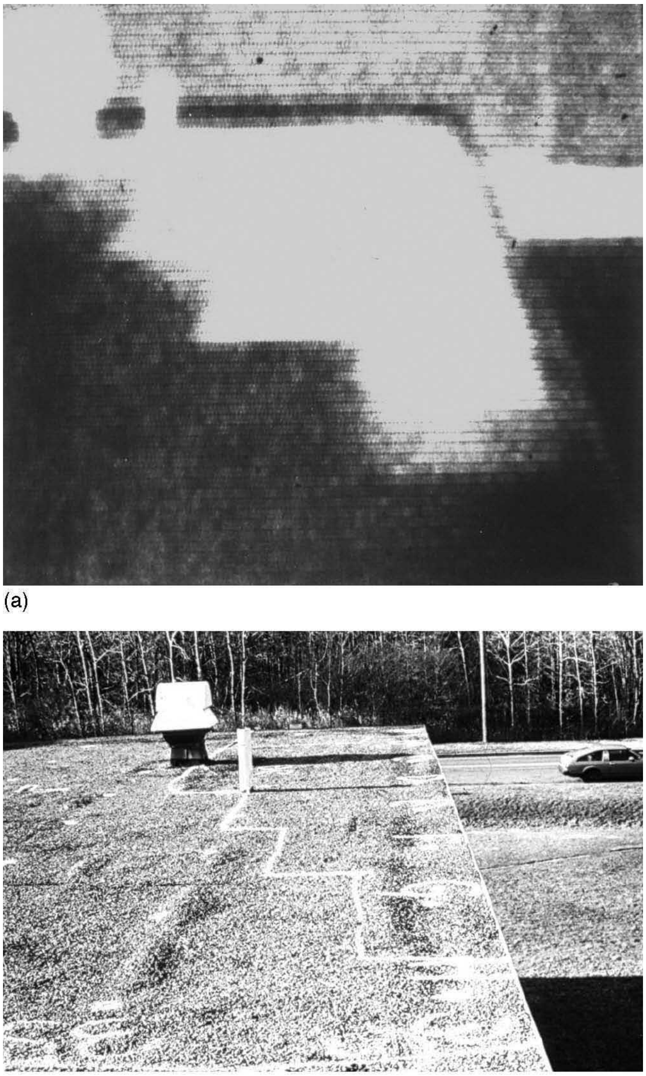
Fig. 57—Surveying a roof with a capacitance meter.

Infrared surveys are best done at night but, sometimes, wet insulation can be found during daytime surveys [147]. They are commonly conducted by walking with the infrared scanner on the roof. However, they can also be conducted from helicopters (Fig. 60) and fixed-wing aircraft [148]. 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 [149]. Remotely controlled, dual-lens infrared scanners are available that allow wide-angle overviews for finding the target [Fig. 61(a)], followed by telephoto views as the aircraft closes in on the target [Fig. 61(b)], and final telephoto views that yield mapping quality images when the aircraft is directly over the target [Fig. 61(c)].

All nondestructive roof moisture surveys need to be verified by taking a few core samples of the insulation in areas

Fig. 56—Surveying a roof with a nuclear meter.

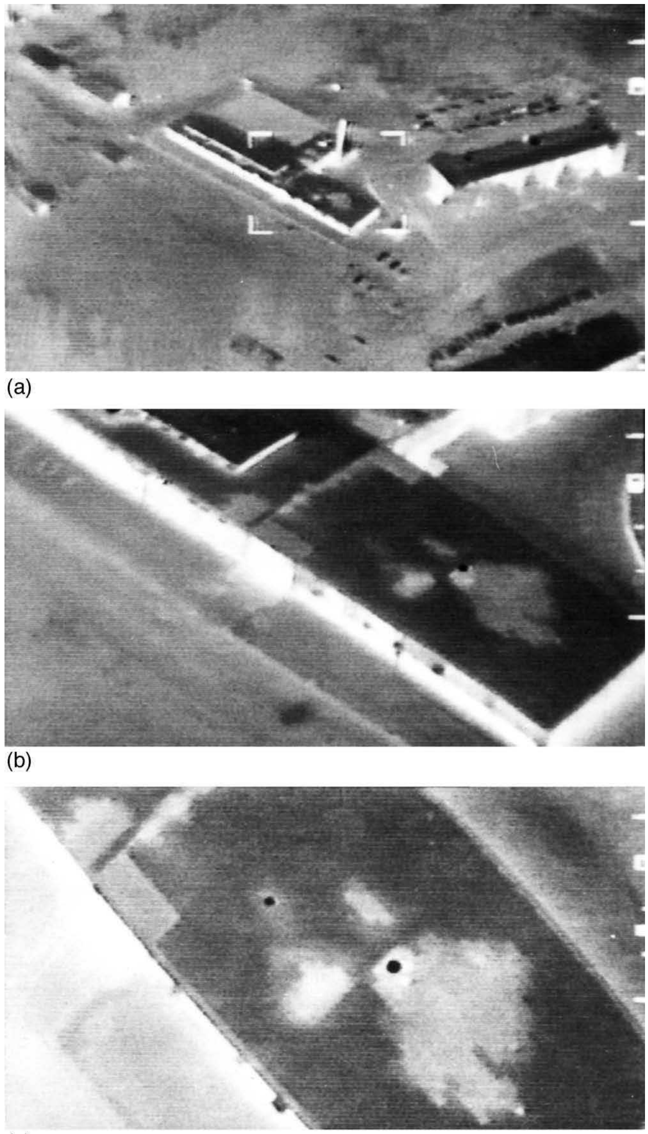
Fig. 58—Surveying a roof with an infrared scanner.



(a) (b)

Fig. 59—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.

Fig. 60—Conducting an airborne infrared roof moisture survey from a helicopter.



(a) (b) (c)

Fig. 61—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.

expected to be wet and others expected to be dry (Fig. 62). 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 ASTM Standard Practice for Roof System Assemblies Employing Steel Deck, Preformed Roof Insulation, and Bituminous Built-up Roofing (E936). ASTM Standard Practice for the Location of Wet Insulation in Roofing Systems Using Infrared Imaging (C1153) describes how to conduct on-the-roof and airborne infrared roof moisture surveys.

Nuclear, capacitance, and infrared surveys find wet insulation and, when it is found, it is then often possible to vi-

Fig. 62—Obtaining cores to verify a roof moisture survey.

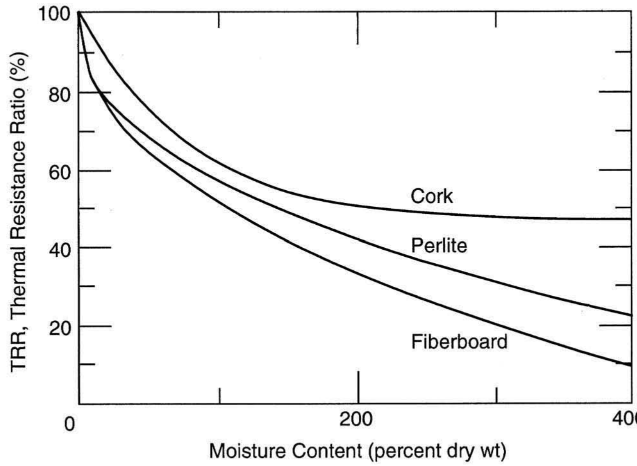


Fig. 63—TRR versus moisture content relationship for cork, fiberboard, and perlite.

sually locate the membrane or flashing flaw where the moisture entered. Newer electronic leak detection techniques [150,151] find the flaw directly but cannot determine how much insulation has been wetted as a consequence of the waterproofing flaw. The *low voltage* method creates an electrical field by surrounding the area to be tested with a wire loop and using a conductive deck, such as steel or concrete, to complete the circuit. The surface of the membrane on which the loop is laid out must be kept wet so that two probes moved about on it can detect the direction of current flow from the loop, to the flaw, down through the wet materials of the roof to the conductive deck. By probing along in the direction of current flow the flaw can be pinpointed. This method does not work on conductive membranes such as EPDM and the moisture that enters the flaw must wet material all the way down to the conductive deck or, at least, to something conductive, like a metal fastener attached to the deck.

The *high voltage* method, like the *low voltage* method, needs to have a conductive deck and wet materials present below the flaw, but it does not require a wire loop to be laid out nor must the surface be wet. In fact, it must be smooth, clean, and dry. It is the faster of the two methods but is not suitable for testing asphalt-based materials.

Electronic leak detection is much faster, safer, simpler, and potentially less damaging than flood testing.

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 [36].

For existing roofs it is reasonable to accept somewhat more moisture. One approach is to use the equilibrium moisture content at 90 % RH [36,152]. 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 [58–61] 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. 63–68 [61]. 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 [61]. Table 3 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. Advo-

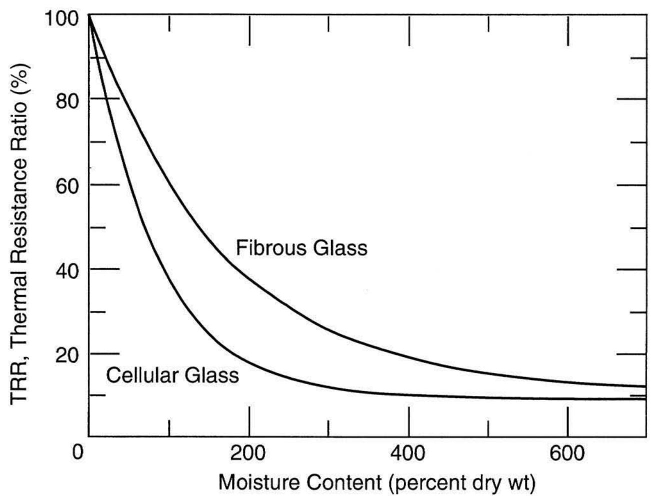


Fig. 64—TRR versus moisture content relationships for fibrous glass and cellular glass.

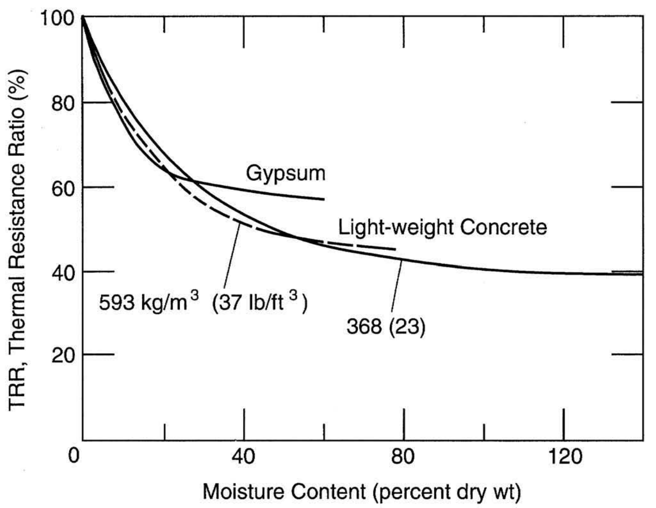


Fig. 65—TRR versus moisture content relationships for gypsum and lightweight concrete.

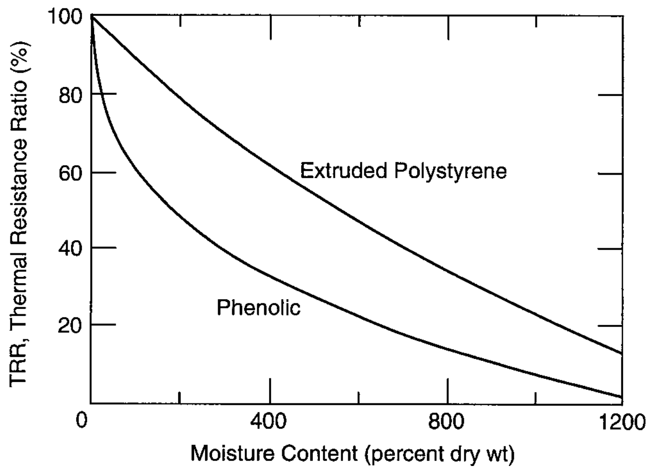


Fig. 67—TRR versus moisture content relationships for extruded polystyrene and phenolic.

cates 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 3 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 [153–155] 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) [155], and a 50 % loss was measured at a moisture content of about 12 % (dry weight basis) [154].

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 [153–155].

The loss in thermal resistance of several roof insulations subjected to freeze-thaw cycling in the presence of moisture is presented in Table 4 [51]. Over half of the insulations tested had a TRR of 80 % (i.e., had lost 20 % of their insulating ability) after less than 25 freeze-thaw cycles. Note that cellular glass is one of these materials. It is quite resistant to wetting when above 0 °C (32 °F) but can be quickly destroyed by freeze-thaw as Fig. 14 shows. It takes many more freeze-thaw cycles to wet expanded bead polystyrene (EPS) but freeze-thaw cycling does deteriorate that material.

Polyurethane (both board and spray foam types), polyisocyanurate and extruded polystyrene (XEPS) are even more resistant to freeze-thaw. Their TRRs remained above 85 % after 400 freeze-thaw cycles.

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

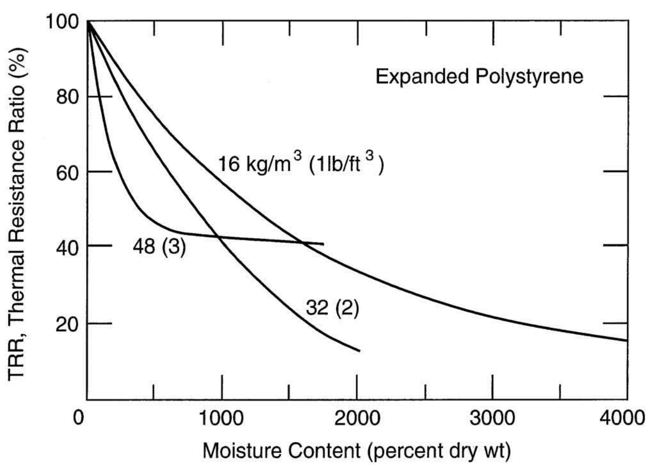


Fig. 66—TRR versus moisture content relationships for expanded polystyrene.

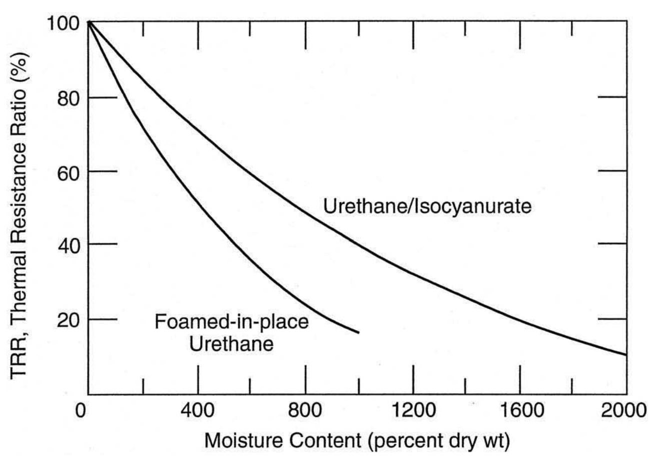


Fig. 68—TRR versus moisture content relationships for urethane/isocyanurate and foamed-in-place urethane.

myriad of roofing systems 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. 26), and breathable membranes have been promoted to dry out wet insulation. Exposure studies in Hanover, New Hampshire [22] and in Saskatoon, Saskatchewan [96] indicate that drying is a very localized and very slow process that takes many years or decades. Table 5 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 [22,96] 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 to the outdoors.

Some success has been achieved in drying fibrous glass insulation in a roof by removing water with a vacuum cleaner [22]. 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 %.

In a laboratory study [156], 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 many 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 [157,158]. This membrane consists of a synthetic fabric with good wicking action between impermeable surfaces. Gaps in

TABLE 3—Comparison of equilibrium moisture contents and those at 80 % TRR for insulations without facers [62].

Insulation	Equilibrium Moisture Content, % of Dry Weight (from Ref. [152]) 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 4—Freeze-thaw cycles to reach 80 % TRR and TRR after 400 cycles [51].

Insulation	Thickness mm (in.)	Density kg/m^3 (lb/ft^3)	Cycles to 80 % TRR	400-cycle TRR (%)
Phenolic	30 (1.2)	40 (2.5)	<25	4
Cellular glass	27 (1.1)	137 (8.6)	<25	9
Fibrous glass	28 (1.1)	143 (9.0)	<25	13
Fiberboard	25 (1.2)	296 (18.5)	<25	22
Perlite	21 (0.8)	189 (11.8)	<25	33
Lightweight concrete	26 (1.0)	391 (24.4)	<25	39
Cork	25 (1.0)	256 (16.0)	<25	52
Gypsum	25 (1.0)	878 (54.8)	<25	55
Expanded bead polystyrene:				
	25 (1.0)	16 (1.0)	190	63
	50 (2.0)	18 (1.1)	238	68
Extruded polystyrene:				
	25 (1.0)	34 (2.2)	675	87
	53 (2.1)	30 (1.9)	>948	94
Sprayed polyurethane	24 (0.9)	54 (3.4)	600	85
Polyisocyanurate	29 (1.2)	30 (1.9)	890	94
Polyurethane	23 (0.9)	30 (1.9)	>948	94

TABLE 5—Time to dry two kinds of insulation in a compact membrane roofing system in New Hampshire [22].

	Time to Remove 29 kg/m^2 (6 lb/ft^2) 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

the impermeable surfaces alternate from side to side with overlaps, as shown in Fig. 69. The overlapping surfaces give the membrane a low permeance to vapor. The hygrodiode membrane may be able to limit the growth 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 into the design of roofs 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. The use of wicking or absorptive layers to facilitate self-drying can also backfire since such inserts can facilitate lateral spreading of wetness created by membrane and flashing flaws.

Use of "smart" vapor retarders allows some moisture to be removed from roofs when the direction of vapor drive reverses. One nylon film vapor retarder has a dry cup permeance less than 60 ng/(s·m^2·Pa) (1 perm) but when the relative humidity of the air on one side increases to 90 %, its permeance increases to 2070 ng/(s·m^2·Pa) (36 perms) [159].

Lightweight 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 [89]. 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 lightweight concretes and the steel deck on 0.6 m (2 ft) centers before installing a new roofing system above [160].

Re-roofing Over Wet Insulation

Full-scale tests have been conducted on three wet roofs that, lacking vapor retarders, have the potential to dry downward [161–163]. The first instrumented test roof [161] was in Tennessee. The old bituminous built-up membrane was coated with 46 mm (1.8 in.) of polyurethane spray foam with a thermal resistance of 1.9 m^2·K/W (11F°·h·ft^2/Btu). The foam was then coated. The existing 15 mm (0.6 in.) thick fibrous glass insulation had lost about 0.40 m^2·K/W (2.3F°·h·ft^2/Btu) of its thermal resistance (i.e., essentially all of it) due to being wet. To reduce the air and vapor tightness of the steel deck, 13 mm (1/2 in.) diameter holes were drilled 0.61 m (24 in.) on center on the roof. Water in the insulation leaked out of those holes into the building creating some problems for the occupants.

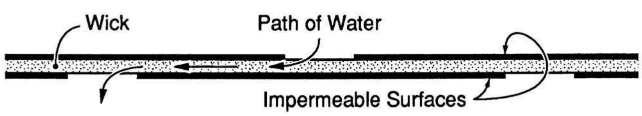


Fig. 69—"Hygrodiode" membrane. It stops air, retards vapor, and allows water to wick away.

Nuclear meter readings 4, 9, and 16 months later revealed some drying but heat flux sensors indicated no overall increase in the thermal resistance of the roof. When the thermal loss expected due to aging of the spray foam was factored out, the gain in R-value of the fibrous glass insulation associated with drying was estimated at about 0.44 m^2·K/W (2.5F°·h·ft^2/Btu). However, this is more than would be possible for such a thin layer of fibrous glass insulation, so this finding is suspect. Nonetheless, some drying did occur and the roof no longer leaked.

The second instrumented test roof [162] was located in Virginia. The existing roof had a bituminous built-up membrane, 51 mm (2 in.) thick wood fiberboard insulation and a steel deck.

Combinations of 13 mm (1/2 in.) and 76 mm (3 in.) thick extruded polystyrene insulation and mechanically-attached black and white single-ply membranes were added. Most of the analysis was done on the portion where the 13 mm (1/2 in.) thick insulation was installed. After a year the gain in thermal resistance by some slow downward drying of the wood fiberboard was only about 0.07 m^2·K/W (0.4F°·h·ft^2/Btu) under the white membrane and 0.04 m^2·K/W (0.2F°·h·ft^2/Btu) under the black membrane. The insulation was much wetter under the white membrane which probably explains why drying was faster under it. For equal amounts of wetness, drying should be faster under the black membrane. Serious corrosion problems were encountered with the fasteners used to attach the new insulation and membranes even though fasteners were chosen with this possibility in mind.

The third instrumented test roof [163] was located in Illinois. It consisted of a bituminous built-up membrane on 38 mm (1.5 in.) thick perlite insulation with a dry thermal resistance of about 0.7 m^2·K/W (4F°·h·ft^2/Btu). That insulation was rather dry having a TRR over 80 %. For many individuals this would not be a "wet" roof. The recover consisted of combinations of black and white mechanically-attached single-ply membrane over either 13 mm (1/2 in.) thick wood fiberboard or 51 mm (2 in.) thick polyisocyanurate insulation.

Nuclear meter readings indicated that a small amount of drying occurred after two years, resulting in an average thermal recovery of less than 0.023 m^2·K/W

(0.13F°·h·ft^2/Btu). The fastest drying rate was about 1.5 times the average rate. It occurred where the least amount of insulation was added. There the thermal recovery was 0.04 m^2·K/W (0.2F°·h·ft^2/Btu). Drying was somewhat faster below the black membrane than the white membrane as would be expected.

These three full-scale tests indicate that some roofs will slowly dry downward but the thermal resistance gained by all that is likely to be very small. If these test roofs are representative of those that can be dried out, there is very little energy to be saved by that process. The big incentive of leaving wet insulation and an aged, deteriorating membrane in place is to avoid the cost of removing them and hauling them to a landfill. That is admirable but, on the other hand, the dump may be a better place for such used-up old things than on the roof of a useful building.

The "plethora of risks" created by overlaying failed, often wet, roofs convince some that "installing overlays negates any realistic potential for a successful project" which "will only damage the reputation of the roofing industry" [164].

Others, like those involved in the three above-mentioned test roofs are more optimistic. Nonetheless, they caution about the need to thoroughly examine a roof, inside and out, before deciding to recover it. They indicate that this should include core sampling to determine what materials are present and the amount of moisture they contain, fastener pull-out tests to determine the structural integrity of metal decks, and compressive strength tests of existing insulation.

Parting Shots

A myriad of roofing materials and systems are available to choose from. Many of these parts and pieces cannot be combined to create successful systems but some can. Roofing technology has advanced greatly during the past few decades but not without a number of setbacks. Those false starts have caused many of the moisture problems that have been experienced but others have been caused by design deficiencies, deficient materials, poor workmanship, lack of preventative maintenance, and, on rare occasions, by acts of God. Many materials and systems perform quite well but, when used without due consideration of their limitations, they fail. It takes a lot of time and effort to understand what works and what does not. Since roofing is a constantly evolving, competitive industry, keeping up with the latest developments is essential.

Fig. 70—By "nailing down" air leakage almost all condensation problems in roofs can be avoided or eliminated.

Most moisture problems experienced by roofs are from rain and other forms of outdoor moisture. When indoor air causes condensation problems, they are usually rather difficult to diagnose and remedy. Almost all condensation problems are the result of one specific weakness in the building envelope. By acknowledging that weakness and reacting to it, as shown in Fig. 70, most condensation problems can be avoided or found and eliminated.

Note: Throughout the text I have expressed slope in degrees followed, in parenthesis, by inches per foot. The following additional conversions are provided:

Degrees	in./ft	%	Ratio
1.2	$\frac{1}{4}$	2	1:48
2.4	$\frac{1}{2}$	4	1:24
4.8	1	8	1:12
7.1	$1\frac{1}{2}$	12	1:8
9.5	2	17	1:6
14	3	25	1:4
18	4	33	1:3
45	12	100	1:1

Acknowledgments

The thoroughness of his review and his handwriting exposed Walter Rossiter as one of the two anonymous ASTM reviewers. His comments were most valuable. I solicited and received additional thorough, valuable reviews from my CRREL colleagues, James Buska and Alan Greatorex, and my mentor, Dick Fricklas. Jim and Alan also helped gather, revise, and format the figures. My wife, Elizabeth, spent many hours helping me proof and assemble everything.

References

[1] Baker, M., *Roofs: Design, Application and Maintenance*, Multiscience Publications Limited, Montreal, Canada, 1980.

[2] Booth, R. and Roberts, K., "The Uses and Performance Requirements of Steep-Slope Roof Underlays in North America and the United Kingdom," *Proceedings, North American Conference on Roofing Technology*, NRCA, Rosemont, IL, 1999, pp. 112–118.

[3] Fricklas, R., Carlson, J., and Simmons, T., "Underlayments for Steep-Slope Roof Construction," *Proceedings, 11th Conference on Roofing Technology*, NRCA, Rosemont, IL, 1995, pp. 10–21.

[4] National Roofing Contractors Association, *Roofing and Waterproofing Manual 5th Edition*, NRCA, Rosemont, IL, 2001.

[5] Canadian Commission on Building and Fire Codes, *The National Building Code of Canada*, National Research Council Canada, Ottawa, Canada, 1995.

[6] National Roofing Contractors Association, *2005-2006 Steep-slope Roofing Materials Guide*, NRCA, Rosemont, IL, 2005.

[7] National Roofing Contractors Association, *2004-05 Low-slope Roofing Materials Guide*, NRCA, Rosemont, IL, 2004.

[8] Griffin, C. and Fricklas, R., *The Manual of Low-Slope Roof Systems*, 3rd ed., McGraw-Hill Inc., New York, 1996 (a 4th edition was published in 2006).

[9] Sheet Metal and Air Conditioning Contractors National Association, *Architectural Sheet Metal Manual 6th Edition*,

SMACNA, Chantilly, VA, 2003.
[10] Patterson, S. and Mehta, M., *Roofing Design and Practice*, Prentice Hall, Upper Saddle River, NJ, 2001.
[11] Laaly, H., *The Science and Technology of Traditional and Modern Roofing Systems*, Laaly Scientific Publishing, Los Angeles, CA, 1992.
[12] Griffin, C. W., "Draining the Roof," *Roof Design*, HBJ Publications, Cleveland, OH, March 1983.
[13] Tobiasson, W., "Roofs in Cold Regions," American Society of Civil Engineers Preprint 80-172A, New York, NY., 1980.
[14] Powell, F. and Robinson, H., "The Effect of Moisture on the Heat Transfer Performance of Insulated Flat-Roof Constructions," *Building Science Series* 37, National Bureau of Standards, Washington, DC, 1971.
[15] Baker, M., "Built-up Roofing," *Canadian Building Digest 24*, National Research Council of Canada, Division of Building Research, Ottawa, Canada, 1961.
[16] Lstiburek, J., and Carmody, J., *Moisture Control Handbook*, Van Nostrand Reinhold, New York, 1993.
[17] Condren, S., "Vapor Retarders in Roofing Systems: When are They Necessary?," *Moisture Migration in Buildings, ASTM STP 779*, ASTM International, West Conshohocken, PA, 1982, pp. 5–27.
[18] Metal Building Manufacturers Association, *Metal Roofing Systems Design Manual lst Edition*, MBMA, Cleveland, OH, 2000.
[19] U. S. Army Corps of Engineers, "Structural Considerations for Metal Roofing," Engineering Instruction 01S926, Washington, DC, 1997.
[20] Stephenson, F., "Design Considerations for Standing Seam Roofs," *Roof Design*, Vol. 1, No. 3, HBJ Publications, Cleveland, OH, Sept. 1983.
[21] Tobiasson, W., and Buska, J., "Standing Seam Metal Roofing Systems in Cold Regions," *Proceedings, 10th Conference on Roofing Technology*, National Roofing Contractors Association, Rosemont, IL, 1993, pp. 34–44.
[22] Tobiasson, W., Korhonen, C., Coutermarsh, B., and Greatorex, A., "Can Wet Roof Insulation be Dried Out?," *Thermal Insulation, Materials and Systems for Energy Conservation in the 80's, ASTM STP 789*, ASTM International, West Conshohocken, PA, 1983, pp. 626–639.
[23] Tobiasson, W., Tantillo, T., and Buska, J., "Ventilating Cathedral Ceilings to Prevent Problematic Icings on Their Eaves," *Proceedings, North American Conference on Roofing Technology*, National Roofing Contractors Association, Rosemont, IL, 1999, pp. 84–97.
[24] Asphalt Roofing Manufacturers Association, "Ventilation and Moisture Control for Residential Roofing," ARMA Tech. Bulletin, Calverton, MD, 1997.
[25] National Roofing Contractors Association, "Ventilation for Steep-Slope Roof Assemblies," Bulletin 98-2, NRCA, Rosemont, IL, May 1998.
[26] Corbin, R., "Attic Ventilation: Why It's Necessary," *Interface*, Roof Consultants Institute, Raleigh, NC, Vol. XVIII, No. 8, Aug. 2000, pp. 20–22.
[27] Rose, W. and TenWolde, A., "Venting of Attics and Cathedral Ceilings," *ASHRAE J.*, Oct. 2002, American Society of Heating, Refrigerating and Air-Conditioning Engineers, Inc., Atlanta, GA, 2002, pp. 26–33.
[28] Tobiasson, W., Buska, J., and Greatorex, A., "Guidelines for Ventilating Attics and Cathedral Ceilings to Avoid Icings at Their Eaves," *Proceedings, Performance of Exterior Envelopes of Whole Buildings VIII*, Department of Energy, Washington, DC, 2001, pp. 1–9.
[29] Asphalt Roofing Manufacturers Association, "Preventing Damage from Ice Dams," ARMA Tech. Bulletin, Calverton, MD, 1993.
[30] Ziegler, R., "Ice Dam Membranes," *Interface*, Roof Consultants Institute, Raleigh, NC, Vol. XIX, No. 4, April 2001, pp. 18–21.
[31] International Code Council, *International Building Code 2003*, ICC, Falls Church, VA, 2002.
[32] International Code Council, *International Residential Code 2000*, ICC, Falls Church, VA, 2000.
[33] International Code Council, *International Energy Conservation Code 2000*, ICC, Falls Church, VA, 1999.
[34] Bushing, H., Mathey, R., Rossiter, Jr., W., and Cullen, W., "Effects of Moisture in Built-Up Roofing—A State-of-the-Art Literature Survey," Technical Note 965, National Bureau of Standards, Washington, DC, 1978.
[35] Bushing, H., "Effects of Moisture and Temperature on Roofing Membranes in Thermally Efficient Roofing Systems," *Proceedings, 5th Conference on Roofing Technology*, National Roofing Contractors Association, Rosemont, IL, 1979, pp. 52–59.
[36] Joy, F., "Premature Failure of Built-Up Roofing," Pennsylvania State University, College of Engineering Better Building Report 5, 1963.
[37] Schwartz, T. and Cash, C., "Equilibrium Moisture Content of Roofing and Roof Insulation Materials and the Effect of Moisture on the Tensile Strength of Roofing Felts," *Proceedings, 1st International Symposium on Roofing Technology*, National Roofing Contractors Association, Oak Park, IL, 1977, pp. 238–243.
[38] Laaly, H., "Effect of Moisture on the Strength Characteristics of Built-up Roofing Felts," *Roofing Systems, ASTM STP 603*, ASTM International, West Conshohocken, PA, 1976, pp. 104–113.
[39] Laaly, H., "Effect of Moisture and Freeze-Thaw Cycles on the Strength of Bituminous Built-up Roofing Membranes," *Proceedings, Symposium on Roofing Technology*, National Roofing Contractors Association, Oak Park, IL, 1977, pp. 244–251.
[40] Cash, C., "Low-Temperature Shrinkage of Membranes Due to Moisture Loss," *Proceedings, 2nd International Symposium on Roofs and Roofing*, Society of Chemical Industry, London, England, Vol. 1, 1981, pp. 573–584.
[41] Shuman, E., "Moisture-Thermal Effects Produce Erratic Motions in Built-Up Roofing," *Engineering Properties of Roofing Systems, ASTM STP 409*, ASTM International, West Conshohocken, PA, 1967, pp. 41–70.
[42] Murray, A., Paroli, R., and Booth, R., "Blistering in Built-Up Roofs: A Review," *Proceedings, 4th International Symposium on Roofing Technology*, National Roofing Contractors Association, Rosemont, IL, 1997, pp. 302–307.
[43] Blanchette, M., "Common Issues with BUR Systems," *Professional Roofing*, National Roofing Contractors Association, Rosemont, IL, Vol. 29, No. 8, Nov. 1999, pp. 29–32.
[44] Cullen, W., "Research and Performance Experience of Asphalt Shingles," *Proceedings, 10th Conference on Roofing Technology*, NRCA, Rosemont, IL, 1993, pp. 6–12.
[45] Noon, M., and Blanchard, W., "Asphalt Shingles—A Century of Success and Improvement," *Proceedings, 10th Conference on Roofing Technology*, NRCA, Rosemont, IL, 1993, pp. 23–33.
[46] Dupuis, R. and Graham, M., "The Effects of Moisture and Heat on the Tear Strength of Glass Fiber-Reinforced Asphalt Shingles," *Proceedings, 12th Conference on Roofing Technology*, National Roofing Contractors Association, Rosemont. IL, 2002, pp. 1–14.
[47] Bollnow, T., "Which Asphalt Shingle is Better?," *Professional Roofing*, National Roofing Contractors Association, Rosemont, IL, Sept. 1999, p. 70.
[48] W. R. Grace & Co., *Contractors Guide*, W. R. Grace, Cambridge, MA, 2004.
[49] Higgs, D., "Unseen Underlayment Can Be Untroubled Link in

Roofing System," *Roofer*, Construction Publications Inc., Ft. Myers, FL, Vol. 15, No. 8, Aug. 1995, pp. 28–29.

[50] Still, M., LeVan, S., and Shuffleton, J., "Degradation of Fire-Retardant-Treated Plywood: Current Theories and Approaches," *Proceedings, 1991 International Symposium on Roofing Technology*, National Roofing Contractors Association, Rosemont, IL, 1991, pp. 517–522.

[51] Tobiasson, W., Young, B., and Greatorex, A., "Freeze-Thaw Durability of Common Roof Insulations," *Proceedings, 4th International Symposium on Roofing Technology*, National Roofing Contractors Association, Rosemont, IL, 1997, pp. 352–359.

[52] Dechow, F. and Epstein, K., "Laboratory and Field Investigations of Moisture Absorption and its Effect on Thermal Performance of Various Insulations," *Thermal Transmission Measurements of Insulation, ASTM STP 660*, ASTM International, West Conshohocken, PA, 1978, pp. 234–260.

[53] Epstein, K. A. and Putnam, L. E., "Performance Criteria for the Protected Membrane Roof System," *Proceedings, 1st International Symposium on Roofing Technology*, National Roofing Contractors Association, Rosemont, IL, 1977, pp. 49–60.

[54] Larsson, L. E., Ondrus, J., and Pattersson, B-A., "The Protected Membrane Roof (PMR)—A Study Combining Field and Laboratory Tests," *Proceedings, 1st International Symposium on Roofing Technology*, National Roofing Contractors Association, Rosemont, IL, 1977, pp. 86–92.

[55] Tobiasson, W., Greatorex, A., and Van Pelt, D., "Wetting of Polystyrene and Urethane Roof Insulations in the Laboratory and on a Protected Membrane Roof," *Thermal Insulation: Materials and Systems, ASTM STP 922*, ASTM International, West Conshohocken, PA, 1984, pp. 421–430.

[56] McFadden, T., "Moisture Effects on Extruded Polystyrene Insulation," *Proceedings, 4th International Conference on Cold Regions Engineering*, American Society of Civil Engineers, New York, 1986, pp. 685–694.

[57] Hedlin, C., "Effect of Moisture on Thermal Resistance of Some Insulations in a Flat Roof Under Field-Type Conditions," *Thermal Insulation, Materials, and Systems for Energy Conservation in the 1980's, ASTM STP 789*, ASTM International, West Conshohocken, PA, 1983, pp. 602–625.

[58] Tobiasson, W. and Ricard, J., "Moisture Gain and Its Thermal Consequence for Common Roof Insulations," *Proceedings, 5th Conference on Roofing Technology*, National Roofing Contractors Association, Oak Park, IL, 1979, pp. 4–16.

[59] Knab, L., Jenkins, R., and Mathey, G., "The Effect of Moisture on the Thermal Conductivity of Roofing Systems," *NBS Building Science Series 123*, National Bureau of Standards, Washington, DC, 1980.

[60] Hedlin, C., "Moisture Gains by Foam Plastic Roof Insulations Under Controlled Temperature Gradients," *Journal of Cellular Plastics*, Vol. 13, No. 5, Sept.–Oct. 1977, pp. 313–319.

[61] Tobiasson, W., Greatorex, A., and Van Pelt, D., "New Wetting Curves for Common Roof Insulations," *Proceedings, 1991 International Symposium on Roofing Technology*, National Roofing Contractors Association, Rosemont, IL, pp. 383–390.

[62] Hedlin, C. P., "Some Design Characteristics of Insulation in Flat Roofs Related to Temperature and Moisture," *Proceedings, 5th Conference on Roofing Technology*, National Roofing Contractors Association, Rosemont, IL, 1979, pp. 17–25.

[63] Canon, R., "Phenolic Foam Class Action Settlements," *Interface*, Roof Consultants Institute, Raleigh, NC, Vol. XVIII, No. 11, Nov. 2000, pp. 32–37.

[64] National Roofing Contractors Association, *Repair Manual for Low-slope Membrane Roof Systems*, NRCA, Rosemont, IL, 1997.

[65] National Roofing Contractors Association, *Manual for Inspection and Maintenance of Built-Up and Modified Bitumen Roof Systems: A Guide for Building Owners*, NRCA, Rosemont, IL, 1996.

[66] Single Ply Roofing Institute and National Roofing Contractors Association, *SPRI/NRCA Manual of Roof Inspection, Maintenance, and Emergency Repair for Existing Single-Ply Roofing Systems*, NRCA, Rosemont, IL, 1992.

[67] National Roofing Contractors Association, *Manual for Inspection and Maintenance of Sprayed Polyurethane Foam-based Roof Systems: A Guide for Building Owners*, NRCA, Rosemont, IL, 1998.

[68] National Roofing Contractors Association, *Manual for Inspection and Maintenance of Low-slope Structural Metal Panel Roof Assemblies: A Guide for Building Owners*, NRCA, Rosemont, IL, 2002.

[69] National Roofing Contractors Association, *Manual for Inspection and Maintenance of Steep-slope Architectural Metal Panel Roof Assemblies: A Guide for Building Owners*, NRCA, Rosemont, IL, 2003.

[70] Shahin, M., Bailey, D., and Brotherson, D., "Membrane and Flashing Condition Indexes for Built-Up Roofs: Volume 1: Development of the Procedure," USA CERL Tech. Report M 87/13, Construction Engineering Research Laboratory, Champaign, IL, Vol. I, 1987.

[71] Shahin, M., Bailey, D., and Brotherson, D., "Membrane and Flashing Condition Indexes for Built-Up Roofs: Volume II: Inspection and Distress Manual," CERL Tech. Report M 87/13, Construction Engineering Research Laboratory, Champaign, IL, Vol. II, 1987.

[72] Bailey, D., Brotherson, D., Tobiasson, W., and Knehans, A., "ROOFER: An Engineered Management System (EMS) for Bituminous Built-Up Roofs," CERL Tech. Report M 90/04, Construction Engineering Research Laboratory, Champaign, IL, 1989.

[73] Bailey, D., Brotherson, D., Tobiasson, W., Foltz, S., and Knehans, A., "ROOFER: Membrane and Flashing Condition Indexes for Single-Ply Membrane Roofs-Inspection and Distress Manual," CERL Tech. Report FM 93/11, Construction Engineering Research Laboratory, Champaign, IL, 1993.

[74] Bailey, D., "ROOFER: Steep Roofing Inventory Procedures and Inspection and Distress Manual for Asphalt Shingle Roofs," CERL Tech. Report 99/100, Construction Engineering Research Laboratory, Champaign, IL, 1999.

[75] Tobiasson, W., "Condensation Control in Low-Slope Roofs," *Moisture Control in Buildings*, Building Thermal Envelope Coordinating Council, Washington, DC, 1984, pp. 47–59.

[76] American Society of Heating, Refrigerating and Air-Conditioning Engineers, *ASHRAE Handbook: 2001 Fundamentals*, ASHRAE, Atlanta, GA, 2001.

[77] Achenbach, P. and Trechsel, H., "Problem Definition Study of Requirements for Vapor Barriers in the Building Envelope," Report CR 83.006, Naval Civil Engineering Laboratory, Port Hueneme, CA, 1982.

[78] Hoher, K., "Environmental and Climatic Factors in the Specification of Roofing Membranes," Sarnafil (U.S.) Inc., Canton, MA, 1982.

[79] Lstiburek, J., "How to Control Moisture in Houses," *Custom Builder*, The Willows Publishing Co., Peterborough, NH, Vol. 2, No. 12, Dec. 1987, pp. 9–14.

[80] DiLenardo, B., Brown, W., Dalgleish, W., Kumaran, K., and Poirier, G., "Technical Guide for Air Barrier Systems for Exterior Walls of Low-Rise Buildings," Canadian Construction Materials Centre, National Research Council Canada, Ottawa, Ontario, 1995.

[81] Anis, W., "Achieving Working and Effective Air Barriers,"*Interface* (*USA*), Vol. XXI, No. 10, Oct. 2003, pp. 32–41.

[82] Tobiasson, W., "Vapor Retarders for Membrane Roofing Sys-

tems," *Proceedings, 9th Conference on Roofing Technology*, National Roofing Contractors Association, Oak Park, IL, 1989, pp. 31–37.
[83] Lstiburek, J., *Builders Guide: Cold Climates*, Building Science Corp., Westford, MA, Feb. 2002.
[84] Lstiburek, J., *Builders Guide: Hot-Dry and Mixed-Dry Climates*, Building Science Corp., Westford, MA, June 1998.
[85] Lstiburek, J., *Builders Guide: Mixed-Humid Climates*, Building Science Corp., Westford, MA, March 2001.
[86] Lstiburek, J., *Builders Guide: Hot-Humid Climates*, Building Science Corp., Westford, MA, Jan. 2002.
[87] Nevander, L., "Roofs and Roofing in Sweden," *Proceedings, 1st International Symposium on Roofing Technology*, National Roofing Contractors Association, Oak Park, IL, 1977, pp. 8–17.
[88] Quirouette, R. L., "The Difference Between a Vapour Barrier and an Air Barrier," Building Practice Note 54, National Research Council of Canada, Division of Building Research, Ottawa, Canada, 1985.
[89] Desjarlais, A. and Karagiozis, A., "Review of Existing Criteria and Proposed Calculations for Determining the Need for Vapor Retarders," *Proceedings, North American Conference on Roofing Technology*, National Roofing Contractors Association, Rosemont, IL, 1999, pp. 79–83.
[90] Tobiasson, W. and Harrington, M., "Vapor Drive Maps for the USA," *Proceedings, Thermal Performance of the Exterior Envelopes of Buildings III*, American Society of Heating, Refrigerating and Air-Conditioning Engineers, Atlanta, GA, 1985, pp. 663–672.
[91] Hogan, L., "Using Two Layers of Insulation in Single-Ply Roof Systems," *Interface*, Roof Consultants Institute, Raleigh, NC, Vol. XIX, No. 6, June 2001, pp. 11–14.
[92] Desjarlais, A., "A New Look at Moisture Control in Low-Slope Roofing," *Proceedings, 4th International Symposium on Roofing Technology*, National Roofing Contractors Association, Rosemont, IL, 1997, pp. 341–346.
[93] Kyle, D. and Desjarlais, A., "Assessment of Technologies for Constructing Self-Drying Low-Slope Roofs," ORNL/CON-380, Oak Ridge National Laboratory, Oak Ridge, TN, 1994.
[94] Desjarlais, A., "Self-Drying Roofs: What! No Dripping!," *Proceedings, Thermal Performance of the Exterior Envelopes of Buildings VI Conference*, American Society of Heating, Refrigerating and Air-Conditioning Engineers, Inc., Atlanta, GA, 1995, pp. 763–773.
[95] Dregger, P., "Air Infiltration: The Enemy of Wind Resistance and Condensation Control," *Interface*, Roof Consultants Institute, Raleigh, NC, Vol. XX, No. 6, June 2002, pp. 21–29.
[96] Baker, M. and Hedlin, C., "Venting of Flat Roofs," *Canadian Building Digest 176*, National Research Council of Canada, Division of Building Research, Ottawa, Canada, 1976.
[97] Tobiasson, W., "Venting of Built-Up Roofing Systems," *Proceedings, 6th Conference on Roofing Technology*, National Roofing Contractors Association, Oak Park, IL, 1981, pp. 16–21.
[98] Korhonen, C., "Blistering of Built-Up Roof Membranes: Pressure Measurements," CRREL Special Report 86-29, Hanover, NH, 1986.
[99] Hoher, K., "Environmental and Climatic Factors in the Specification of Roofing Membranes," Sarnafil (U.S.) Inc., Canton, MA, 1982.
[100] Midwest Roofing Contractors Association, "Recommended Performance Criteria for PVC Single-Ply Roof Membrane Systems," MRCA MP-10, MRCA, Kansas City, MO, 1981.
[101] Dupuis, R., "Field Survey of Moisture Gain Behavior Within Single-Ply Roof Systems," *Proceedings, 2nd International Symposium on Roofing Technology*, National Roofing Contractors Association, Chicago, IL, 1985, pp. 261–264.
[102] Walters, R. B., "Condensation Modeling of EPDM Single-Membrane Roof Systems," *Proceedings, 2nd International Symposium on Roofing Technology*, National Roofing Contractors Association, Oak Park, IL, 1985, pp. 391–395.
[103] Nielson, A. F., and Paulsen, E. M., "Thermal Design of Highly Insulated Inverted Roofs," *Proceedings, 2nd International Symposium on Roofing Technology*, National Roofing Contractors Association, Oak Park, IL, 1985, pp. 293–296.
[104] Hedlin, C. P., "Moisture Content in Protected Membrane Roof Insulations—Effect of Design Features," *Roofing Systems, ASTM STP 603*, ASTM International, West Conshohocken, PA, 1976, pp. 36–50.
[105] Aamot, H. W. C. and Schaefer, D., "Protected Membrane Roofs in Cold Regions," CRREL Report 76-2, Cold Regions Research and Engineering Laboratory, Hanover, NH, 1976.
[106] Schaefer, D., "Water Absorption of Insulation in Protected Membrane Roofing Systems," CRREL Report 76-38, Cold Regions Research and Engineering Laboratory, Hanover, NH, 1976.
[107] Christensen, G., "Protected Membrane Roofs," *Proceedings, Thermal Performance of the Exterior Envelopes of Buildings III*, American Society of Heating, Refrigerating and Air Conditioning Engineers, Atlanta, GA, 1985, pp. 974–984.
[108] Beech, J. C., "The Performance of Light-Weight Inverted Flat Roofs," *Proceedings, 2nd International Symposium on Roofing Technology*, National Roofing Contractors Association, Oak Park, IL, 1985, pp. 285–296.
[109] Tobiasson, W., Buska, J., and Young, B., "Reroofing with Protected Membranes," Cold Regions Research and Engineering Laboratory (CRREL) videotape, Hanover, NH, 1989.
[110] Hutcheon, N. and Handegord, G., *Building Science for a Cold Environment*, John Wiley and Sons, Toronto, Canada, 1983.
[111] Cornish, J., and Sanders, C., "Parameters Affecting Condensation in Pitched Roofs," *Proceedings, 2nd International Symposium on Roofs and Roofing*, Society of Chemical Industry, London, England, Vol. 1, 1981, pp. 331–342.
[112] Burch, D. and Harrje, D., "A State-of-the-Art Research Assessment for Residential Attic Condensation," *Proceedings, BTECC Workshop "Moisture Control in Buildings*," Building Thermal Envelope Coordinating Council, Washington, DC, 1985, pp. 21–29.
[113] Eyre, D. and Jennings, D., "Air-Vapour Barriers," Energy, Mines and Resources Canada, Ottawa, Canada, 1983.
[114] Marbek Resource Consultants, *Handbook on Air Sealing Homes for Energy Conservation*, Energy, Mines and Resources Canada, Ottawa, Canada, 1983.
[115] Kearns, S., "Framing a Cold Roof," *Fine Homebuilding*, The Taunton Press, Taunton, MA, Issue 63, Nov. 1990, pp. 32–44.
[116] Mackinlay, I. and Flood, R., "Roof Slopes, Ice Dams and Cold Roofs," *Interface*, Roof Consultants Institute, Raleigh, NC, Vol. XVII, No. 1, Jan. 1999, pp. 5–9.
[117] Marsh, P., *Thermal Insulation and Condensation*, The Construction Press, Longman Inc., New York, 1979.
[118] Buska, J., Tobiasson, W., and Greatorex, A., "Roof Ventilation to Prevent Problematic Icings at Eaves," *ASHRAE Transactions*, Paper TO-98-17-4, ASHRAE, Atlanta, GA, Vol. 104, Pt. 2, 1998, pp. 1–8.
[119] Tobiasson, W., "Roof Design in Cold Regions," *Proceedings, 1st International Conference on Snow Engineering*, Special Report 89-6, Cold Regions Research and Engineering Laboratory, Hanover, NH, 1989, pp. 462–472.
[120] de Marne, H., "Field Experience in Control and Prevention of Leaking from Ice Dams in Northern New England," *Proceedings, 1st International Conference on Snow Engineering*, Special Report 89-6, Cold Regions Research and Engineering Laboratory, Hanover, NH, 1989, pp. 473–482.
[121] Grange, H. L. and Hendricks, L. T., "Roof-Snow Behavior and

Ice-Dam Prevention in Residential Housing," Bulletin 399, University of Minnesota Agricultural Extension Service, St. Paul, MN, 1976.

[122] Klinge, A. F., "Ice Dams," *Popular Science*, Times Mirror Magazines Inc., New York, Nov. 1978, pp. 119–120.

[123] Tobiasson, W., "Wood-Frame Roofs and Moisture," *Custom Builder*, Peterborough, NH, March 1988, pp. 33–37.

[124] American Society of Civil Engineers, "Minimum Design Loads for Buildings and Other Structures," ASCE Standard 7-02, ASCE, Reston, VA, 2002.

[125] Buska, J., Tobiasson, W., Greatorex, A., and Fyall, W., "Electric Heating Systems for Combating Icing Problems on Metal Roofs," *Proceedings, 4th International Symposium on Roofing Technology*, NRCA, Rosemont, IL, 1997, pp. 153–162.

[126] Buska, J., and Tobiasson, W., "Minimizing the Adverse Effects of Snow and Ice on Roofs," *Proceedings, International Conference on Building Envelope Systems and Technologies* (*ICBEST-2001*), Institute for Research in Construction, National Research Council Canada, Ottawa, Ontario, 2001, pp. 339–346.

[127] Tobiasson, W., Buska, J., and Greatorex, A., "Snow Guards for Metal Roofs," *Interface*, Roof Consultants Institute, Raleigh, NC, Vol. XV, No. 1, Jan. 1997, pp. 12–19.

[128] Dickens, H. and Hutcheon, N., "Moisture Accumulation in Roof Spaces Under Extreme Winter Conditions," Technical Paper 228, National Research Council of Canada, Division of Building Research, Ottawa, Canada, 1966.

[129] Hansen, A., "Points to Watch When Insulating Wood-Framed Flat Roofs," *Canadian Builder*, Vol. XIII, No. 5, May 1963, p. 66.

[130] Warren, J. W., "Condensation in Flat Roof Spaces," *Proceedings, Thermal Performance of the Exterior Envelopes of Buildings III*, American Society of Heating, Refrigerating and Air Conditioning Engineers, Atlanta, GA, 1985, pp. 539–555.

[131] Tamura, G., Kuester, G., and Handegord, G., "Condensation Problems in Flat Wood Frame Roofs," *Proceedings, 2nd International Symposium on Moisture Problems in Buildings*, Rotterdam, The Netherlands (also available as Paper NRCC 14589, National Research Council of Canada, Ottawa, Canada, 1974).

[132] Building Research Station, "Ventilation of Cold Deck Flat Roofs," *BRE News of Construction Research*, Building Research Station, Garston, Hertfordshire, UK, August 1986.

[133] Korsgaard, V., Christensen, G., Prebensen, K., and Bunch-Nielsen, T., "Ventilation of Timber Flat Roofs," *Building Research and Practice*, Paris, France, Vol. 13, No. 4, July–Aug. 1985, pp. 211–219.

[134] Tobiasson, W., "Vapor Retarders to Control Summer Condensation," *Proceedings, Thermal Performance of the Exterior Envelopes of Buildings IV*, American Society of Heating, Refrigerating and Air-Conditioning Engineers, Atlanta, GA, 1989, pp. 566–572.

[135] Fricklas, R., "Insulation: Does Below-Deck Placement Increase Value?" *Specifying Engineer*, Feb. 1977, pp. 66–68.

[136] Stewart, M., "Moisture Control in Retrofit Roof Insulations," *Thermal Insulation, Materials and Systems for Energy Conservation in the 80's, ASTM STP 789*, ASTM International, West Conshohocken, PA, 1983, pp. 640–650.

[137] Hart, G. H. and Carlson, T. C. G., "Moisture Condensation Above Insulated Suspended Ceilings—Experimental Results," *Proceedings, Thermal Performance of the Exterior Envelopes of Buildings*, Publication SP 28, American Society of Heating, Refrigerating and Air-Conditioning Engineers, New York, 1981, pp. 847–855.

[138] Musgrave, D. S., "Moisture Transport in a Metal Building Roof Insulation System," *Moisture Migration in Buildings, ASTM STP 779*, ASTM International, West Conshohocken, PA, 1982, pp. 54–64.

[139] Fricklas, R., "Technical Aspects of Retrofitting," *Proceedings, 5th Conference on Roofing Technology*, National Roofing Contractors Association, Oak Park, IL, 1979, pp. 30–43.

[140] Sheahan, J., "Early Leak Detection Capabilities," *Interface*, Roof Consultants Institute, Raleigh, NC, Vol. XIX, No. 2, Feb. 2001, pp. 3–12.

[141] Bailey, D., Ditman, J., Dupuis, R., and Buckner, A., "Survey of Passive Leak Detection Technologies for Membrane Roofing," USACERL Tech. Report FM-94/04, Construction Engineering Research Laboratory, Champaign, IL, 1994.

[142] Bailey, D., Ditman, J., Dupuis, R., and Buckner, A., "Laboratory Investigation of Selected Sensors for Use with Passive Roof Leak Detection Systems," USACERL Tech. Report 98/09, Construction Engineering Research Laboratory, Champaign, IL, 1998.

[143] Kilpatrick, D., "Mother Nature Offers Alternative to Traditional NDT Roof Moisture Surveys," *Interface*, Roof Consultants Institute, Raleigh, NC, Vol. XIX, No. 2, Feb. 2001, pp. 22–24.

[144] Tobiasson, W. and Korhonen, C., "Roof Moisture Surveys: Yesterday, Today and Tomorrow," *Proceedings, 2nd International Conference on Roofing Technology*, National Roofing Contractors Association, Rosemont, IL, pp. 438–443 (also available as CRREL Misc. Paper MP 2040, Hanover, NH, 1985).

[145] Jenkins, D., Mathey, R., and Knab, L., "Moisture Detection in Roofing by Nondestructive Means—A State-of-the-Art Survey," NBS Technical Note 1146, National Bureau of Standards, Washington, DC, 1981.

[146] Robinson, J., Bradford, D., Mitchell, J., and Majkoski, P., "A Comparison of Three Different Technologies for Performing Nondestructive Roof Moisture Survey," *Proceedings, North American Conference on Roofing Technology*, National Roofing Contractors Association, Rosemont, IL, 1999, pp. 47–55.

[147] Lucier, R., "Daytime Infrared Roof Inspections," *Interface*, Roof Consultants Institute, Raleigh, NC, Vol. XXII, No. 8, Aug. 2004, pp. 20–22.

[148] Stockton, G., "The Case for Aerial Infrared," *Interface*, Roof Consultants Institute, Raleigh, NC, Vol. XVIII, No. 4, April 2000, pp. 25–29.

[149] Korhonen, C., Tobiasson, W., and Greatorex, A., "Comparison of Aerial to On-the-Roof Infrared Moisture Surveys," *Proceedings of the Society of Photo-Optical Instrumentation Engineers* (*SPIE*), Thermosense VI, Bellingham, WA, Vol. 446, 1984, pp. 95–105.

[150] Thornton, S., "Electronic Leak Detection," *Interface*, Roof Consultants Institute, Raleigh, NC, Vol. XIX, No. 2, Feb. 2001, pp. 15–18.

[151] Capolino, R., "Integrity Testing," *Interface*, Roof Consultants Institute, Raleigh, NC, Vol. XXII, No. 8, Aug. 2004, pp. 12–18.

[152] Cash, C. G., "Moisture and Built-Up Roofing," *Proceedings, 2nd International Symposium on Roofing Technology*, National Roofing Contractors Association, Rosemont, IL, 1985, pp. 416–427.

[153] Hedlin, C. P., "Heat Flow Through a Roof Insulation Having Moisture Contents Between 0 and 1 Percent by Volume in Summer," *ASHRAE Transactions*, American Society of Heating, Refrigerating and Air-Conditioning Engineers, Atlanta, GA, Vol. 94, 1988, pp. 1579–1594.

[154] Sandberg, P. I., "Thermal Resistance of a Wet Mineral Fiber Insulation," *Thermal Insulation: Materials and Systems, ASTM STP 922*, ASTM International, West Conshohocken, PA, 1987, pp. 394–404.

[155] Courville, G. E., Childs, P. W., and Linkous, R. L., "Analysis of Roof Systems Thermal Performance from Field Data," *Proceedings, 3rd International Symposium on Roofing Technology*, National Roofing Contractors Association, Rosemont,

IL, 1991, pp. 115–123.

[156] Hedlin, C. P., "Some Factors Affecting Drainage of Moisture from Wet Insulation in Flat Roofs," *Moisture Migration in Buildings, ASTM STP 779*, ASTM International, West Conshohocken, PA, 1982, pp. 28–40.

[157] Korsgaard, V. and Pedersen, C. R., "Transient Moisture Distribution in Flat Roofs with Hygro Diode Vapor Retarder," *Proceedings, Thermal Performance of the Exterior Envelopes of Buildings IV*, American Society of Heating, Refrigerating and Air-Conditioning Engineers, Atlanta, GA, 1989, pp. 556–565.

[158] Korsgaard, V. and Pedersen, C., "Laboratory and Practical Experience with a Novel Water-Permeable Vapor Retarder," *Proceedings, Thermal Performance of the Exterior Envelopes of Buildings V*, American Society of Heating, Refrigerating and Air-Conditioning Engineers, Atlanta, GA, 1992, pp. 480–490.

[159] Kuenzel, H., "More Moisture Load Tolerance of Construction Assemblies Through the Application of a Smart Vapor Retarder," *Proceedings, Thermal Performance of the Exterior Envelopes of Buildings VII*, American Society of Heating, Refrigerating and Air-Conditioning Engineers, Atlanta, GA, 1998, pp. 129–132.

[160] Funk, S., "Suggested Repair Specifications for Built-Up Roofs over Wet Lightweight Concrete Decks," *Proceedings, 2nd International Symposium on Roofing Technology*, National Roofing Contractors Association, Chicago, IL, 1985, pp. 18–36.

[161] Desjarlais, A., Petrie, D., Christian, J., McLain, H., and Childs, P., "A Whole Building Demonstration of Re-cover Over an Existing Wet Roof," *Proceedings, 11th Conference on Roofing Technology*, National Roofing Contractors Association, Rosemont, IL, 1995, pp. 111–119.

[162] Patten, J., Desjarlais, A., Sheahan, J., Choiniere, S., and Garrigus, P., "The Pembroke Project: A Full-Scale Demonstration of Roof Re-Cover," *Proceedings, 4th International Symposium on Roofing Technology*, National Roofing Contractors Association, Rosemont, IL, 1997, pp. 334–340.

[163] Desjarlais, A., Sheahan, J., and Garrigus, P., "Reroofing Over Failed Roofs Containing Moisture," *Interface*, Roof Consultants Institute, Raleigh, NC, Vol. XIX, No. 9, Sept. 2001, pp. 7–16.

[164] Jerga, L., "Re-Cover: Reroofing by Superimposing New Roof Systems Over Existing—A Dissenting Opinion," *Proceedings, 4th International Symposium on Roofing Technology*, National Roofing Contractors Association, Rosemont, IL, 1997, pp. 185–191.

MNL18-EB/Oct. 2009

17

Moisture Control for New Residential Buildings

Joseph Lstiburek[1]

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
- 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.[2]

Of the mechanisms involved in the surface wetting and interstitial wetting of building assemblies, the most significant is liquid flow where rain and groundwater are the moisture sources. Controlling rain entry above grade and groundwater entry below 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 a similar manner by liquid flow (rain and groundwater as moisture sources). Accordingly, while the rain loads may vary, techniques for the control of liquid flow 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 can be different based on climate and may not be interchangeable.

The "duality" that air movement and vapor diffusion possess with respect to their ability to move moisture from both the interior and exterior into the building enclosure 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 enclosure 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.

Climate Dependence of Moisture Control

Buildings should be suited to their environment, both exterior and interior. It is not typically practical to construct the same manner of building in Montreal, Memphis, Mojave, and Miami. It is cold in Montreal, humid in Memphis, hot and dry in Mojave, and hot and wet in Miami. And that is just the outside environment. It is also not desirable to construct the same manner of building to enclose a garage, house, and swimming pool. The interior environment also clearly influences design of the building enclosure and mechanical system.

Environmental Loads

Hygro-thermal regions and rain exposure zones are defined as environmental loads [1]. These loads should be used in the design, construction, operation, diagnosis, and understanding of building enclosures and mechanical systems (see sidebar). The mantra "location, location, and location" applies not just to real estate but also to building science.

Surface Mold and Other Biological Growth

The following conditions are necessary and sufficient for mold and other biological growth to occur on surfaces:

[1] *Building Science Corporation, www.buildingscience.com*

[2] A good example is a very permeable polymeric type of water resistive barrier (WRB) with WV permeability about 100 perms that allows diffusion drying but also wetting under reversal of thermal gradients during solar radiation periods.

- mold spores must be present
- a nutrient base must be available (most surfaces contain nutrients)
- temperature range between 40°F (4.4°C) and 100°F (37.7°C) relative
- humidity adjacent to surface above 70 % [2].

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 other biological growth can be controlled. Since relative humidities are dependent on both temperature and vapor pressure, mold control is dependent on controlling both the temperature and vapor pressure near surfaces.

In cold and very cold 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 enclosure 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 cold climates during the heating season are limited to the 25 % to 30 % 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 enclosure), 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 30 % 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 30 % to 40 % relative humidity range at 700°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 these climate zones.

In hot, humid 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 hot humid climates is limiting 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 slight positive air pressure to the exterior (approximately 2 Pa to 3 Pa). Pressurization of building enclosures is. expedited by airtight construction (200 $l/(s \cdot m^2)$@75 Pa) [3].

In hot humid climates interior moisture levels within the conditioned space should also be limited to 60 % relative humidity at 75°F (23.8°C) by dehumidification, air conditioning and source control to prevent mold growth on the interior surfaces within the conditioned space.

Experience has also shown that where conditions 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 [4].

General Moisture Control Practices for All Climates

Building assemblies need to be protected from wetting via rainwater, groundwater, air transport, and vapor diffusion. The typical strategies use drainage planes, air barriers, air pressure control, vapor retarders and control of interior moisture levels through ventilation and dehumidification. Climate location and season determine the location of air barriers and vapor retarders, pressurization versus depressurization, and ventilation versus dehumidification.

Moisture usually moves from warm to cold (driven by the thermal gradient) and from more to less (driven by the concentration gradient). In cold climates, moisture from the interior flows towards the exterior by passing through the building enclosure. In hot climates, moisture from the exterior flows toward the cooled interior by passing through the building enclosure.

The most important sources of moisture requiring control are:

- rainwater
- groundwater air
- transport vapor
- diffusion.

Rainwater

The fundamental principle of rainwater control is to shed water by layering materials in such a way that water is directed downwards and outwards from the building or away from the building. It applies to assemblies such as walls, roofs, and foundations, as well as to the components that can be found in walls, roofs, and foundations such as windows, doors, and skylights. It also applies to assemblies that connect to walls, roofs, and foundations such as balconies, decks, railings, and dormers.

Layering materials to shed water applies to the building as a whole. Overhangs can be used to keep water away from walls. Canopies can be used to keep water away from windows, and site grading can be used to keep water away from foundation perimeters.

Drainage is the key to rainwater control:

- drain the site
- drain the ground
- drain the building
- drain the assembly
- drain the opening
- drain the component
- drain the material.

All exterior claddings pass some rainwater; siding leaks, brick leaks, stucco leaks, stone leaks, etc. As such some control of this penetrating rainwater is required. In most walls this penetrating rainwater is controlled by a drainage plane that directs the penetrating rainwater downwards and outwards.

Drainage planes are water repellent materials (building paper, house wrap, foam insulation, etc), which are located behind the cladding and are designed and constructed to drain water that passes through the cladding. They are interconnected with flashings, window and door openings, and other penetrations of the building enclosure to provide drainage of water to the exterior of the building. The materials that form the drainage plane overlap each other shingle fashion or are sealed so that water flow is down and out of the wall.

Reservoir claddings on the exterior of buildings can be a problem. Reservoir claddings are materials that can store rainwater; sponges that get wet when it rains. Once the reservoirs get wet, the stored water can migrate elsewhere and cause problems. Common reservoirs are brick veneers, stuccos, wood siding, wood trim, and fiber cement cladding.

Reservoir claddings should be uncoupled from the building. Back priming (painting all surfaces, back, front, edges, and ends of wood siding, cement siding, and all wood trim) are techniques that can limit the moisture storage issue with these materials.

Back venting brick veneers and installing them over foam sheathings also disconnects or uncouples the brick veneer moisture reservoir from the building. Installing stucco over two layers of building paper or over an appropriate capillary break such foam sheathing similarly addresses stucco reservoirs.

To state an obvious fact: we build outside. And often it rains when we are building outside. This means that walls without roofs on them will get wet. It is not a good idea to build these walls with exterior gypsum board that is paper faced. This is a major concern with party walls or firewalls in multifamily buildings. Glass faced gypsum board or other alternatives should be used.

Groundwater

The fundamental principles of ground water control are to keep rainwater away from the foundation wall perimeter and to drain groundwater with subgrade perimeter drains before it gets to the foundation wall. The subgrade perimeter drain (“footing drain”) should be protected from clogging with a geotextile filter fabric and connected to a sump pump, daylight or municipal drainage system. Drainage requirements apply to slabs, crawlspaces, and basements regardless of whether they are newly constructed or undergoing rehabilitation.

Concrete and masonry are sponges: they can wick water due to capillarity. This is the main reason that damp proofing (the black tar-like coating) is applied to exterior basement walls. The damp-proofing fills in the pores in the concrete and masonry to reduce ground water absorption. The damp-proofing acts as a capillary break.[3] Under concrete floor slabs, the stone layer combined with polyethylene serves a similar function (they act as capillary breaks). Unfortunately, the capillary rise through footings is typically ignored. This can be a major problem if foundation perimeter walls are finished or insulated.

In new construction, a capillary break should be installed on the top of the footing between the footing and the perimeter foundation wall. This can be done by damp-proofing the top of the footing or by installing a membrane at this location.

In new construction, the interior insulation and finishing approach must take into account the moisture migrating up through the footing. This is best accomplished by installing vapor semi-permeable rigid foam insulation on the interior of the assembly to protect the interior finishes and to release the capillary water to the interior in a controlled manner, at a rate that does not damage interior finishes or lead to mold.

The best foams to use on basement walls have a perm rating greater than 1 perm for the full thickness used. This means limiting extruded polystyrene insulation to less than 1-inc. thickness for walls (more than 1 inc. thick and they do not breathe sufficiently) and making sure that the rigid insulation is not faced with polypropylene skins or foil facings. Additionally, since foams need to be protected from fire, and

[3] Another way to provide a capillary break is to apply exterior basement insulation that has capillary breaking properties such as drainable mineral fiber.

this is often done with gypsum board, only latex paint should be used on interior gypsum finishes (since it breathes).

Capillary control also applies to slab-on-grade construction and crawlspaces. Monolithic slabs need plastic ground covers that extend under the perimeter grade beam and upwards to grade. Additionally, the exposed portion of floor slabs should be painted with latex paint to reduce water transmission and a capillary break should be installed under perimeter wall framing.

Air Transport

The fundamental principle of ground air transported moisture is the use of an air barrier. Air barriers are systems of materials designed and constructed to control airflow between a conditioned space and an unconditioned space. The air barrier system is the primary air enclosure boundary that separates indoor (conditioned) air and outdoor (unconditioned) air. fu multi-unit/townhouse/apartment construction, the air barrier system also separates the conditioned air from any given unit and adjacent units. Air barrier systems also typically define the location of the pressure boundary of the building enclosure.

In multi-unit/townhouse/apartment construction, the air barrier system is also the fire barrier and smoke barrier in inter-unit separations. The inter-unit separation must also meet the specific fire resistance rating requirement for the given separation.

The air barrier system also separates garages from conditioned spaces. In this regard the air barrier system is also the "gas barrier" and provides the gas-tight separation between a garage and the remainder of the house or building.

Air barriers are intended to resist the air pressure differences that act on them. Rigid materials such as gypsum board, exterior sheathing materials like plywood or OSB, and supported flexible barriers are typically effective air barrier systems if joints and seams are sealed. Spray foam systems can also act as effective air barrier systems either externally applied over structural elements or internally applied within cavity systems.

Air barrier systems keep outside air out of the building enclosure or inside air out of the building enclosure depending on climate or configuration. Sometimes, air barrier systems do both.

Air barrier systems can be located anywhere in the building enclosure: at the exterior surface, the interior surface, or at any location in between. In cold climates, interior air barrier systems control the exfiltration of interior, often moisture-laden air, whereas exterior air barrier systems control the infiltration of exterior air and prevent wind-washing through cavity insulation systems.

Air barrier systems typically are assembled from materials incorporated in assemblies that are interconnected to create enclosures. Each of these three elements has measurable resistance to airflow. The recommended minimum resistances or air permeance for the three components are listed as follows [3]:

- Material $0.02\ 1/(s \cdot m^2)$@75 Pa
- Assembly $0.02\ 1/(s \cdot m^2)$@75 Pa
- Enclosure $2.00\ 1/(s \cdot m^2)$@75 Pa.

Materials and assemblies that meet these performance requirements are said to be air barrier materials and air barrier assemblies. Air barrier materials incorporated in air barrier assemblies that in turn are interconnected to create enclosures are called air barrier systems.

Vapor Diffusion

The fundamental principle of control of water in the vapor form is to keep it out and to let it out if it gets in. It gets complicated because sometimes the best strategies to keep water vapor (WV) out also trap water vapor. This can be a real problem if the assemblies start out wet because of rain or the use of wet materials.

It gets even more complicated because of climate. In general water vapor moves from the warm side of building assemblies to the cold side of building assemblies. Logically, this means we need different strategies for different climates. We also have to take into account differences between summer and winter.

A Vapor Retarder is defined as follows: the element that is designed and installed in an assembly to retard the movement of water by vapor diffusion.

The unit of measurement typically used in characterizing the water vapor permeance of materials. is the "perm." Several classes of vapor retarders are further defined as follows [5]:

- Class I WV permeance 0.1 perm or less
- Class II WV permeance 1.0 perm or less and greater than 0.1 perm
- Class III Wv permeance 10 perm or less and greater than 1.0 perm.

Test Procedure for vapor retarders: ASTM E-96 Test Method A (the desiccant method or dry cup method).

Finally, a Vapor Barrier is defined as a Class I vapor retarder.

Materials can be separated into four general classes based on their permeance [5]:

- Vapor impermeable 0.1 perm or less
- Vapor semi-impermeable 1.0 perm or less and greater than 0.1 perm
- Vapor semi-permeable 10 perms or less and greater than 1.0 perm
- Vapor permeable greater than 10 perms.

Based on the definitions, the following general principles should be followed in assembly design:

- Avoidance of using vapor barriers where semi-impermeable materials will provide satisfactory performance. Avoidance of using semi-impermeable materials where semi-permeable materials will provide satisfactory performance, thereby encouraging drying mechanisms over wetting prevention mechanisms.
- Avoidance of the installation of vapor barriers on both sides of assemblies; i.e., "double vapor barriers" in order to facilitate assembly drying in at least one direction.
- Avoidance of the installation of vapor barriers such as polyethylene vapor barriers, foil faced batt insulation, and reflective radiant barrier foil insulation on the inte-

rior of air-conditioned assemblies, a practice that has been linked with moldy buildings.
- Avoidance of the installation of vinyl wall coverings on the inside of air-conditioned assemblies.

Moisture Control Practices for Cold Climates

A cold climate has 5400 heating degree days or greater and a very cold climate has 9000 heating degree days or greater. Intermittent cooling (air conditioning) typically occur in cold climates, but is uncommon in most very cold climates. The climate zone specifications are 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 cold 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 cold climates, wetting from the interior during the heating season by air movement is a major concern. In cold climates, building enclosures are constructed in an airtight manner to control air leakage openings 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 can be a concern in cold climates and is typically a concern in very cold climates. Vapor diffusion retarders, when specified in cold climates and very cold climates, are located towards the interior of the thermal insulation. When vapor retarders are used, 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 these climates has led to the widespread use of basements with foundation footings located below ground frost penetration depth. Frost-protected crawl spaces are common in the more moderate regions of cold climates. Concrete and masonry foundations are common with limited use of wood foundations. Above-grade frame walls predominate.

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 air changes, 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, sheathing temperatures can be controlled via the use of insulating sheathings, 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 can controlled by the use of vapor retarders in walls, roofs, and foundations or by controlling temperatures via the use of exterior insulating sheathings.

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 [6].

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 and the materials should be allowed to dry prior to being enclosed.

Ice Damming[4]

Heat loss into roof and attic assemblies during the heating months can lead to ice damming. This is most often caused by locating heating and cooling ductwork and air handlers/furnaces in vented attic spaces. The obvious solution is to not locate ductwork and heating/cooling systems in vented attics. Ice damming can also be 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. Controlled ventilation systems meeting ASHRAE Standard 62.2 requirements should be installed [7].

Cold interior surfaces during the heating months arising from thermal bridges or wind blowing through insulations create high interior surface relative humidities and of-

[4] Ice damming is caused when snow on a roof melts because of high attic temperature and the melt water runs down to the roof overhang, where is exposed to cold weather and freezes. Any warming of the attic can cause ice damming.

ten 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 is 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 mechanical 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 mechanical ventilation.

Air change (infiltration/exfiltration combined with mechanical 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 30 % or lower at 70°F (21.1°C) within the conditioned spaces in cold climates during the heating months (the key is to prevent 70 % relative humidity from occurring adjacent to surfaces in order to control mold, mildew, and other biological growth). In very cold climates, the interior relative humidity should be maintained at even lower levels during the coldest month of the year. 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 [8].

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 wann 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 [9].

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). The ductwork system and air handler should be tested for leakage (less than 5 % leakage at 25 Pa).

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 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 en\closure 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. Wood stoves should also have their own supply of exterior air ducted directly to their firebox [10].

Moisture Control Practices for Mixed Climates

Mixed climates have 5400 degree days heating or less combined with a significant number of cooling (air-conditioning) hours. In these climate zones, heating and cooling both occur for significant periods of time. The climate zone specification 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, and interior mold 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 from the interior is typically not a concern. Accordingly, interior vapor retarders are typically not necessary.

In mixed climates, wetting by vapor diffusion from the exterior can be a concern, particularly where reservoir claddings are used. One approach to control the outward to inward vapor diffusion drive in this climate is to use an exterior vapor retarder. Where vapor retarders are located to the exterior, building assembly components located to the interior should be vapor permeable to facilitate drying to the interior.

If vapor 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 [11].

Due to shallow ground frost penetration, this climate is marked by a mix of basement foundations, crawlspaces, and slab-on-grade construction. Concrete and masonry foundations are common, with limited use of wood foundations and wood crawlspaces. Frame walls predominate.

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 coupled with the trend toward 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, 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 is typically not a concern in mixed climates; interior vapor retarders are typically unnecessary and should be in general avoided.

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.

Where wet masonry, wet lumber (greater than 19 % moisture content by weight), or wet-applied insulation (wet spray cellulose or wet-blown fiberglass) is installed in building assemblies, those assemblies should be designed and built in such a manner that they can dry to the exterior or interior or the materials should be allowed to dry prior to enclosure.

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. Controlled ventilation systems meeting ASHRAE Standard 62.2 requirements should be installed.

If thermal bridges or wind blowing through insulation 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 comers, 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 62.2, the strength of pollutant sources within enclosures and/or authorities having jurisdiction.

Relative humidity should be maintained at 40 % or lower at 70°F 21.1°C) within the conditioned space 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 long 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 crawlspaces must be air sealed with mastic (tapes are ineffective). The ductwork system and air handler should be tested for leakage (less than 5 % leakage at 25 Pa). 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 crawlspaces 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 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.

Should duct work be installed in attics and/or vented crawlspaces (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). The ductwork system and air handler should be tested for leakage (less than 5 % leakage at 25 Pa).

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 arid 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 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. Wood stoves should also have their own supply of exterior air ducted directly to their firebox.

Moisture Control Practices for Hot, Humid Climates

A hot humid climate is a warm, humid climate with a significant number of cooling (air-conditioning) hours. It generally follows the ASHRAE definition [12] 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 hot, humid climates, the principal moisture concerns are rain penetration and groundwater. In hot, humid climates interior mold linked to high interior levels of humidity during cooling periods is also a concern. High exterior levels of humidity encourage mold growth, as do cool interior surfaces due to the air conditioning of enclosures.

In hot, humid climates, wetting from the exterior during the cooling season by air movement is a major concern. In hot, humid climates, building enclosures are constructed in an airtight manner to control air leakage openings, to expedite air pressure control (pressurization of the building enclosure 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 hot, humid climates. Accordingly, vapor diffusion retarders in hot, humid climates can be located toward the exterior and walls, and other building assemblies can be 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 crawlspace and ground slab construction. Basement foundations are rare, if not completely nonexistent. Both frame walls and masonry walls are common.

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.

Vinyl interior wall coverings are not exclusive to masonry or concrete wall systems and are also used with wood frame construction. Vinyl interior wall coverings should never be used in this climate zone.

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 either the interior or exterior or the materials should 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 hot, 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—approximately 2 Pa to 3 Pa), 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. Pressurization of building enclosures is expedited by airtight construction (2.00 $l/(s \cdot m^2)$@75 Pa).

Moisture movement by vapor diffusion from the exterior can be controlled by the use of exterior vapor retarders in walls, roofs, and crawlspaces. Moisture movement by vapor diffusion from the interior is not a concern in hot humid or hot climates—interior vapor retarders are unnecessary and should avoided.

High air change due to infiltration/exfiltration, duct leakage, and excessive ventilation can lead to elevated interior levels of moisture. This is contrary to cold 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 hot 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 hot, 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 62.2, the strength of pollutant sources within enclosures 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 crawlspace ground covers and subslab vapor barriers.

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). The ductwork system and air handler should be tested for leakage (less than 5 % leakage at 25 Pa). 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 crawlspaces 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 crawlspaces 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 hot, humid 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.

Should duct work be installed in attics and/or vented crawlspaces (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). The ductwork system and air handler should be tested for leakage (less than 5 % leakage at 25 Pa).

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 dewpoint 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 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 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. Wood stoves should

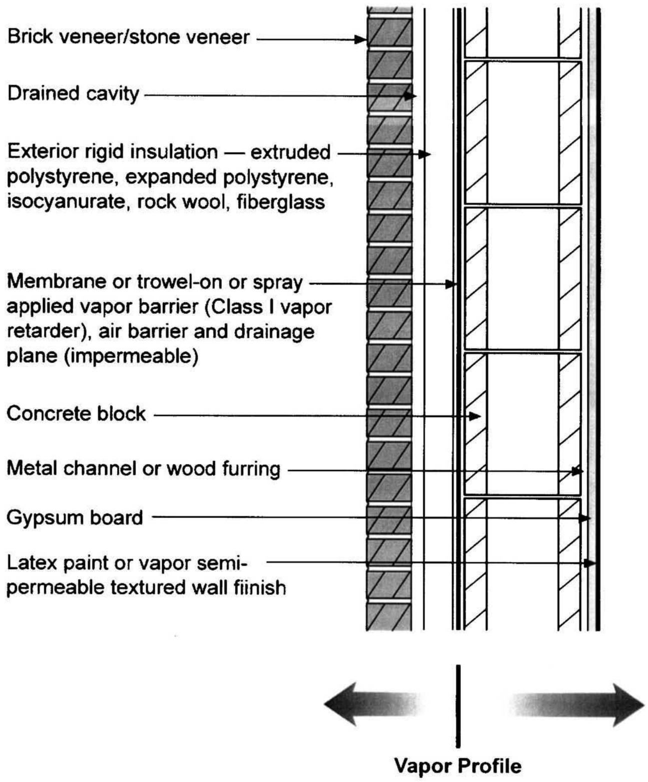


Fig. 1—Concrete block with exterior insulation and brick or stone veneer.

also have their own supply of exterior air ducted directly to their firebox.

Wall Assemblies

Applicability: all hygro-thermal regions.

The assembly pictured in Fig. 1 is arguably the most durable wall assembly available to architects and engineers. It is constructed from non-water-sensitive materials and due to the block construction has a large moisture storage (or hygric buffer) capacity. It can be constructed virtually anywhere. In cold climates, condensation is limited on the interior side of the vapor barrier as a result of installing all of the thermal insulation on the exterior side of the vapor barrier (which is also the drainage plane and air barrier in this assembly). In hot climates, any moisture that condenses on the exterior side of the vapor barrier will be drained to the exterior since the vapor barrier is also a drainage plane. This wall assembly will dry from the vapor barrier inwards and will dry from the vapor barrier outwards.

Applicability: limited to mixed-humid, hot-humid, mixed-dry, hot-dry, and marine regions. It should not be used in cold, very cold, or subarctic/arctic regions.

This wall assembly (Fig. 2) has all of the thermal insulation installed to the interior of the vapor barrier and therefore should not be used in cold regions or colder. It is also a durable assembly due to the block construction and the associated moisture storage (hygric buffer) capacity. The wall assembly does contain water-sensitive cavity insulation (except where spray foam is used) and it is important that this assembly can dry inwards, therefore, vapor semi-impermeable interior finishes such as vinyl wall coverings should be avoided. In this wall assembly, the vapor barrier is also the drainage plane and air barrier.

Applicability: all hygro-thermal regions.[5]

This assembly (Fig. 3) has all of the thermal insulation installed on the interior of the concrete block construction but differs from Fig. 2 since it does not have a vapor barrier on the exterior. The assembly also does not have a vapor barrier on the interior of the assembly. It has a large moisture storage (hygric buffer) capacity due to the block construction. The rigid insulation installed on the interior should be non-moisture-sensitive and should allow the wall to dry inwards, hence the recommended use of vapor semi-permeable foam sheathing. Note that the foam sheathing is not faced with aluminum foil or polypropylene skins. It is important that this assembly can dry inwards except in very cold and subarctic/arctic regions; therefore, vapor semi-impermeable interior fInishes such as vinyl wall coverings should be avoided in assemblies, except in very cold and subarctic/arctic regions. Vapor impermeable foam sheathings should be used in place of the vapor semi-permeable foam sheathings in very cold and subarctic/arctic regions. The drainage plane in this assembly is the latex painted stucco rendering. A Class III vapor retarder is located on both the interior and exterior of the assembly (the latex paint on the stucco and on the interior gypsum board.

Applicability: all hygro-thermal regions.[6]

The assembly shown in Fig. 4 is a variation of Fig. 3. It also has all of the thermal insulation installed on the interior of the concrete block construction but differs from Fig. 3 due to the addition of a frame wall to the interior of the rigid insulation. This assembly also does not have a vapor barrier on the exterior, nor on the interior of the assembly. It has a large moisture storage (hygric buffer) capacity due to the block construction. The rigid insulation installed on the interior should be non-moisture-sensitive and allow the wall to dry inwards; hence the recommended use of vapor semi-permeable foam sheathing. Note that the foam sheathing is not faced with aluminum foil or polypropylene skins. It is important that this assembly can dry inwards even in very cold and subarctic/arctic regions; therefore, vapor semi-impermeable interior finishes such as vinyl wall coverings should be avoided in assemblies. Vapor impermeable foam sheathings should be used in place of the vapor semi-permeable foam sheathings in very cold and subarctic/arctic regions. The drainage plane in this assembly is the latex painted stucco rendering. A Class III vapor retarder is located on both the interior and exterior of the assembly (the latex paint on the stucco and on the interior gypsum board).

Applicability: all hygro-thermal regions.

This wall (Fig. 5) is a variation of Fig. 1, but without the moisture storage (or hygric buffer) capacity. This wall is also a durable wall assembly. It is constructed from non-water-sensitive materials and has a high drying potential inwards

[5] In very cold and subarctic/arctic regions, vapor impermeable foam sheathings are recommended.

[6] In very cold and subarctic/arctic regions, vapor impermeable foam sheathings are recommended. Additionally, the thickness of the foam sheathing should be determined by hygro-thermal analysis so that the interior surface of the foam sheathing remains above the dewpoint temperature of the interior wall.

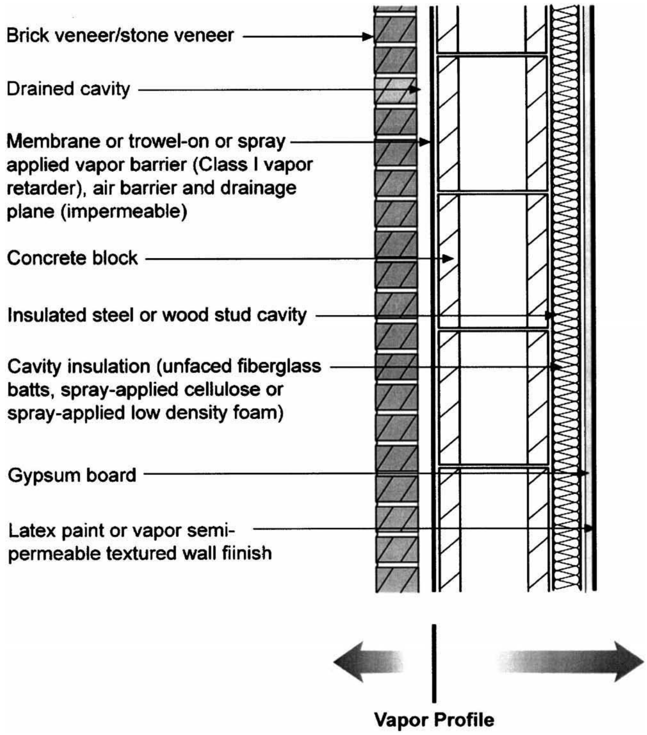


Fig. 2—Concrete block with interior frame wall cavity insulation and brick or stone veneer.

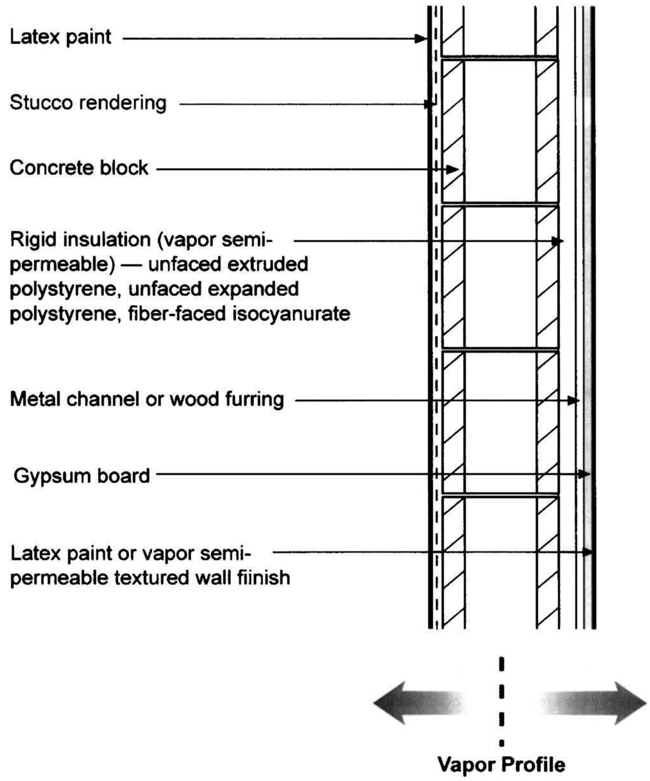


Fig. 3—Concrete block with interior rigid insulation and stucco.

due to the frame wall cavity not being insulated. It can also be constructed virtually anywhere. In cold climates, condensation is limited on the interior side of the vapor barrier as a result of installing all of the thermal insulation on the exterior side of the vapor barrier (which is also the drainage plane and air barrier in this assembly). In hot climates, any moisture that condenses on the exterior side of the vapor barrier will be drained to the exterior since the vapor barrier is also a drainage plane. This wall assembly will dry from the vapor barrier inwards and will dry from the vapor barrier outwards.

Applicability: Limited to mixed-humid, hot-humid, mixed-dry, hot-dry, and marine regions; can be used with hygro-thermal analysis in some areas in cold regions. It should not be used in very cold or subarctic/arctic regions.

This wall (Fig. 6) is a flow-through assembly: it can dry to both the exterior and the interior. It has a Class III vapor retarder on the interior of the assembly (the latex paint on the gypsum board). It is critical in this wall assembly that the exterior brick veneer (a “reservoir” cladding) be uncoupled from the wall assembly with a ventilated and drained cavity. The cavity behind the brick veneer should be at least 2 inc. wide (source: Brick Institute of America) and free from mortar droppings. It must also have air inlets (“weep holes”) at its base and air outlets (“weep holes”) at its top in order to provide back ventilation of the brick veneer. The drainage plane in this assembly is the building paper or building wrap. The air barrier can be any of the following: the interior gypsum board, the exterior gypsum wallboard, or the exterior building wrap.

Applicability: limited to mixed-humid, hot-humid, mixed-dry, hot-dry, and marine regions. It can be used with

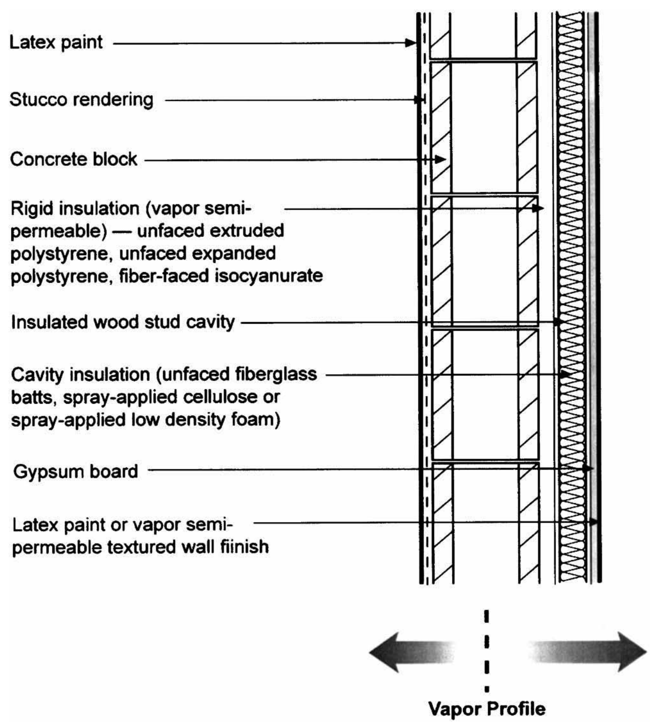


Fig. 4—Concrete block with interior rigid insulation/frame wall with cavity insulation and stucco.

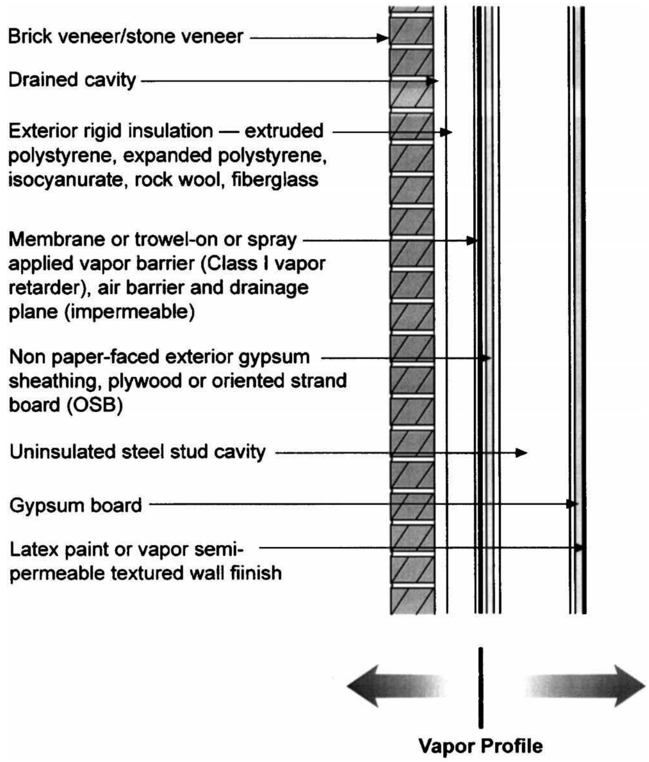


Fig. 5—Frame wall with exterior insulation and brick or stone veneer.

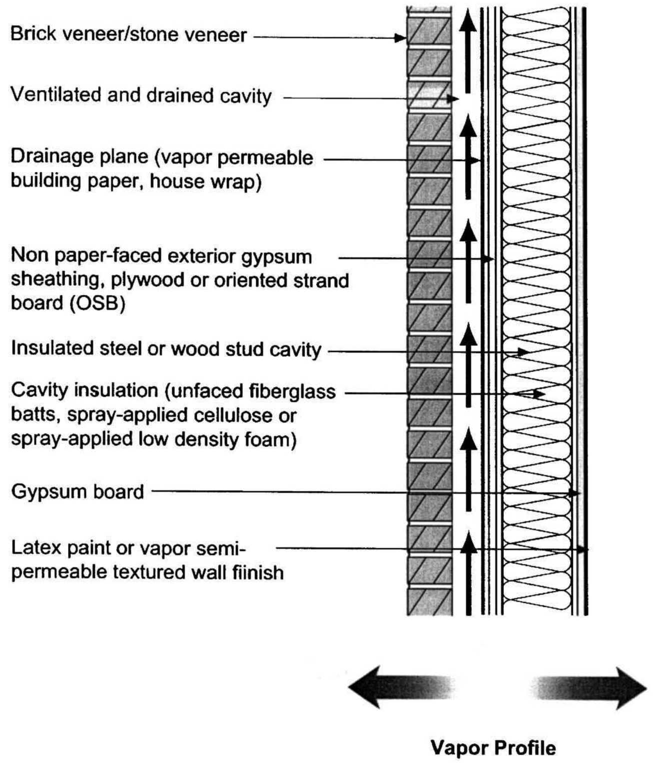


Fig. 6—Frame wall with cavity insulation and brick or stone veneer.

hygro-thermal analysis in some areas in cold regions; it should not be used in very cold or subarctic/arctic regions.

The wall depicted in Fig. 7 is a variation of Fig. 6. The exterior gypsum sheathing becomes the drainage plane. As in Fig. 6, this wall is a flow-through assembly: it can dry to both the exterior and the interior. It has a Class Ill vapor retarder on the interior of the assembly (the latex paint on the gypsum board). It is also critical in this wall assembly that the exterior brick veneer (a "reservoir" cladding) be uncoupled from the wall assembly with a ventilated and drained cavity. The cavity behind the brick veneer should be at least 2 inc. wide (source: Brick Institute of America) and free from mortar droppings. It must also have air inlets ("weep holes") at its base and air outlets ("weep holes") at its top in order to provide back ventilation of the brick veneer. The air barrier in this assembly can be either the interior gypsum board or the exterior gypsum sheathing.

Applicability: all hygro-thermal regions except subarctic/arctic. In cold and very cold regions the thickness of the foam sheathing should be determined by hygro-thermal analysis so that the interior surface of the foam sheathing remains above the dew point temperature of the interior air.

This wall (Fig. 8) is a variation of Fig. 5. In cold climates, condensation is limited on the interior side of the vapor barrier as a result of installing some of the thermal insulation on the exterior side of the vapor barrier (which is also the drainage plane and air barrier in this assembly). In hot climates, any moisture that condenses on the exterior side of the vapor barrier will be drained to the exterior since the vapor barrier is also a drainage plane. This wall assembly will dry from the

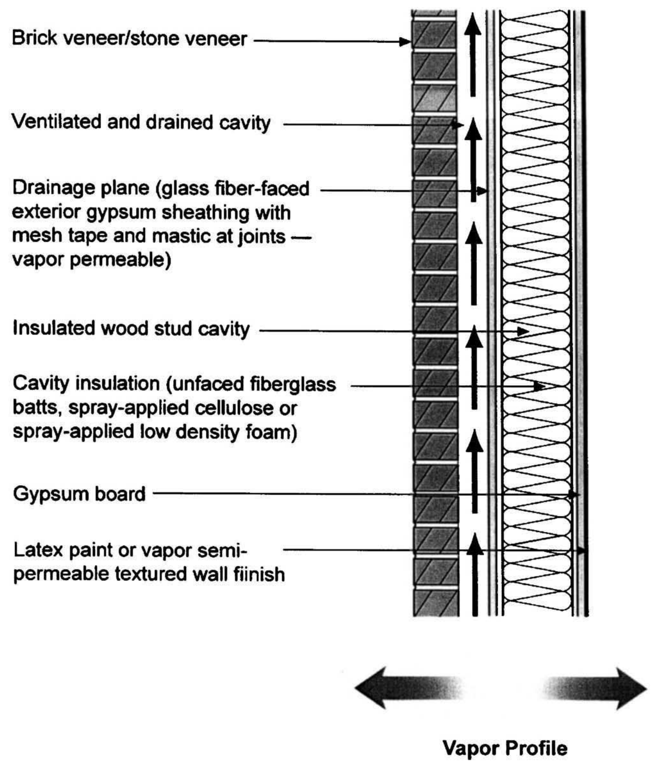


Fig. 7—Frame wall with cavity insulation and brick or stone veneer.

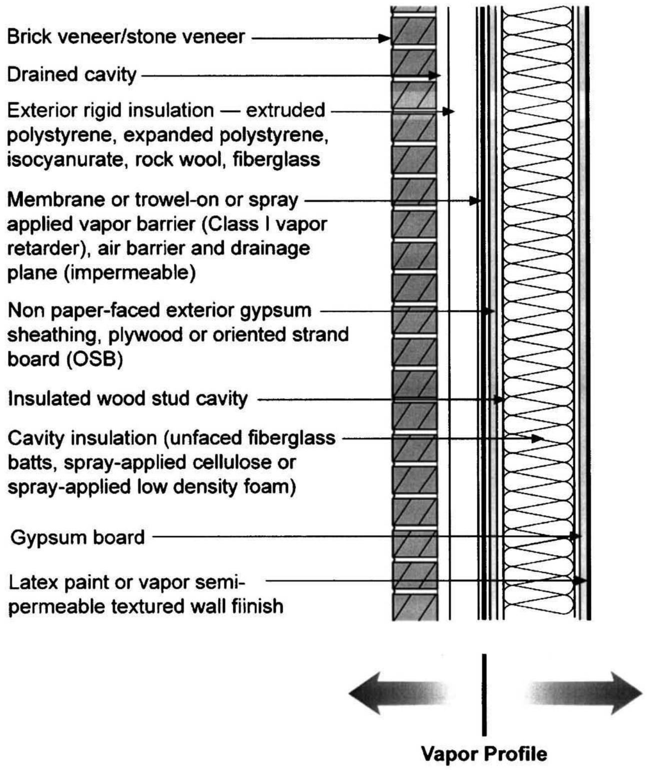


Fig. 8—Frame wall with exterior rigid insulation with cavity insulation and brick or stone veneer.

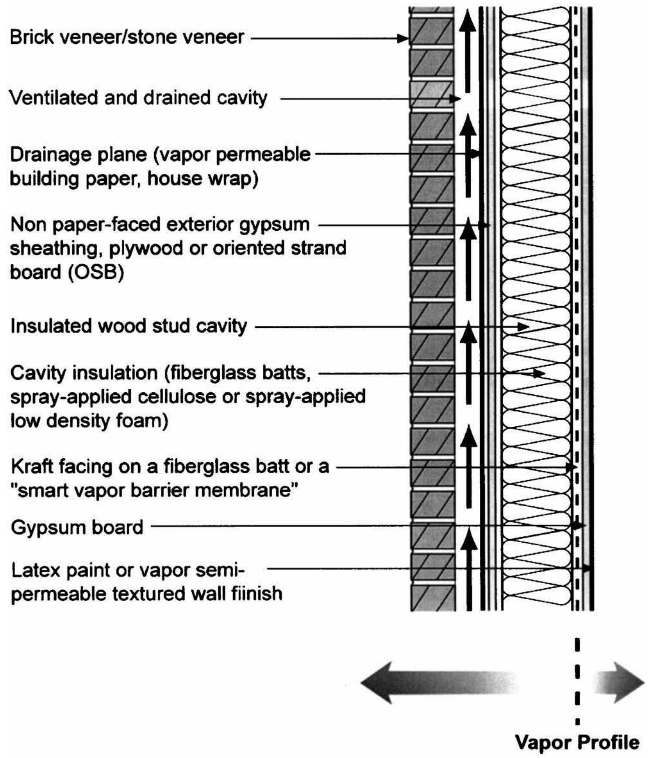


Fig. 9—Frame wall with cavity insulation and brick or stone veneer with interior vapor retarder.

vapor barrier inwards and will dry from the vapor barrier outwards. Since this wall assembly has a vapor barrier that is also a drainage plane, it is not necessary to back vent the brick veneer reservoir cladding as in Figs. 6 and 7. Moisture driven inwards out of the brick veneer will condense on the vapor barrier/drainage plane and be drained outwards.

Applicability: limited to cold and very cold regions.

This wall (Fig. 9) is a variation of Fig. 6 except that it has a Class II vapor retarder on the interior limiting its inward drying potential, but not eliminating it. It still considered a flow-through assembly—it can dry to both the exterior and the interior. It is critical in this wall assembly—as in Figs. 6 and 7—that the exterior brick veneer (a "reservoir" cladding) be uncoupled from the wall assembly with a ventilated and drained cavity. The cavity behind the brick veneer should be at least 2 inc. wide (source: Brick Institute of America) and free from mortar droppings. It must also have air inlets ("weep holes") at its base and air outlets ("weep holes") at its top in order to provide back ventilation of the brick veneer. The drainage plane in this assembly is the building paper or building wrap. The air barrier can be any of the following: the interior gypsum board, the exterior gypsum board or the exterior building wrap.

Applicability: limited to very cold, subarctic and arctic regions.

This wall (Fig. 10) is a further variation of Fig. 6 but now it has a Class I vapor retarder on the interior (a "vapor barrier") completely eliminating any inward drying potential. It is considered the "classic" cold climate wall assembly. It is critical in this wall assembly—as in Figs. 6, 7, and 9—that the exterior brick veneer (a "reservoir" cladding) be uncoupled

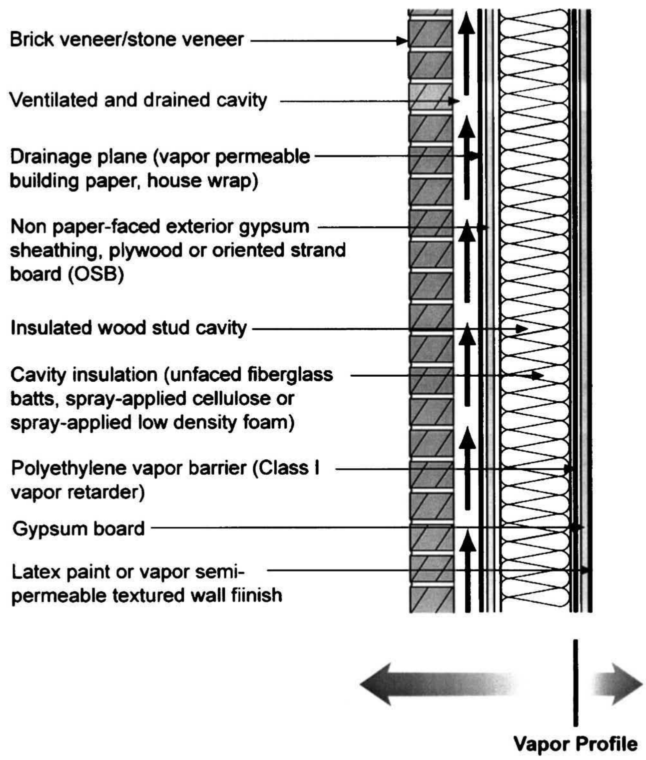


Fig. 10—Frame wall with cavity insulation and brick or stone veneer with interior vapor barrier.

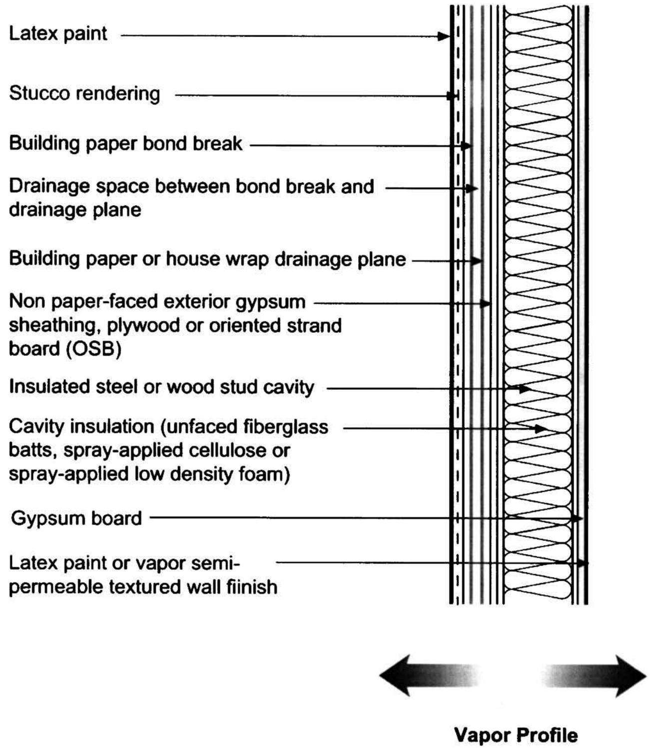


Fig. 11—Frame wall with cavity insulation and stucco.

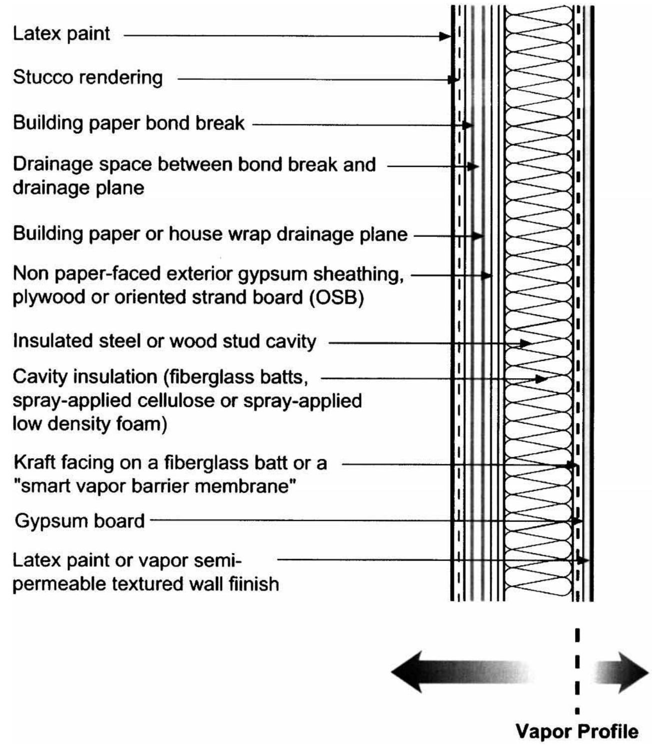


Fig. 12—Frame wall with cavity insulation and stucco with interior vapor retarder.

from the wall assembly with a ventilated and drained cavity. The cavity behind the brick veneer should be at least 2 inc. wide (source: Brick Institute of America) and free from mortar droppings. It must also have air inlets at its base and air outlets at its top in order to provide back ventilation of the brick veneer. The drainage plane in this assembly is the building paper or building wrap. The air barrier can be any of the following: the interior polyethylene vapor barrier, the interior gypsum board, the exterior gypsum board or the exterior building wrap.

Applicability: limited to mixed-humid, hot-humid, mixed-dry, hot-dry, and marine regions. It can be used with hygro-thermal analysis in some areas in cold regions; it should not be used in very cold or subarctic/arctic regions.

This wall (Fig. 11) is also a flow-through assembly similar to Fig. 6, but without the brick veneer: it has a stucco cladding. It can dry to both the exterior and the interior. It has a Class III vapor retarder on the interior of the assembly (the latex paint on the gypsum board). It is critical in this wall assembly that a drainage space be provided between the stucco rendering and the drainage plane. This can be accomplished by installing a bond break (a layer of tar paper) between the drainage plane and the stucco. A spacer mat can also be used to increase drainability. Alternatively, a textured or profiled drainage plane (building wrap) can be used. The drainage plane in this assembly is the building paper or building wrap. The air barrier can be any of the following: the interior gypsum board, the exterior stucco rendering, the exterior sheathing or the exterior building wrap.

Applicability: limited to cold and very cold regions.

This wall (Fig. 12) is a variation of Figs. 6 and 11 except it has a Class II vapor retarder on the interior limiting its inward drying potential, but not eliminating it. It still considered a flow-through assembly—it can dry to both the exterior and the interior. It is critical in this wall assembly, as in Fig. 11, that a drainage space be provided between the stucco rendering and the drainage plane. This can be accomplished by installing a bond break (a layer of tar paper) between the drainage plane and the stucco. A spacer mat can also be used to increase drainability. Alternatively, a textured or profiled drainage plane (building wrap) can be used. The drainage plane in this assembly is the building paper or building wrap. The air barrier can be any of the following: the interior gypsum board, the exterior stucco rendering, the exterior sheathing or the exterior building wrap.

Applicability: all hygro-thermal regions except subarctic/arctic. In cold and very cold regions, the thickness of the foam sheathing should be determined by hygro-thermal analysis so that the interior surface of the foam sheathing remains above the dewpoint temperature of the interior air.

Figure 13 depicts a water managed exterior insulation finish system (EIFS). Unlike "face-sealed" EIFS, this wall has a drainage plane inboard of the exterior stucco skin that is drained to the exterior. It is also a flow-through assembly similar to Fig. 6. It can dry to both the exterior and the interior. It has a Class III vapor retarder on the interior of the assembly (the latex paint on the gypsum board). It is critical in this wall assembly that a drainage space be provided between the exterior rigid insulation and the drainage plane. This can be accomplished by installing a spacer mat or by providing drainage channels in the back of the rigid insulation. Alternatively, a textured or profiled drainage plane (building wrap) can be used. The drainage plane in this assembly is the building paper or building wrap. The air bar-

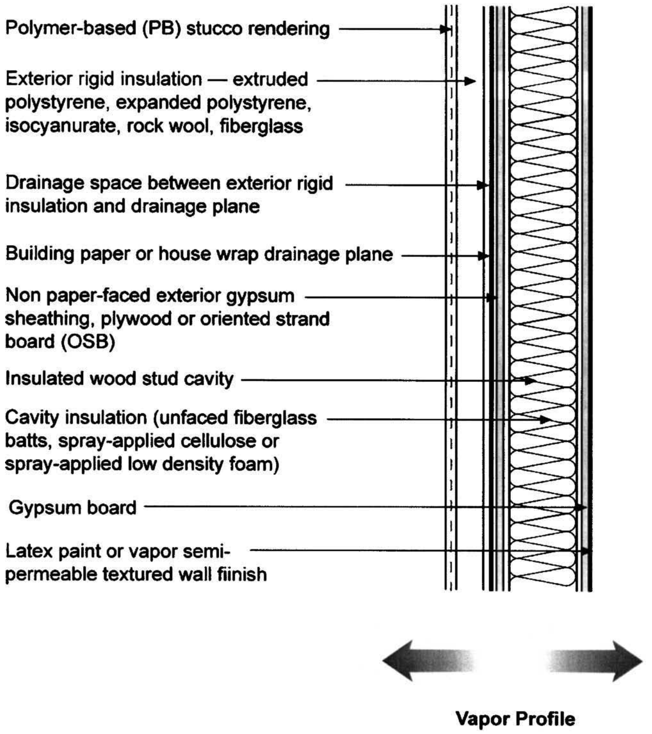


Fig. 13—Frame wall with exterior rigid insulation with cavity insulation and stucco.

rier can be any of the following: the interior gypsum board, the exterior stucco rendering, the exterior sheathing, or the exterior building wrap.

Applicability: limited to mixed-humid, hot-humid, mixed-dry, hot-dry, and marine regions. It should not be used in cold, very cold, or subarctic/arctic regions.

The vapor barrier in the assembly pictured in Fig. 14 is the precast concrete itself. Therefore, this wall assembly has all of the thermal insulation installed to the interior of the vapor barrier. Of particular concern is the fact that the thermal insulation is air permeable (except where spray foam is used). Therefore, this wall assembly should not be used in cold regions or colder. It has a small moisture storage (hygric buffer) capacity due to the precast concrete construction. The wall assembly does contain water-sensitive cavity insulation (except where spray foam is used) and it is important that this assembly can dry inwards; therefore, vapor semi-impermeable interior finishes such as vinyl wall coverings should be avoided. In this wall assembly the precast concrete is also the drainage plane and air barrier.

Applicability: all hygro-thermal regions.[7]

This assembly (Fig. 15) has all of the thermal insulation installed on the interior of the precast concrete. The assembly also does not have a vapor barrier on the interior of the assembly. It has a small moisture storage (hygric buffer) capacity due to the precast concrete construction. The rigid insulation installed on the interior should be non-moisture-sensitive and allow the wall to dry inwards, hence the recommended use of vapor semi-permeable foam sheathing. Note that the foam sheathing is not faced with aluminum foil

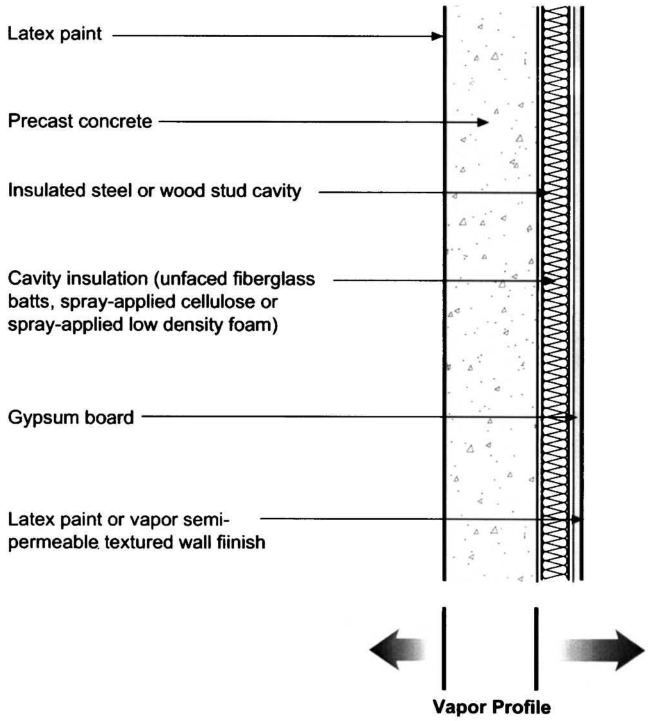


Fig. 14—Precast concrete with interior frame wall cavity insulation.

or polypropylene skins. It is important that this assembly can dry inwards except in very cold and subarctic/arctic regions, Therefore, vapor semi-impermeable interior fInishes such as vinyl wall coverings should be avoided in assemblies, except in very cold and subarctic/arctic regions. Vapor im-

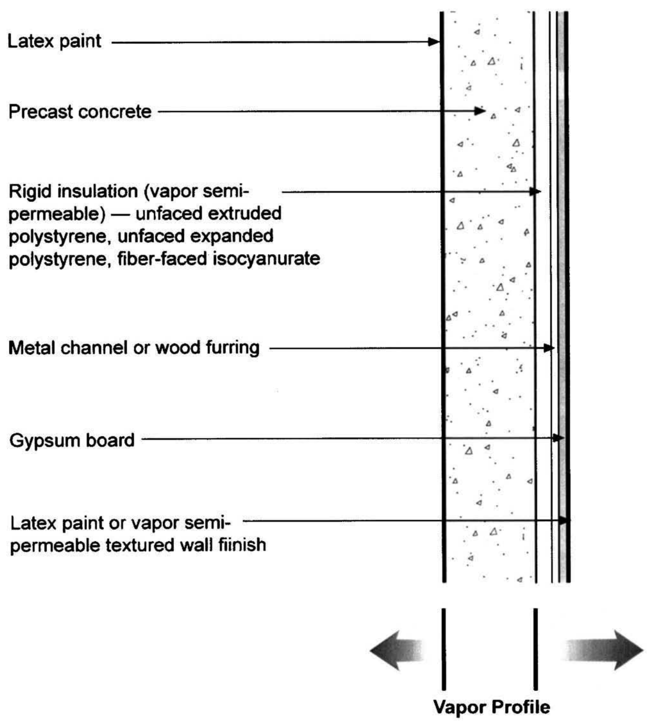


Fig. 15—Precast concrete with interior rigid insulation.

[7] In very cold and subarctic/arctic regions, vapor impermeable foam sheathings are recommended.

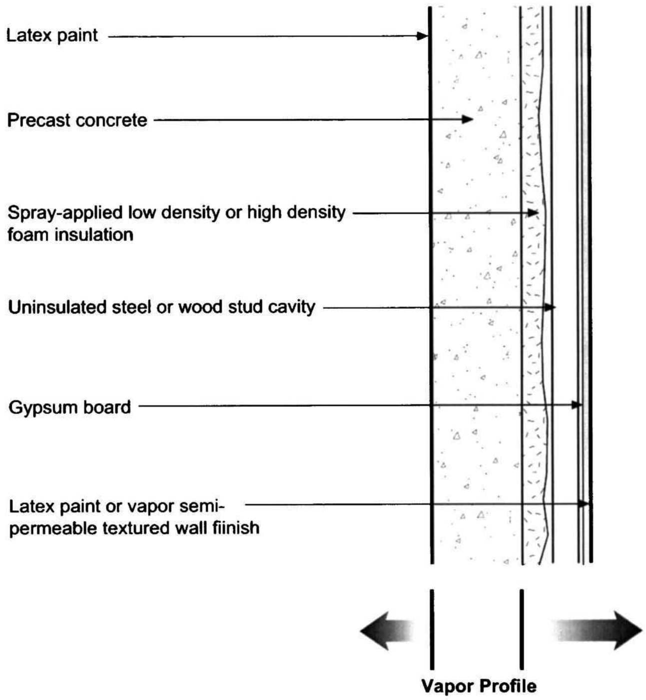


Fig. 16—Precast concrete with interior spray applied foam insulation.

permeable foam sheathings should be used in place of the vapor semi-permeable foam sheathings in very cold and subarctic/arctic regions. The drainage plane in this assembly is the latex painted precast concrete. A Class Ill vapor retarder is located on both the interior and exterior of the assembly (the latex paint on the stucco and on the interior gypsum board.

Applicability: all hygro-thermal regions.[8]

This assembly (Fig. 16) has all of the thermal insulation installed on the interior of the precast concrete. The assembly also does not have a vapor barrier on the interior of the assembly. It has a small moisture storage (hygric buffer) capacity due to the precast concrete construction. The spray foam insulation installed on the interior of the precast concrete is non-moisture-sensitive and allows the wall to dry inwards. It is important that this assembly can dry inwards except in very cold and subarctic/arctic regions; therefore, vapor semi-impermeable interior finishes such as vinyl wall coverings should be avoided in assemblies, except in very cold and subarctic/arctic regions. High-density spray foam, due to its vapor semi-impermeable characteristics, should be used in place of low-density foam in very cold and subarctic/arctic regions. The drainage plane in this assembly is the latex painted precast concrete. A Class III vapor retarder is located on both the interior and exterior of the assembly (the latex paint on the stucco and on the interior gypsum board.

Roof Assemblies

Applicability: all hygro-thermal regions.

This assembly (Fig. 17) can be constructed anywhere.

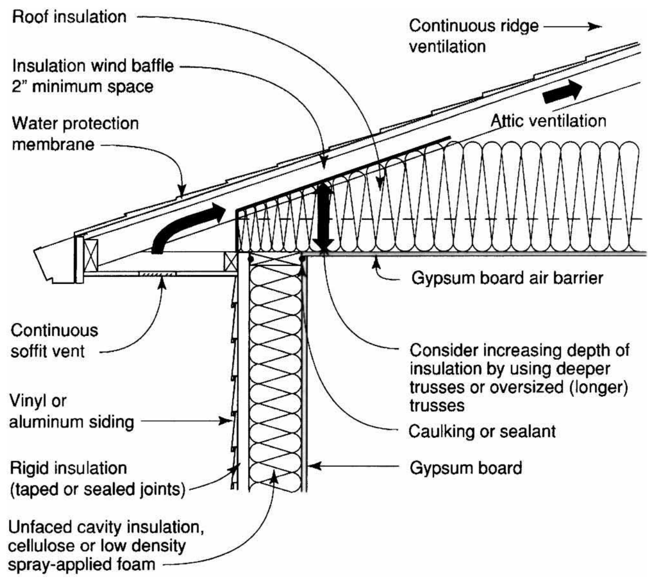


Fig. 17—Vented attic flat ceiling.

The key to its performance is the airthightness of the ceiling plane—the "air barrier" in this particular assembly. In cold climates and very cold climates, a Class II vapor retarder is also required at the ceiling plane. Ventilation is provided with continuous soffit vents and continuous ridge ventilation. The ventilation area is typically according to the 1:300 ratio. In cold climates and very cold climates, a water protection membrane is also added at roof perimeters and at valleys to limit water damage associated with ice damming, although the most effective control for ice damming is controlling the temperature of the roof deck by flushing the heat away from the underside by a minimum 2 in. airspace, increasing the depth of insulation at the perimeter, and not locating heat producing features in the attic assembly such as air handlers and ductwork or allowing air leakage from the conditioned space.

Applicability: all hygro-thermal regions.

This assembly (Fig. 18) can be constructed anywhere. The key to its performance is control of the temperature of the roof deck such that condensation does not occur during

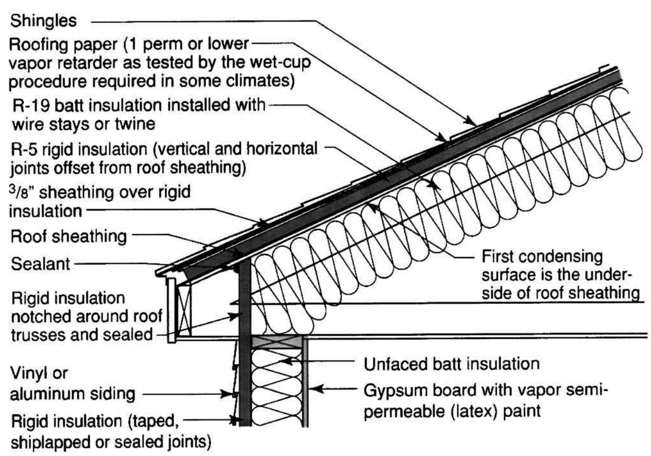


Fig. 18—Conditioned attic: cathedralized.

[8] In very cold and subarctic/arctic regions, high-density spray foam (vapor semi impermeable) is recommended.

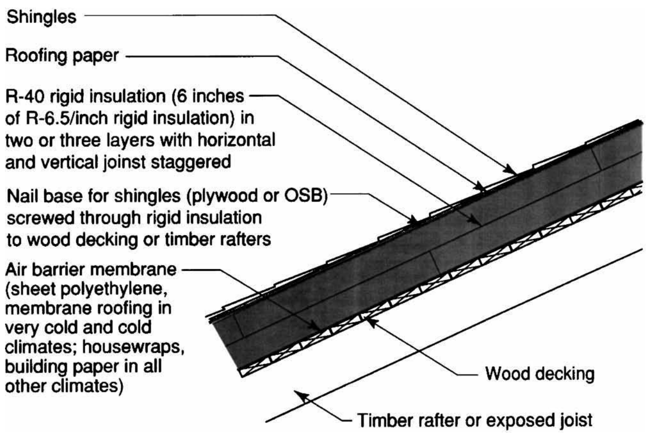


Fig. 19—Conditioned attic: cathedralized compact.

winter months. Temperature control of the roof deck is provided by locating a percentage of the thermal insulation above the roof deck such that the temperature of the roof deck is maintained above the design dewpoint temperature of the air vapor mixture within the building enclosure (typically a 45 °F dewpoint). For design purposes, the exterior design temperature used is the average temperature of the coldest month of the year, not the heating system design temperature (which is typically the 2.5 % temperature). A vapor retarder is not located to the interior of this type of assembly permitting inward drying. The advantage of this type of assembly is that ductwork and air handlers can be located in attic spaces that are now conditioned.

Applicability: all hygro-thermal regions.

This assembly (Fig. 19) can be constructed anywhere. The key to its performance is control of the temperature of the roof deck such that condensation does not occur during winter months. Temperature control of the roof deck is provided by locating all of the thermal insulation above the roof deck. This approach makes this assembly suited for particularly hostile climates such as high elevations and pool enclosures. A Class I vapor retarder can be located on the top of

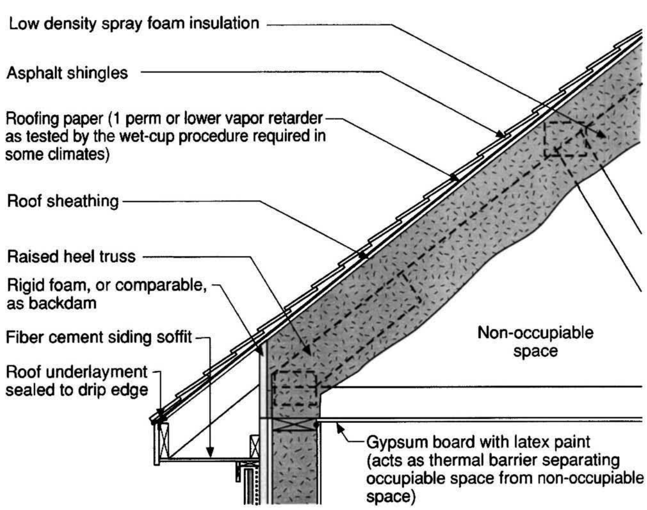


Fig. 20—Conditioned attic: cathedralized air impermeable insulation.

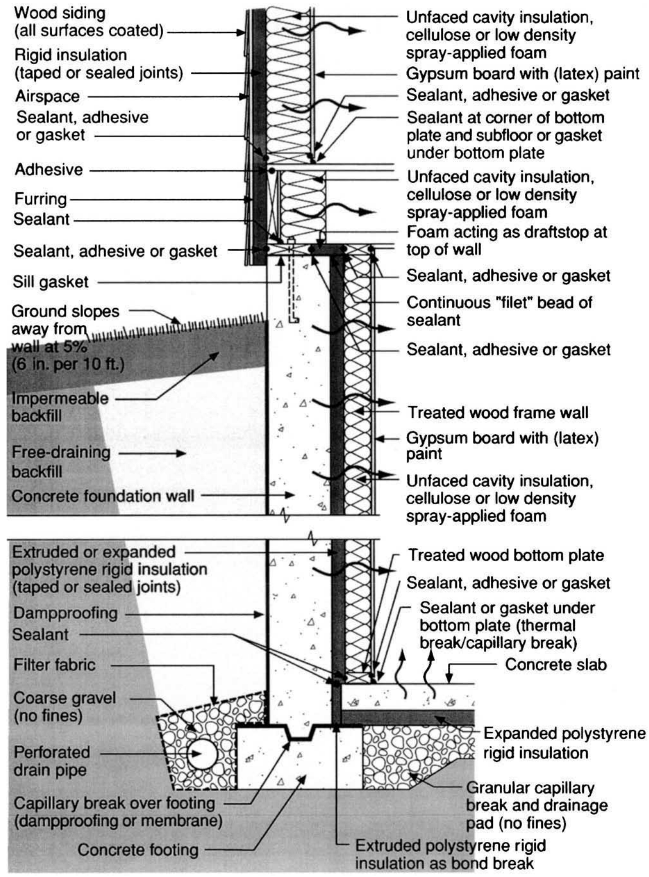


Fig. 21—Concrete basement with interior insulation.

this roof deck in cold and very cold climates. It is recommended that the rigid insulation be installed in two layers with the joints staggered and offset to limit the development of three-dimensional airflow pathways. The advantage of this type of assembly is that ductwork and air handlers can be located in attic spaces that are now conditioned.

Applicability: all hygro-thennal regions.

This assembly (Fig. 20) can be constructed anywhere. The key to its performance is control of the temperature of the roof deck such that condensation does not occur during winter months. Temperature control of the roof deck is provided by installing and air impermeable insulation to the underside of the roof deck. 'Air impermeable' is defined as $0.021/(s \cdot m^2)$@75 Pa. This level of airtightness can be achieved with spray foam insulation. In cold climates and very cold climates, a Class II vapor retarder must be applied in direct contact with the underside of the insulation. This is typically done by spray painting the spray foam insulation with a low perm paint or by selecting a spray foam insulation whose permeance at the applied thickness meets the Class II requirement. A low perm roofing paper is recommended in hot, humid climates to control solar-driven moisture where asphalt shingles are used. The advantage of this type of assembly is that ductwork and air handlers can be located in attic spaces that are now conditioned.

Foundation Assemblies

Applicability: all hygro-thermal regions.

The key to the assembly shown in Fig. 21 is the use of

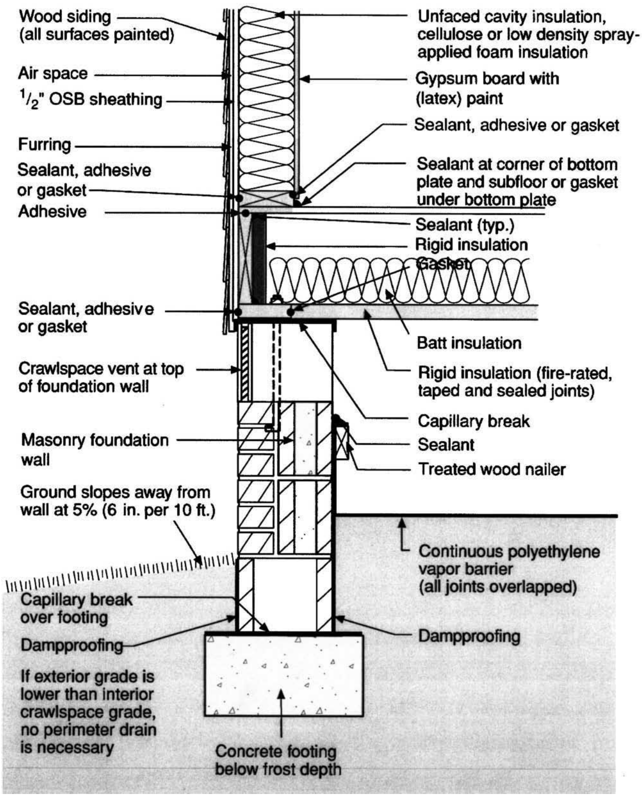


Fig. 22—Vented crawlspace.

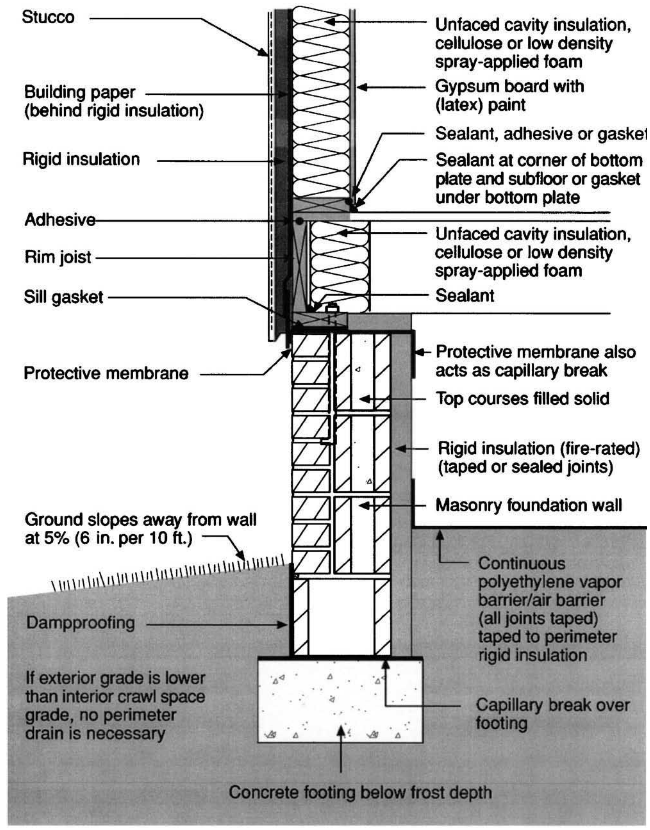


Fig. 23—Conditioned crawlspace.

non-water-sensitive rigid insulation on the interior that still permits drying to the interior. The recommended permeance of the interior rigid insulation layer is approximately 1 perm. This typically limits the thermal resistance of the interior rigid insulation layer and an insulated frame wall assembly can be located to the interior of the interior rigid insulation. No interior vapor retarder is located within the frame wall permitting inward drying. All interior concrete surfaces are wrapped with the rigid insulation layer, particularly at the top of the wall and at foundation "step downs." Exterior rigid insulation is located at the rim joist floor framing to control summer condensation. When insulating sheathing is not used, rigid insulation should we installed to the interior of the rim joist or an air impermeable insulation be applied at the rim joist assembly. Note the capillary break at the top of the footing.

Applicability: all hygro-thermal regions.

The key to this assembly (Fig. 22) is the use of a Class I vapor retarder insulating sheathing at the underside of the floor framing protecting the floor frame assembly. In most regions, the exterior air is above the dewpoint temperature of both the ground surface temperature in crawlspaces and the temperature of the floor assembly. The rigid insulation protects the floor assembly from the condensation. A ground cover is also recommended to limit evaporation of water from the soil. The interior grade should be higher than the exterior grade. Floor cavity insulation should be located in contact with the rigid insulation. Rim joists should be internally insulated with rigid insulation to control condensation or an air impermeable insulation should be applied to the interior of the rim joist. Alternatively, exterior insulating sheathing can be used.

Applicability: all hygro-thermal regions.

The key to this assembly (Fig. 23) is conditioning the

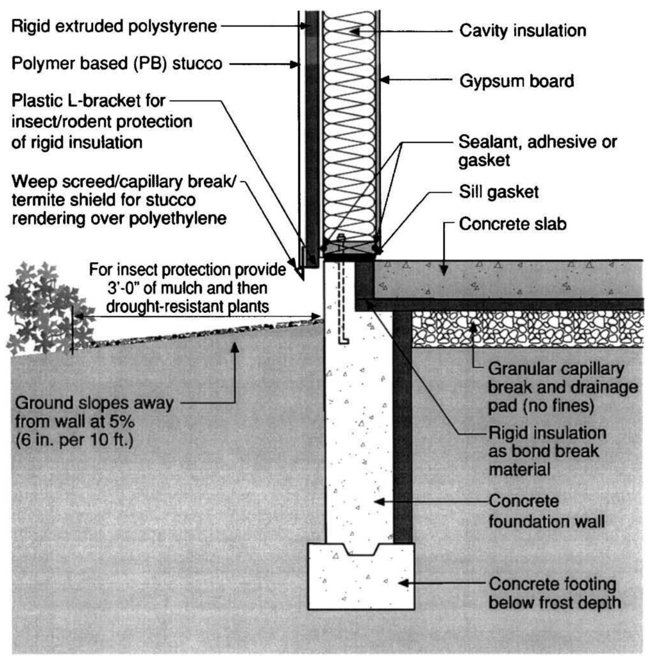


Fig. 24—Insulated stem wall slab foundation.

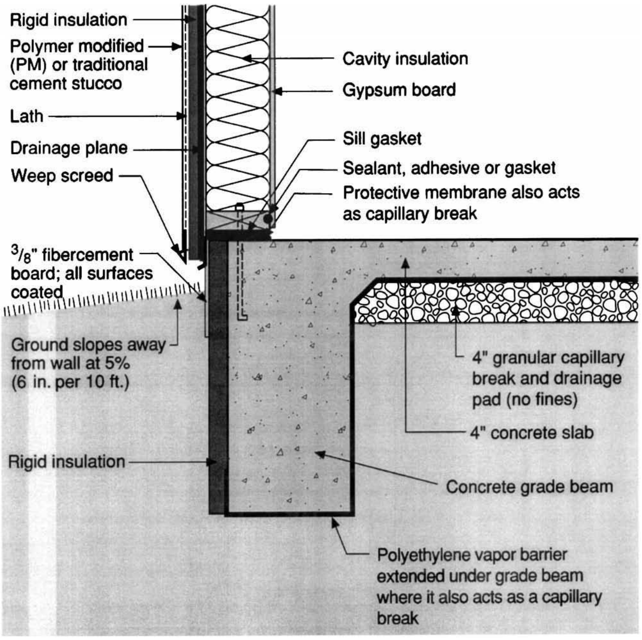


Fig. 25—Externally insulated monolithic slab foundation.

crawlspace. A provision for moisture removal must be provided by conditioning the crawl space with a duct distribution system providing supply and return air or by installing a dehumidifier or by exhaust venting the crawlspace with an exhaust fan. Non-water-sensitive rigid insulation should be installed at the perimeter and rigid insulation should be installed at rim joist areas (either internally or externally). The interior grade should be higher than the exterior grade. A ground cover should be installed such that it also acts as an air barrier.

Applicability: all hygro-thermal regions.

The key to this assembly (Fig. 24) is completely thermally uncoupling the concrete slab from the surrounding ground. Note the rigid insulation as a bond break and the full height interior insulation extending from the top of the footing to the underside of the slab as well as the rigid insulation extending horizontally inward. The sill gasket is typically an adhered membrane strip that also provides an air and soil gas seal between the concrete slab and the stem wall.

Applicability: all hygro-thermal regions.

The key to this assembly (Fig. 25) is protecting the exterior rigid insulation with a non-water-sensitive protection board such a fiber cement that is coated on all six surfaces. The protection board should be installed within the formwork prior to placing the concrete so that the insulation is protected from the start of the project. Additionally, the polyethylene vapor barrier should extend under the grade beam so that it can effectively act as a capillary break.

REFERENCES

[1] Lstiburek, J. W., "Moisture Control For Buildings," *ASHRAE J.*, Vol. 44, 2002, pp. 36–41.

[2] Samuelson, I. and Samuelson, R., *Conditions for Growth of Mold on Wood Products*, Swedish Testing Institute, Boras, Sweden, 1990.

[3] Lstiburek, J. W., "Understanding Air Barriers," *ASHRAE J.*, Vol. 47, 2005, pp. 24–30.

[4] *Building Air Quality-A Guide for Building Owners and Facility Managers*, DHHS (NIOSH) Publication No 91-114, Environmental Protection Agency, Washington, DC, December 1991.

[5] Lstiburek, J. W., "Understanding Vapor Barriers," *ASHRAE J.*, Vol. 46, 2004, pp. 40–51.

[6] Wilson, A. G., "Condensation in Insulated Masonry Walls in Summer," RILEM/Cm Symposium on Moisture Problems in Buildings, NRC 9130, Helsinki, 1965.

[7] ASHRAE Standard 62.2, "Ventilation for Acceptable Indoor Air Quality in Low Rise Residential Buildings," American Society of Heating, Refrigerating, and Air Conditioning Engineers, Inc., Atlanta, 2002.

[8] Tooley, J. J. and Moyer, N. A., "Mechanical Air Distribution and Interacting Relationships," Proceedings, EEBA Conference, Denver, CO, March 1990.

[9] Tooley, J. J. and Moyer, N. A., "Pressure Differential: Measurement of the New Decade," Proceedings, EEBA Conference, Indianapolis, IN, March 1991.

[10] Rinella, J., Kohli, G., and Timusk, J., "Impact of Residential Air Supply and Demand on Ventilation of Gas Appliances," Proceedings, 1986 International Gas Research Conference, Toronto, Ontario, 1986.

[11] Handegor, G. O., Prediction of the Moisture Performance of Walls, *ASHRAE Trans.* 91, 1985, pp. 1501–1509.

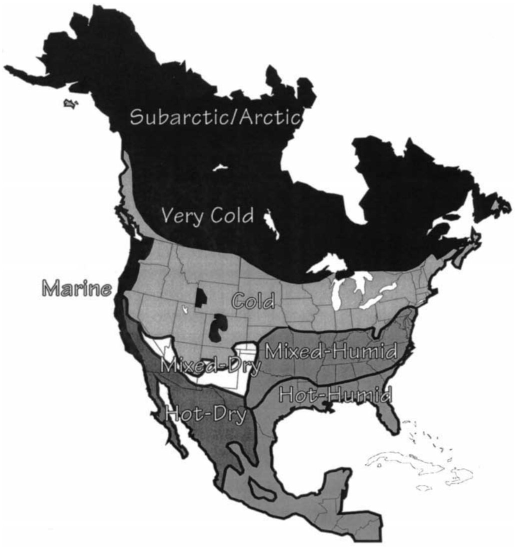
[12] *Fundamentals Volume-ASHRAE Handbook*, American Society of Heating, Refrigerating, and Air Conditioning Engineers, Inc., Atlanta, 2005.

[13] Baker, M. C., *Roofs: Design, Application and Maintenance*, Multi-Science Publications, Ltd., Montreal, Canada, 1980.

[14] Lstiburek, J. W., "Insulation Induced Paint and Siding Failures," *J. Therm. Insul.*, Vol. 13, January, 1990.

Environmental Loads

Hygro-Thermal Regions



Subarctic and Arctic

A subarctic and arctic climate is defined as a region with approximately 12 600 heating degree days (65°F basis) [7000 heating degree days (18°C basis)] or greater.

Very Cold

A very cold climate is defined as a region with approximately 9000 heating degree days or greater (65°F basis) [5000 heating degree days (18 degrees C basis)] or greater and less than 12 600 heating degree days (65°F basis) [7000 heating degree days (18°C basis)].

Cold

A cold climate is defined as a region with approximately 5400 heating degree days (65°F basis) [3000 heating degree days (18 degrees C basis)] or greater and less than approximately 9000 heating degree days (65°F basis) [5000 heating degree days (18°C basis)]

Mixed-Humid

A mixed-humid and warm-humid climate is defined as a region that receives more than 20 inc. (50 cm) of annual precipitation with approximately 4500 cooling degree days (50°F basis) [2500 cooling degree days (10°C basis)] or greater and less than approximately 6300 cooling degree days (50°F basis) [3500 cooling degree days (10°C basis)] and less than approximately 5400 heating degree days (65°F basis) [3000 heating degree days (18°C basis)] and where the average monthly outdoor temperature drops below 45°F (7°C) during the winter months.

Marine

A marine climate meets is defmed as a region where all of the following occur:

- a mean temperature of the coldest month between 27°F (–3°C) and 65°F (18°C);
- a mean temperature of the warmest month below 72°F (18°C);
- at least four months with mean temperatures over 50°F (10°C); and
- a dry season in the summer, the month with the heaviest precipitation in the cold season has at least three times as much precipitation as the month with the least precipitation.

Hot-Humid

A hot-humid climate is defined as a region that receives more than 20 inc. (50 em) of annual precipitation with approximately 6300 cooling degree days (50°F basis) [3500 cooling degree days (10°C basis)] or greater and where the monthly average outdoor temperature remains above 45°F (7°C) throughout the year.

This definition characterizes a region that is similar to the ASHRAE definition of hot-humid climates where one or both of the following occur:

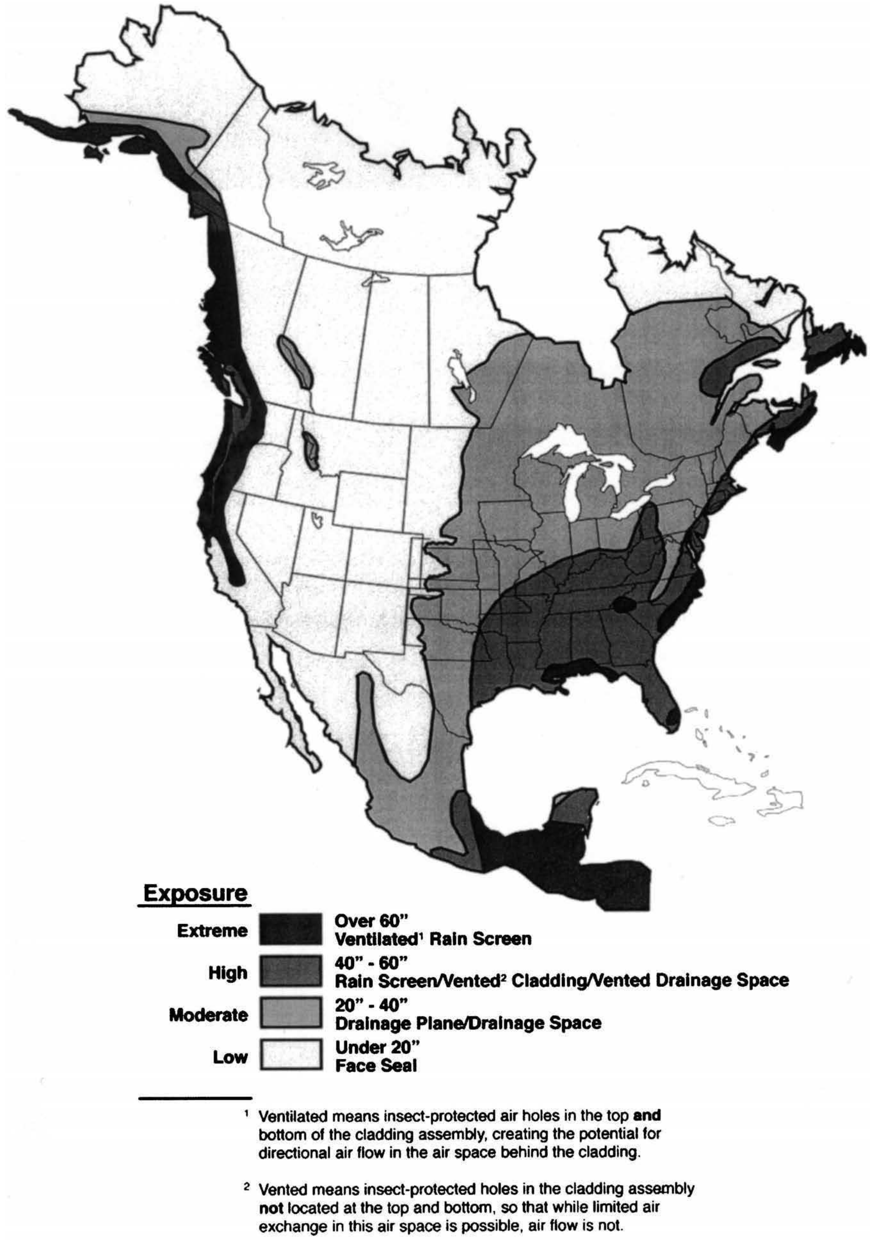
- a 67°F (19.5°C) or higher wet bulb temperature for 3000 or more hours during the warmest six consecutive months of the year; or
- a 73°F (23°C) or higher wet bulb temperature for 1500 or more hours during the warmest six consecutive months of the year.

Hot-Dry, Warm-Dry, and Mixed-Dry

A hot-dry climate is defined as region that receives less than 20 inc. (50 cm) of annual precipitation with approximately 6300 cooling degree days (50°F basis) [3500 cooling degree days (10°C basis)] or greater and where the monthly average outdoor temperature remains above 45°F (7°C) throughout the year.

A warm-dry and mixed-dry climate is defined as a region that receives less than 20 inc. (50 cm) of annual precipitation with approximately 4500 cooling degree days (50°F basis) [2500 cooling degree day (10°C basis)] or greater and less than approximately 6300 cooling degree days (50°F basis) [3500 cooling degree days (10°C basis)] and less than approximately 5400 heating degree days (65°F basis) [3000 heating degree days (18°C basis)] and where the average monthly outdoor temperature drops below 45°F (7°C) during the winter months.

Rain Exposure Zones



MNL18-EB/Oct. 2009

18

New Commercial, Institutional, and High-Rise Buildings

Gustav Handegord[1]

Preface

PUBLISHED INFORMATION RELATING TO THE DE-sign of commercial, institutional and particularly high-rise buildings in North America over the past forty years has been readily available from the Division of Building Research of the National Research Council of Canada (DBR/NRCC) (now the Institute for Research in Construction, IRC/NRCC) and is currently available on the website http://irc.nrc-cnrc.gc.ca. Over 200 Canadian Building Digests (CBDs) specifically prepared for the building design professional are listed by subject and title and are available at no charge. Many other NRCC publications related to building research and practice are also listed and are currently available at nominal charge.

The Canada Mortgage and Housing Corporation has more current reports and research studies on high-rise residential buildings at www.cmhc.ca/en/hoinpr/aren/index.cfm, which can be provided to interested professionals on request.

Reference to these publications is used extensively in this chapter, particularly the Canadian Building Digests (CBDs) and are identified by author and title in the list of references.

Introduction

Practitioners who are responsible for the initial design of new commercial, institutional, and high-rise buildings are often dealing with hypothetical situations involving different occupancies, building configurations, and methods of construction, and where assumptions must be made as to the nature of the indoor environment, the characteristics of the proposed building, the services and equipment to be installed, and the selection and arrangement of components for the proposed building envelope design.

Although the basic design considerations remain unchanged since the first edition of this manual, more detailed procedures for prediction of the moisture performance of the exterior envelope are available. The more sophisticated computer modeling methods can provide more precise predictions, but many do not consider air leakage or involve more considerable computation time to be suitable for preliminary design estimates.

A simpler, graphical method for preliminary assessment is proposed that may best be introduced by an updated review of the principles relating to moisture performance of the building envelope. It considers the use of the moisture storage concept by the building designer as well as estimation of the indoor humidity based on the moisture balance between indoor activities and ventilation with outdoor air throughout the year.

Basic Design Considerations

The basic approach to the avoidance of moisture problems in building envelopes involves minimizing the extent to which moisture can enter the system and maximizing the extent to which it can be removed.

- Moisture can enter or be carried out of the building envelope by diffusion of water vapor from or to the indoor or outdoor air under a vapor pressure gradient.
- Moisture can be carried into or out of the building envelope as a result of air leakage from indoors or outdoors under an air pressure difference.
- Moisture can enter as a result of rain or melt water leaking into the envelope under the action of wind, gravity, or capillarity.
- Moisture may also be introduced during construction by the moisture content in the materials used or stored on site.
- Moisture within the envelope can be absorbed, drain by gravity to the outside, migrate back and forth under temperature induced diffusion, or can escape to indoors or outdoors by diffusion.
- In some mechanisms, the potential for both the entry of moisture and for its removal will depend on the difference between indoor and outdoor conditions throughout the year.

The Migration of Water Vapor by Diffusion

Water vapor can enter a building envelope due to a difference in vapor pressure between the indoor and outdoor air. The rate at which it enters will depend on the resistance to vapor flow presented by the series of materials making up the assembly and whether condensation occurs at some layer in its flow path. The location of this layer will depend on the relative water vapor permeance of the layers which it encounters and can be calculated as discussed in Chapter 10.

If condensation occurs, the rate at which moisture accumulates at the condensation plane will depend on the difference in vapor pressure between the higher vapor pressure side and the saturation vapor pressure at the temperature of the condensation plane (the dew point temperature) and the

[1] *429-180 Oak Park Blvd., Oakville, Ontario L6H 0A6, Canada.*

water vapor permeability of the materials in between.

Vapor retarders are used to reduce the rate of vapor entry from the higher vapor pressure side in order to reduce the accumulation of condensation in the assembly. A common requirement is that they have a minimum vapor permeance 1 perm or 57 $ng/(s \cdot m^2 \cdot Pa)$. Values of the permeance and permeability of various building materials and components are given in Chapter 2. A cursory review will indicate that many building materials can be regarded as having some resistance to vapor flow.

The location of the vapor retarder is usually more important than its permeance since it will inhibit drying during periods of the year when the temperature of the accumulated or absorbed moisture rises above the dew point temperature of the indoor or outdoor air. This suggests that a consideration of conditions on an annual rather than a single extreme case be considered.

Moisture Migration as a Result of Air Leakage

Moist air moving into a building envelope under an air pressure difference from a warmer to a colder region may be cooled by contact with a surface that is below its dew point temperature, and condensation will result. The vapor pressure at that wetted surface will be that corresponding to the saturation vapor pressure at that temperature (the dew point temperature) and will establish both the vapor pressure and moisture content of the air at that location.

The rate at which condensation accumulates at that surface will depend not only on the difference in moisture content between that of the source air and that at the surface, but on the rate of air flow to the condensing surface. This rate will depend on the cross-sectional area of the openings and the pressure difference causing the flow.

In this respect, the process differs markedly from that of vapor diffusion. In vapor diffusion, the rate of condensation depends only on the difference in vapor pressure between the source and condensation plane. It also means that air leakage can occur both from a region of higher vapor pressure (dew point) to lower vapor pressure (dew point) or the reverse. If air flows from a region of lower dew point temperature under an air pressure difference and comes in contact with the surface wetted by condensation that is at a higher dew point temperature, it could act to remove moisture from the wetted surface and carry it out from the envelope.

Air leakage will occur through openings around components and not, as is the case for vapor diffusion, through the pores of the components themselves. The major, and probably the only exceptions being fibrous thermal insulation or air spaces.

Almost all components involved in the exterior envelope are air barriers unless they are perforated or have openings cut into them that remain unsealed. A typical example would be interior gypsum board in which openings are cut for electrical outlets. In most other instances the air leakage openings occur between components. The "airtight drywall approach" (ADA) involves the sealing of joints between components that exist or might develop due to shrinkage. No special air barrier is involved. The term air barrier has unfortunately come to mean some special material that needs to be included in the envelope design.

The location at which the resistance to air flow occurs is not important as far as air flow through the envelope is concerned, but may well influence the movement of air into and out of the envelope by convection. Air leakage openings into the air space or stud space with fibrous insulation may allow air to circulate by convection into and out of the envelope, either bringing moisture into or carrying it out of the space [1].

Moisture Entry Due to Rain or Melt Water

The exterior cladding acts as the first line of defense in sheltering the occupancy from rain and snow. The wall cladding material may itself be waterproof, such as metal or glass, or may be absorptive, such as stucco, brick, or concrete, but in all cases, there will be joints between materials or components where water penetration may occur.

Gravity acts to promote liquid flow into all joints, and in porous materials, "wicking" or capillarity may tend to draw water into a wetted material. Where a joint is bridged with water, the air pressure difference created by wind can act to drive the water inward. An air pressure difference will not move absorbed water through a material unless it is fully saturated.

Roofs are the most vulnerable to rain or melt water entry since all the rain falling will impinge upon the cladding. Sloping the roof surface limits the time that rain or melt water will bridge an opening; the greater the slope, the less the amount of leakage. The unsealed joints between overlapping units such as shingles will not leak unless water is dammed up by some obstruction such as ice or snow, or forced up by wind pressure to a vertical height that is greater than the height or "head" of the shingle overlap. The lower the slope, the smaller will be the overlap height and the lower the resistance to leakage.

It is well to remember the relationship between pressure and the head of water. One pascal is equivalent to a head of water of about 0.1 mm; thus, 1 kPa is equivalent to a head of water of approximately 100 mm, or about 4 in. One kilopascal is equal to the pressure created by a wind velocity of 140 km/h (88 mph).

Low-sloped or "flat" roofs will usually require some impermeable membrane to prevent leakage but should always have some slope to drains in order to reduce the time that rain or melt-water stands on the surface as well as flashings of suitable height at roof openings or penetrations. The leakage that occurs through any accidental opening or any openings that develop through time will obviously be minimized if drainage is effective.

Slopes specified for flat roofs should equal at least twice that of the expected maximum structural deflection unless the drains are located at midspan. Otherwise, ponding of water at low spots will serve to increase the load and resultant deflection, leaving evaporation as the only means for removal.

The tendency to lower costs by using "controlled flow" drainage systems that pond water on the roof temporarily may not always provide an optimum design. Nor will cost cutting measures that place drains at column locations prove economical in the longer term since these constitute the "high points" of the roof. Unfortunately, this practice is all too common in the industry, as can be observed during landing from aircraft by the dirt settlement patterns on the flat roofs of industrial and commercial buildings.

Wind-Driven Rain Penetration

The rain wetting of walls will not be as universal as for roofs, but will depend primarily on the effect of wind. Wide eaves on low buildings serve to protect the wall surface immediately beneath them, but the lower portions will be exposed directly to wind-driven rain.

The upper edges and corners of taller buildings will be the first to become wetted by wind-driven rain with runoff moving down the facade when the surface of the cladding becomes saturated and rainfall continues. With impermeable cladding or when the surface of porous cladding becomes saturated, the runoff will tend to be concentrated by lateral wind flow at internal corners or at those formed by vertical window and curtain wall frames, mullions, or projecting columns on the facade as well as at vertical joints.

Joints are often the locations where runoff will lead to bridging of the joint with water. If openings occur through the cladding at such locations, the pressure difference created by wind across the opening and the force of gravity may combine to move water inward and downward in the joint. Two distinctly different approaches are taken to avoid this kind of rain penetration; either sealing of the joint at the exterior, so-called "face-sealed" joints, or using open joints that are wide enough to avoid water bridging with a seal inward of the face—called "two-stage" joints.

The two-stage concept originated in Norway, where wind-driven rain is a particular problem. It is based on the fact that, aside from raindrops propelled into an open joint by their momentum, rain water that bridges the opening will not likely be forced inward unless a pressure difference develops across it. Thus, if a seal existed or could be installed inward of the outer face where it is not likely to be wetted, the pressure difference due to wind would be taken across this nonwetted inner seal and there would be little or no pressure difference acting across the rain water that bridged over the open joint.

With a face-sealed joint, the face seal is better than the inner seal, and most of the pressure difference will occur across the outer seal. If a small crack develops in the joint due to expansion and contraction, or because the sealant was not properly adhered initially, most of the pressure difference will act across the crack. Since it can readily be bridged by water flowing down the joint, rain penetration is most likely. Once in the joint, if the water has little chance of escaping, it will accumulate, find its way to some moisture sensitive material, or maintain a high relative humidity that will promote mold, mildew, or corrosion.

Vertical joints should always have some capability for drainage so that any water that penetrates an open joint or is forced through a crack or gap in a face-sealed system can be directed to the outside at a lower level, provided that the inner upstand of the flashing is higher than the maximum head of water that could develop across the drainage opening. Drainage openings (weep holes) should also be provided at horizontal joints or joints left open with flashings extending out from the lower edge to provide a drip, and extending inward to form a dam against water penetrating the inner wall components. The height of this dam should be greater than the maximum pressure difference expected to occur across the inner components. It is suggested that this height be at least 100 mm (about 4 in.).

Moisture Migration Within the Envelope

Moisture Initially in the Materials of Construction

Moisture that is initially uniformly distributed in the materials used in the envelope will tend to migrate by vapor diffusion from warmer to colder (higher vapor pressure to lower vapor pressure) regions so that under each reversal of temperature gradient, the moisture will tend to move back and forth within the assembly.

The moisture will also tend to migrate from the wettest regions to dryer regions by capillary action which, under a temperature gradient, may be the opposite to that of vapor diffusion. This was demonstrated by Paxton and Hutcheon in a study of wetted sawdust exposed to a temperature gradient in a closed, guarded hot plate [1] and forms the basis for the wetting and drying diagrams in Chapter 16, as considered in CBD 73 [2] and advanced by Baker [3].

Moisture From Wetted Cladding

Although rain penetration into the occupied space can usually be avoided by incorporating drained cavities within the envelope, moisture that is held in absorptive cladding can be driven inward by vapor diffusion under the action of solar heating. The temperature conditions and relative vapor permeance or surface characteristics of the components inward of the cladding will determine if and where condensation is likely to occur.

This phenomenon was first described at a RILEM/CIB Symposium in 1965 by Wilson in a study of some small masonry test buildings in Ottawa, Canada [4]. The heated and humidified huts featured brick and concrete masonry walls with mineral fiber batt insulation between 2 by 2 wood furring strips on the interior, covered with a polyethylene vapor barrier and interior gypsum dry wall. The interior dry wall was removed in summer after 1-1/2 years of operation and the outer surface of the vapor barrier of the south facing walls of the brick test hut was very wet. Some similar wetting was observed on the vapor barrier of the south facing walls of a hollow concrete block test hut. In July of the following year the observed conditions were similar, and the east and west walls of one of the brick huts showed more extensive wetting, with evidence of deterioration of the vapor barrier, drywall and wood furring at the lower levels, the east wall being most severe. The annual totals of the horizontal component of rain measured at the site indicated that values for the eastern exposure were the highest.

Condensation, or "sweating" on the outside of an interior polyethylene vapor barrier was also reported at the above grade section of a south facing, similarly insulated basement wall in western Canada, and some more recent studies on brick veneer walls in a test building in Waterloo, Ontario have reported a similar condition.

If a material is saturated, the moisture in the material will be at the saturation vapor pressure corresponding to its temperature (the dew point temperature). Under solar heating this temperature could be much higher than that of the outdoor air and the vapor pressure would exceed that of the outdoor air temperature, resulting in drying to outdoors by evaporation.

It could also be higher than the indoor temperature and of components within the envelope toward the interior. Under such conditions a vapor pressure gradient toward the indoors would also occur and vapor driven inward could condense on a surface within the assembly that is at a lower temperature than that of the wet cladding.

Condensation on and within gypsum drywall finished with vinyl wallpaper in walls has been observed in some air conditioned hotel/motel buildings in humid climates, which was attributed to the infiltration of moist outdoor air [5]. It is possible that solar-driven moisture from the wetted cladding could also have been involved.

These observed phenomena suggest that changing temperature gradients within an exterior envelope can influence the migration of moisture inward and outward during the year as well as at any time of day due to the effects of solar radiation.

Moisture from Condensation in the Envelope

Condensation on a component may occur as surface moisture or be absorbed into the material directly depending on the characteristics of the condensing surface. A surface that resists wetting (hydrophobic) such as polyolefin "house wrap" will act as a condensing surface even though the material has a high vapor permeance [6]. A build-up of surface droplets will tend to drain by gravity to lower regions immediately but the absorbent surface will have to become saturated before drainage will commence. If the condensing surface is exposed to a vertical air space or channel, both drainage and venting offer a means for removal. In many instances, however, a condensing surface may be in contact with a porous or fibrous insulation and condensed moisture may be held in place by the contacting material, inhibiting drainage [7].

Moisture that remains at the temperature of the condensation plane will exhibit a vapor pressure according to the saturation vapor pressure at that temperature (the dew point temperature) and can act as a sink for water vapor that is at a higher pressure (dew point temperature) and a source for evaporation to a region of lower vapor pressure (dew point temperature).

Such wetting and drying processes will be determined by the temperature and moisture changes that occur within the envelope resulting from the changes in outdoor and indoor conditions throughout the year.

Commercial and Institutional Buildings

General Design and Construction Features

Walls

Typical wall constructions would be concrete block or brick masonry insulated on the interior or insulated masonry cavity walls where the insulation is on the exterior of the interior wythe. Brick veneer and steel-stud (BVSS) walls have also become popular for such buildings. Stucco clad and exterior insulation finish systems (EIFS) could also be used, but masonry or precast concrete cladding tend to be preferred at ground level because of its durability and low maintenance costs and because of its resistance to physical damage from activities around the building.

Windows

Fewer windows are usually involved because of privacy and security reasons, except at entrances or in reception or office areas. Their thermal properties may be lower than that of the walls, so they may be the likely locale of surface condensation during periods of extremely low outdoor temperatures or high indoor humidity.

Roofs

The larger roof area of many warehouse and factory-type buildings frequently consists of a metal deck supported by steel beams and open web steel joists and purlins. Roof mounted fans and heating and air conditioning equipment are common, involving a considerable number of roof penetrations. Stacks for plumbing and other venting purposes are flashed in order to prevent water entry, but often provide direct leakage openings from inside the building directly to outdoors.

From an energy conservation aspect, insulating the relatively large roof area exceeds by far the requirement to insulate the wall area to prevent condensation on the interior surface. Extensive rain wetting of walls may not be of concern, but the adequate drainage of rain and melt water from the roof area is a basic requirement.

The Effect of Wind, Stack Effect, and Mechanical Systems

For single- or two-story high buildings, the maximum stack effect pressure is not very high-even at low outside temperatures. For an outdoor temperature of −20°C and an inside temperature of 23°C, the maximum stack effect pressure can be calculated as 10 Pa, or 5 Pa acting out at the top and 5 Pa acting in at the bottom, if the leakage openings are equal above and below the neutral pressure plane [1].

In many low-rise commercial buildings, there will likely be many openings through the roof assembly at exhaust fans and other penetrations, even when the fans are not operating. The total leakage area through the roof will likely be much greater than through the walls and the stack effect pressure will primarily be inward through the walls in heated buildings. When the exhaust fans are operating, as would occur in many cases, infiltration through the exterior walls would be the primary effect in most buildings.

In winter, there would be a decreased potential for cold weather condensation. In air-conditioned or cooled buildings in humid climates there may be a greater chance for condensation if the indoor air temperature, and hence the interior cladding, are below the outdoor dew point temperature.

Low-rise buildings, unless built in rural areas, will be surrounded by other buildings and wind effects will likely be localized and unpredictable. Being close to ground level, wind velocities will be low and the lack of height will result in minimal pressure differences due to the stack effect. The relative greater area of roof compared to wall area and the many penetrations through the roof around vents and through fan openings will tend to reduce the outward acting stack effect pressure difference below its nominally low value for a one- or two-story height. More important, however, is the fact that these buildings are frequently operated under negative pressure, relying on air leakage through entrances and wall leakage openings for make-up air.

The Indoor Environment

Estimating Indoor Conditions

Retail stores and service buildings will usually be conditioned for the comfort of the occupants and customers. There will not likely be any operable windows; the ventilation rates will likely be constant and at the minimum required in order to conserve energy. Specific stores may require special exhaust systems, but the provision of specific make-up air supply systems will usually be ignored and reliance placed on general infiltration from air leakage.

The indoor temperature conditions will likely be in the human comfort range of 20°C to 26°C (68°F to 79°F) with relative humidity maintained between an upper dew point limit of 19°C based on ASHRAE Standard 55 [8], and a lower limit of 2°C (36°F) or about 30 % relative humidity at 20°C in winter to avoid discomfort from dryness in the nose and throat.

Recommended levels of temperature and humidity for some commercial or institutional buildings are outlined in the *ASHRAE Applications Handbook* [9], but for most commercial buildings, humidity levels can be assumed to fluctuate between the recommended limits throughout the year, being dependent on the balance between interior moisture gains and ventilation with outdoor air. The indoor moisture gains might be reasonably constant, but the outdoor air moisture content (dew point) could vary considerably in some regions. In view of the efforts to conserve energy and the standards adopted it could be assumed that constant, minimum ventilation rates will be the usual case.

In buildings intended mainly for human occupancy and on the basis of the information in Chapter 7, a moisture output of 0.26 L/h or 0.26 kg/h per person in residential occupancies for light to moderate activity might be considered as rough basis for a the occupied space, as could a corresponding minimum ventilation rate of 10 L/s per person. For institutional, office, and warehousing occupancies, significantly lower moisture output rates seem justified.

This ventilation rate corresponds to a volumetric rate of flow of $(10 \times 3600)/1000 = 36\ m^3/h$ and a mass rate of flow, assuming a specific volume of $0.84\ m^3/kg$ of $36/0.84 = 43$ kg/h. If the rate of moisture added per person is 0.26 kg/h, this would raise the moisture content of the outdoor air by about $0.26/43 = 0.006$ kg/kg. In most retail applications an occupancy would only be for 10 h to 12 h, so the average rate of addition per day would be about half or 0.003 kg/kg (0.003 lb/lb).

Under these assumptions, the average indoor air moisture content for each month can be estimated by the addition of 0.003 kg/kg (0.003 lb/lb) to the average outdoor air moisture content and dew point temperature obtained using a psychrometric chart or tables.

Predicting Moisture Performance

A Cold Climate Example: Minneapolis

A graphical approach to predicting the moisture performance of a building envelope can be applied using a representation of the climatic conditions for a particular locality, such as in Fig. 1 for Minneapolis. The monthly average outdoor air temperatures obtained from the weather records are plotted on the upper chart as open circles connected by a solid line with the coincident monthly average dew point temperatures plotted as open diamonds connected by a dotted line. Total monthly hours of sunshine are indicated by large open circles in the lower chart with the total monthly precipitation shown as vertical bars.

The average monthly values shown are based on data provided in the 1996 World Meteorological Organization publication WMO/OMM-No.847 [10].

Indoor Conditions

The indoor temperature has been assumed constant at 23°C (73°F) and the indoor dew point temperature determined by locating the moisture content at the outdoor dew point for each month, adding the assumed increase due to indoor moisture supply of 0.003 kg/kg (0.003lb/lb) to determine the estimated indoor dew point from a psychrometric chart. The resultant indoor conditions have been plotted as the shaded line connecting the values for each month, modified to show the dew point limits of 19°C and 2°C (66°F and 36°F).

Assessing the Potential for Condensation

For initial assessment, the outdoor air temperature can be considered as being close to the temperature of the components outside of the thermal insulation; the outer wythe of a masonry cavity wall or the exterior sheathing of a steel-stud and brick veneer or stucco clad wall. The indoor temperature can represent the temperature of the interior wythe of a masonry wall or the indoor dry wall of an insulated stud space. In masonry walls there are no such obvious condensation planes unless one considers the interior faces of hollow masonry, but the likely condensation planes will be on the colder side of any thermal insulation.

In the case of Minneapolis, it can be noted that the outdoor air temperature falls below the indoor dew point from September to April and rises above the indoor dew point for the remaining months. This suggests that wetting of the outer wythe or exterior sheathing could accumulate by absorption during the condensation period and drying of these moist component to the outdoors (or indoors) could occur during the rest of the year.

Insulated Masonry Cavity Wall

An insulated masonry cavity wall is well suited to this application since all of the thermal insulation is usually installed on the exterior of the structural components and the plane of condensation will be beyond the insulation. Water vapor migrating from indoors is most likely to condense on the inner face of the outer wythe and to be absorbed or drain to the weep holes. Any absorbed moisture could also dry to the outdoors when its temperature, and hence vapor pressure was above the dew point temperature of the outdoor air. An air barrier and vapor retarder at the outer face of the interior wythe or vapor resistant insulation would thus inhibit moist air or vapor entry from indoors as well as preventing moisture from condensation or rain wetting being driven inward by solar heating.

Brick Veneer and Steel-Stud Wall

A brick veneer and steel-stud assembly with insulation only in the stud space could present problems since the likely winter condensation plane would be on the sheathing outside of the insulation. If the condensed moisture wets the

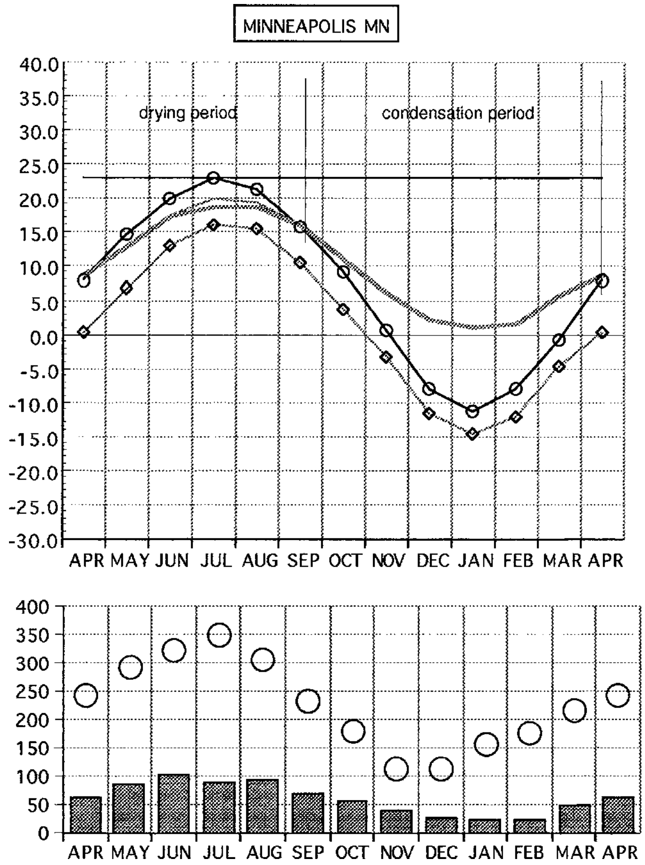


Fig. 1—Climate chart for Minneapolis.

surface of the sheathing or is further absorbed there is a possibility of mold or structural deterioration of the core material. If the moisture drains as liquid water, it could accumulate in the lower channel, and could lead to corrosion of the lower channel and associated studs. A vapor barrier installed at the interior cladding would inhibit vapor diffusion into the stud space, but air leakage through openings in the drywall or the punched holes in the steel studs for wiring and services will afford ample opportunity for indoor air to enter the stud space, even from remote locations in partition walls.

Providing at least one-third of the thermal insulation outside of the sheathing would tend to reduce moisture accumulation in the stud space and the potential problems from lack of drainage from the lower channel.

Any condensation on the sheathing during periods when lower outdoor temperatures or higher indoor dew points were experienced would not be prevented from drying to the indoors by a vapor retarder at the interior cladding. The insulation layer on the outside of the sheathing has the additional advantage of minimizing the high heat conduction paths afforded by the steel studs.

Air leaking outward into the drained space behind the brick cladding could result in condensation at the inner face of the brick but could eventually drain or be absorbed for subsequent drying to the outdoors. An air and vapor barrier or vapor resistant insulation applied to the exterior of the sheathing would reduce the rate of vapor passing through to the brick veneer as well as inhibiting any moisture from condensation or rain wetting of the brick exterior being driven inward by solar heating.

The foregoing analysis applies when both vapor diffusion and air leakage are acting from indoors to outdoors. Outward air leakage will no doubt add to the accumulation of condensation during periods when the indoor dew point temperature is above the temperature of components within the envelope to an extent dependent on the outward acting air pressure difference. During the "drying period" indicated, the indoor dew point could be below the temperature (dew point) of the condensation plane and hence the outward moving air would act as a drying force.

Exterior Insulation Finish Systems

Designs which involve thermal insulation on the exterior of the envelope offer the best solution to successful thermal and moisture performance. The structural components are maintained at near constant temperature and thermal expansion and contraction are avoided. The resistance to both air and vapor flow can be provided at a location where penetrations or openings can be minimized and continuous membranes applied more easily. In the case of exterior insulation finish systems (EIFS) the use of high-impact resistant EIFS or some other method of protection from physical damage is required at lower stories.

Roofs

There has long been a question as to whether flat or near flat (generally referred to in the United States as low-slope roofs), nonvented roof systems require a vapor barrier, one concern being that the vapor barrier and roofing membrane would create a sealed system with no means of moisture removal. Possible venting systems that rely on vapor diffusion or "pumping" due to pressure changes have not proven to be effective (CBD 176) [11].

Steel roof decks provide, in principle, a perfect indoor vapor barrier but this only occurs at the flange areas. The flutes are unsealed at their intersection with the exterior walls and are left open at all penetrations through the roof structure such as at mechanical equipment and plumbing stacks. The flutes are also often penetrated by holes for electrical wiring. Although mechanical fasteners penetrate the flanges they offer a tight seal against water vapor entry.

The impermeable roofing membrane precludes any air leakage through the roof, but indoor air circulation through the flutes or vapor diffusion into the flutes is possible. Both processes can result in the air in the flutes approaching the conditions of the indoor environment, but the extent to which this occurs is difficult to predict. It does mean that the sole means for water vapor to enter the roof system from indoors is by means of vapor diffusion and only at the areas over the flutes.

The possibility of water entry into the flutes from membrane or flashing leaks can result in a relative humidity close to 100 % at indoor air temperature in the effected flutes, and the water causing such conditions will tend to accumulate at the low point in the flutes at midspan. Conventional practice usually places drains at column locations, leaving little opportunity for the accumulated water to be removed.

Under winter conditions, vapor from water in the flutes, water vapor from indoor air in the flutes, or moisture within the insulation will tend to diffuse upward to condense beneath the colder roofing membrane. Solar heating during the day will increase the temperature and hence the vapor pressure (dew point temperature) of the wetted insulation under the membrane will drive the moisture downward to condense on the steel deck or vapor barrier if it is at a temperature below that of the roofing membrane.

On sunny days, the temperature reached by sunlit surfaces will depend on the proportion of solar radiation that is absorbed, the rate of heat transfer into the envelope, the rate of air flow over the surface, and the rate at which heat is lost or gained through radiation to other surfaces that the surface "sees." For opaque elements, the sol-air temperature, which can be thought of as the temperature reached by a surface exposed to solar radiation which is not losing heat by conduction into the envelope, can be considered the upper limit of temperature that might be reached by the outer surface of a building exposed to the sun for a particular outdoor temperature.

The actual temperature at the surface of the membrane will depend on its mass and ability to conduct heat into the substrate. Thermal insulation immediately beneath the membrane will act to inhibit the rate at which heat is conducted inward and tend to increase the temperature rise. As discussed in CBD 47 and 65 [12,13]. To account for these effects and to offer a means to estimate maximum temperatures, the following relations were suggested for horizontal roof surfaces in CBD 70 [14], (and can be considered for sunlit walls).

For roofs with insulation beneath the surface membrane or walls with light weight cladding,

$$\text{Maximum temperature} = \{\text{Air temperature} + (55 \times a)\}\,^\circ\text{C}.$$

For roofing membranes applied directly to a concrete deck or walls with heavier cladding,

$$\text{Maximum temperature} = \{\text{Air temperature} + (42 \times a)\}\ ^\circ\text{C}$$

where a = solar absorption coefficient.

The values for solar absorption coefficient often used for initial assessment are $a = 1$ for dark surfaces and $a = 0.5$ for light colored surfaces. As a first approximation it might be assumed that solar radiation could raise a sunlit surface about 20 K (20°C) (68°F) above air temperature. To estimate the temperature that might be reached by a sunlit surface, this increase could be added to the outdoor temperature.

These values are based on calculations and experimental observations at a latitude of 45° N. At lower latitudes the peak values for vertical surfaces will be about the same in summer and winter, but for horizontal surfaces in summer, the peak values will be about the same as for 45° N, but at 20° N latitude will be about double those at 45° N because of the higher solar angle.

Considering the potential temperature of a roofing surface as 20 K above the monthly average outdoor air temperature provides an indication as to when downward diffusion of vapor from wetted insulation could be experienced. It could be suggested that for Minneapolis, downward diffusion could occur periodically during those months when the sunlit temperature of the roof surface (outdoor temperature plus 20 K) is above the indoor air temperature (temperature of the steel deck). The periodic reversal of temperature gradient from night to day or sunshine to cloud could result in lateral redistribution of moisture within the insulation and periodic wetting of the upper surface of the vapor barrier or of an unprotected steel deck even over the flange area. Such periodic wetting could result in corrosion of the deck if the vapor retarder was not an effective moisture barrier.

The current practice of covering the steel deck with some acceptable rigid boards as a base for application of the insulation and roofing membrane provides a logical plane to install a moisture barrier that could satisfy any code vapor retarder requirements and serve as a means to prevent moisture from roof leaks or inherent moisture in the insulation from contacting the steel deck and providing protection to the steel deck from corrosion.

Moisture control in such roofs could also be better achieved if the deck was adequately sloped to drains, a procedure followed by some structural designers but often neglected by builders. It has been suggested that if the structure was sloped to drains, a double drain system could be employed to lessen the problems occasioned by moisture accumulation in such roofing systems (CBD 99) [15].

Protected membrane roof (PMR) systems (CBD 150) [16] offer the advantage over conventional BUR systems in northern climates because the insulation provides protection from the low winter temperature that increase the thermal stresses of exposed membranes due to the increased coefficient of thermal expansion/contraction experienced at below freezing temperatures (CBD 181) [17]. The insulation also reduces the problems of membrane slippage, shrinkage, and ridging caused by localized or continued expansion and contraction as influenced by the wide temperature fluctuations induced by solar heating (CBD 211) [18].

A Colder Climate Example: Fairbanks, Alaska

The climate of Fairbanks represents the inland climate of the far north, similar to those of inland Canadian cities at this latitude and is represented in Fig. 2, with the indoor conditions plotted, based on the same procedure as for Minneapolis.

It can be seen that the estimated indoor dew point temperature falls below the outdoor temperature during the period from mid-August through to early May, suggesting that condensation due to vapor diffusion or indoor air exfiltration could accumulate in the colder parts of the envelope during this period while the potential for drying would be from May to mid-August.

Walls

In January, the indoor dew point (2°C) is about halfway between the indoor and outdoor temperature, so that if half of the total thermal insulation were to be installed outside of the sheathing, there would be less likelihood that moisture would accumulate in the stud space. This might be accomplished using a double stud system with fibrous insulation in both stud spaces, applying foamed plastic insulation to the exterior of the sheathing, or by having all of the insulation on outside of a masonry wall. Alternatively, the thickness of the insulation in the stud space could be reduced to equal that of any insulating sheathing applied. The vapor barrier would be best applied on the exterior of the stud space or inner wythe of a cavity wall.

Because of the low levels of rainfall, rain penetration or

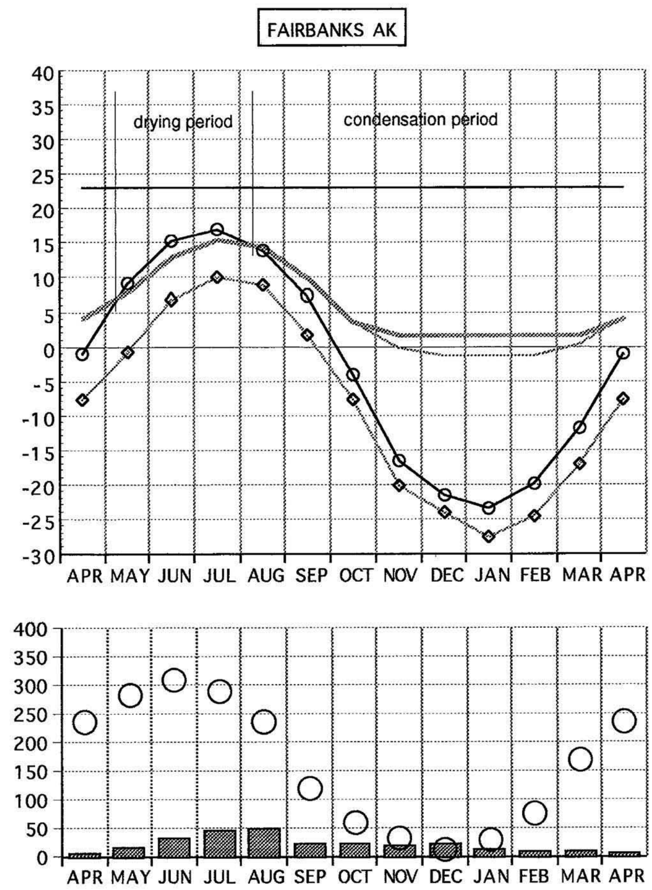


Fig. 2—Climate chart for Fairbanks.

rain wetting of exterior cladding will not likely be a problem.

Windows

Sealed multiple glazed windows would be preferred, installed in low conductivity frames. Although some solar heat gain might be experienced in spring and fall, the lack of sun in winter should be considered as offering little energy conservation advantage.

Roofs

Ventilated roofs of any type should be avoided because of the possible entry of wind-driven snow and the difficulty of avoiding air leakage through the ceiling. If such vented roofs are unavoidable, means to close off the vents during winter should be considered. One such case in the Canadian north utilized a small electric fan to pressurize the roof space with outdoor air during winter [19]. Protected membrane roof (PMR) systems could be considered but with nonvented BUR systems with adequate drainage provisions would not likely be prone to condensation with an adequate vapor retarder and the limited potential for air exfiltration.

A Coastal City in the Far North: Juneau, Alaska

Figure 3 shows the predicted indoor and outdoor temperature and dew point conditions for the assumed moisture balance for Juneau, a coastal city where the summer to winter conditions are influenced by its proximity to the Gulf of Alaska. Outdoor temperatures in summer are cooler and winter temperatures much warmer than those experienced in Fairbanks. These more moderate temperatures and much greater rainfall contribute to more humid conditions and higher dew point temperatures throughout the year.

Walls

Since the estimated indoor dew point is above the outdoor temperature throughout the year, there is little potential for any drying period. The January indoor dew point at 5 °C is about two-thirds of the way into the insulation. Thus, if at least one-third of the total insulation was placed outside of the stud space or inner masonry wythe, accumulation of condensation due to air leakage or vapor diffusion could be avoided. A vapor retarder and air barrier on the exterior of the sheathing or inner wythe could be applied with less likelihood of holes or openings and would limit the amount of condensation on the inside of exterior cladding.

The significantly high rainfall suggests that rain penetration and wetting of exterior cladding could be experienced so that vented and drained metal siding might be considered an option. The two-stage or "open rain screen" approach to joint design in exterior cladding should be considered and exterior masonry of low moisture absorption or treatment for moisture resistance could be considered. Placement of the vapor retarder or moisture resistant insulation on the exterior of the stud space or inner wythe would control the inward diffusion of vapor, even though solar heating may not be significant.

Roofs

Ventilated roofs of any type should be avoided because of the possible entry of wind-driven snow and the difficulty of avoiding air leakage through the ceiling. If such vented roofs are unavoidable, means to close off the vents during winter should be considered as for Fairbanks. Protected membrane roof (PMR) systems could be considered but nonvented BUR systems with adequate drainage provisions would not likely be prone to condensation with an adequate vapor retarder and the limited potential for air exfiltration. In such cases the protection of roof insulation from rain during site storage or application should be assured.

A More Moderate West Coast Example: Portland Oregon

The predicted conditions for a more southern west coast city have been plotted on the climate chart for Portland, Oregon in Fig. 4. The moderating effect of the Pacific Ocean on the summer to winter temperature variation is apparent, but temperature levels are higher than in Juneau, due to the lower latitude and increase in the hours of sunshine. Dew point temperatures are higher for Portland but in both cases the predicted indoor dew point falls within the ASHRAE comfort envelope.

Walls

Condensation in the colder regions of the wall are likely during the period from late September to mid-May with the potential for the drying of accumulated condensation during the remainder of the year. The indoor dew point in January is at 9 °C, about three quarters of the way into the insulation so that placement of at least one-quarter of the total thermal insulation on the exterior of the exterior sheathing in a BVSS wall, no accumulation would be expected to occur in an insulated stud space. A vapor retarder and air barrier located

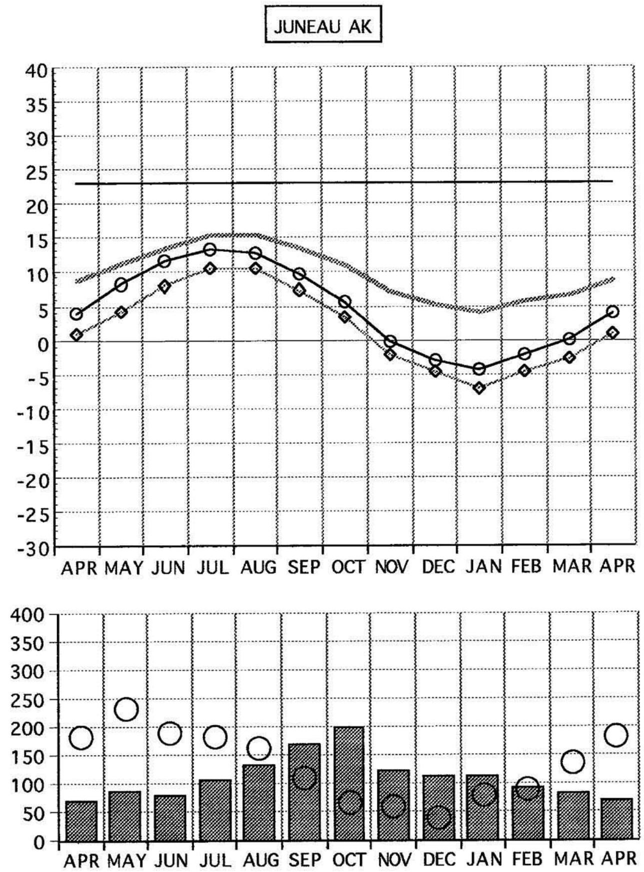


Fig. 3—Climate chart for Juneau.

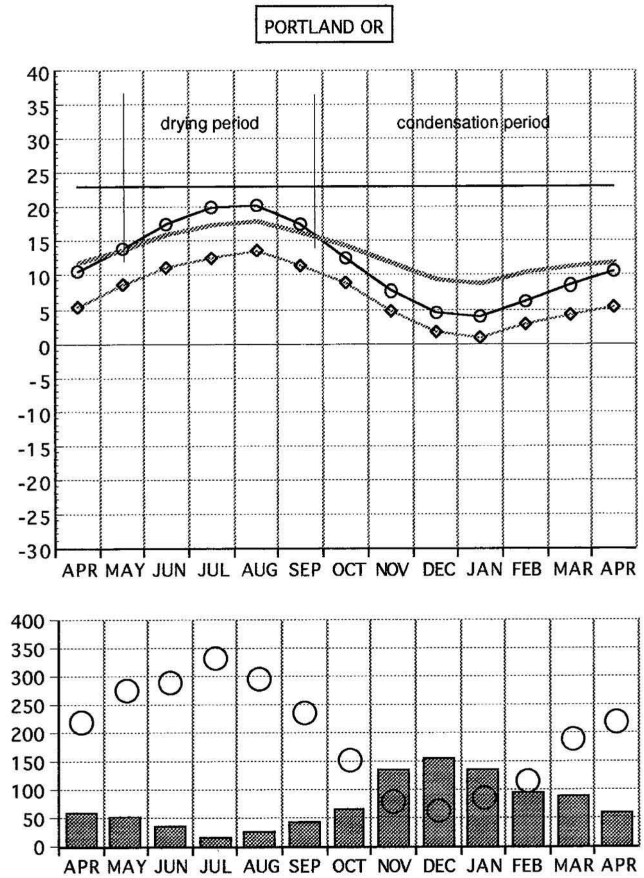


Fig. 4—Climate chart for Portland.

on the exterior of the sheathing could allow for drying of any occasional moisture in the stud space to indoors and minimize the amount of vapor reaching the colder brick cladding. The same arrangement would apply to the interior wythe of an insulated masonry cavity wall.

The rainfall experienced in Portland could lead to the wetting of exterior cladding, and heating of the cladding by solar radiation (approximately 20 K) could raise the cladding temperature above the indoor temperature for most of the year. Location of the vapor retarder and air barrier at the exterior of the sheathing in BVSS walls or the outside surface of the inner wythe of masonry cavity walls would avoid inward diffusion past these barriers. Rain penetration at joints between the exterior cladding and widows should involve the rain screen, two-stage approach, and adequate drainage to avoid moisture accumulation within the assembly.

A Semi-Arid Climate Example: Boise, Idaho

Figure 5 represents an example of an inland city at the same latitude as Portland but with the semi-arid climate of the mountain and foothill regions of Canada and the United States. The indoor dew point temperatures predicted for Boise are lower than those for Portland but remain within the ASHRAE comfort limits. Monthly average outdoor temperatures are slightly higher and winter temperatures lower. The low outdoor dew point temperatures could allow for evaporative cooling if increased summer ventilation is not adequate for comfort.

Walls

The period during which the accumulation of moisture within a building envelope due to outward vapor diffusion and indoor air exfiltration could occur is from mid-October to mid-April with a potential drying period for the remainder of the year. If one-quarter to one-third of the total thermal insulation was located outside of the insulated stud space of a BVSS wall or on the exterior of a masonry wall, no accumulation would be expected in the stud space. With a continuous vapor retarder and air barrier on the exterior sheathing, any condensation on the exterior cladding would be minimized and the possibility of inward diffusion due to solar heating of wetted cladding avoided, even if wetting is unlikely because of the low rainfall expected.

Roofs

Although winter temperatures are more moderate than for Minneapolis, the same suggestions with regard to roofs are applicable.

An East Coast Example: Boston, Massachusetts

Summer conditions in Boston, as indicated in Fig. 6 are similar to those of Minneapolis, but winter conditions are milder because of the proximity to the Atlantic Ocean. Monthly average temperatures fall slightly below freezing during January and February. Compared to Portland, Or-

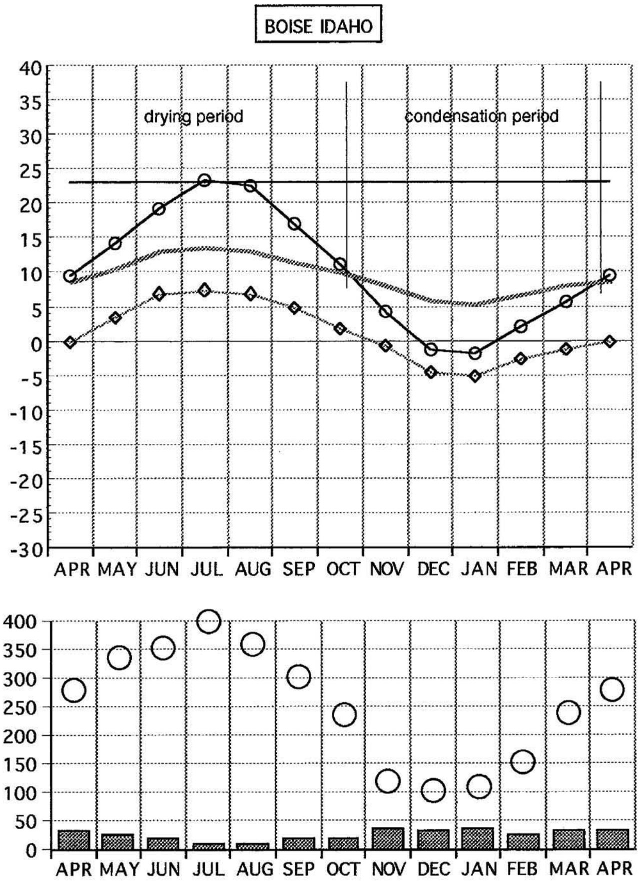


Fig. 5—Climate chart for Boise.

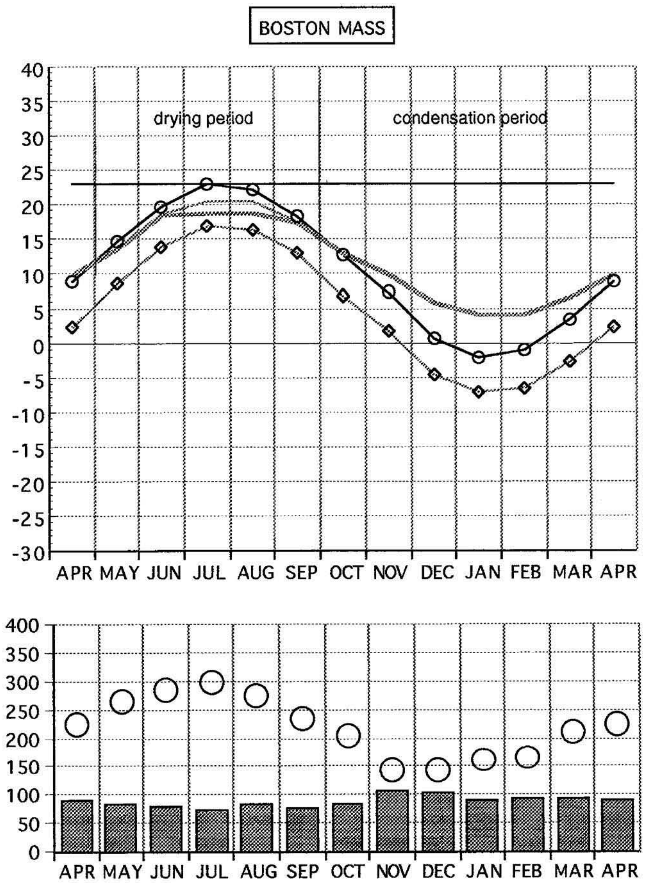


Fig. 6—Climate chart for Boston.

egon, Boston has higher summer and lower winter temperatures, more uniform monthly rainfall, and slightly less monthly sunshine.

The predicted indoor dew point in summer exceeds the limit of 19°C of the ASHRAE comfort envelope and outdoor temperatures are high enough to require cooling during the summer months. Conventional air-conditioning systems should be capable of maintaining indoor conditions within the comfort envelope.

Walls

Under the estimated indoor conditions, condensation from outward diffusion and air leakage is likely to accumulate during the period from October to April and drying would be likely during the period May to September. For BVSS walls, placement of at least two-fifths of the total thermal insulation outside of the sheathing would avoid accumulation in the insulated stud space, and the use of low permeance insulation or vapor retarder and air barrier on the outer surface of the sheathing would minimize condensation accumulation on colder components.

Such features would also guard against the inward diffusion of moisture from wetted cladding and allow drying for any condensation to outdoors from a vented space inward of the exterior cladding. Suitable flashing and drainage openings to outdoors at the base of the wall should be provided to assist in controlling rain penetration. The two-stage design and drainage of joints between cladding components would be desirable in view of the potential for wind-driven rain throughout the year.

Roofs

The design of roofs should follow the recommendations for Minneapolis.

A More Southern East Coast City: Savannah, Georgia

The estimated indoor conditions for Savannah are shown in Fig. 7, where the indoor dew point temperature is above the limit of 19°C from May to October. Cooling and dehumidification will be necessary during this period and cooling for a longer time. During some periods in spring and fall, outdoor temperatures might be low enough for increased ventilation to maintain indoor conditions within the comfort envelope.

Walls

The conditions predicted for Savannah suggest that some condensation might occur during the winter months. With the indoor dew point at the 19°C limit, the monthly average outdoor air dew point temperature would be above that indoors during June, July, August, and September and vapor could be carried inward by diffusion or air infiltration and condense on the interior gypsum dry wall if indoor air temperatures were below 21°C. With the relatively heavy rainfall, moisture from wetted cladding could also be driven inwards from solar heating to condense on interior wall components. Application of the vapor retarder and air barrier on the outer surface of the sheathing in a BVSS wall or outer surface of a masonry cavity wall would restrict this inward migration and allow drying of moisture from the stud space or inner wythe to indoors. All measures to reduce the entry of wind-driven rain and drainage to outdoors will be required to avoid moisture accumulation within the assembly.

Roofs

In view of the rainfall expected throughout the year, good drainage provisions on all roofs is a requirement. The increased possibility of insulation becoming wet from inadequate storage efforts or rain during application should be recognized.

An Inland Example: Memphis, Tennessee

For the city of Memphis, illustrated in Fig. 8, summer conditions are similar to Savannah, but lower winter conditions prevail. However, because of the high dew point conditions in summer, some conventional air conditioning systems may not be capable of reducing the indoor dew point to 19°C without overcooling, and high indoor humidity might be experienced during the peak days in summer.

Walls

The predicted indoor conditions for Memphis are similar to those of Savannah, but the colder winters suggest that some condensation from outward acting air and vapor flow could accumulate. For a BVSS wall, if one-fifth of the total insulation, say, in the form of insulating sheathing, was applied, the possibility of condensation accumulation in the stud space would be reduced. If the vapor retarder and air barrier were applied to the outer surface of the sheathing, or if vapor and water resistant insulated sheathing were applied, any condensation occurring during colder periods would be able to dry to indoors through the permeable indoor drywall.

With the major vapor and air flow resistance located outside of the stud space, air infiltration or vapor diffusion inward due to periods of high outdoor dew point or solar heating of wetted cladding would be inhibited from entering the stud space and condensing on a colder interior drywall.

An Inland, Arid Climate Example: Las Vegas, Nevada

The climatic conditions are markedly different in cities of the south western states such as Las Vegas, represented in Fig. 9, where similar winter temperatures occur, but much higher temperatures and much lower dew point temperatures are experienced in summer. As in Boise, evaporative cooling or conventional air-conditioning systems will be capable of maintaining indoor air temperatures and dew point temperatures within the comfort zone, even though direct evaporative systems may result in increased indoor humidity in summer. With conventional mechanical cooling systems, indoor humidity may be reduced during the summer months and little variation from summer to winter will be expected. Even in buildings without indoor cooling, solar shading, night ventilation, or evaporative cooling of roofs might be sufficient to maintain acceptable indoor conditions.

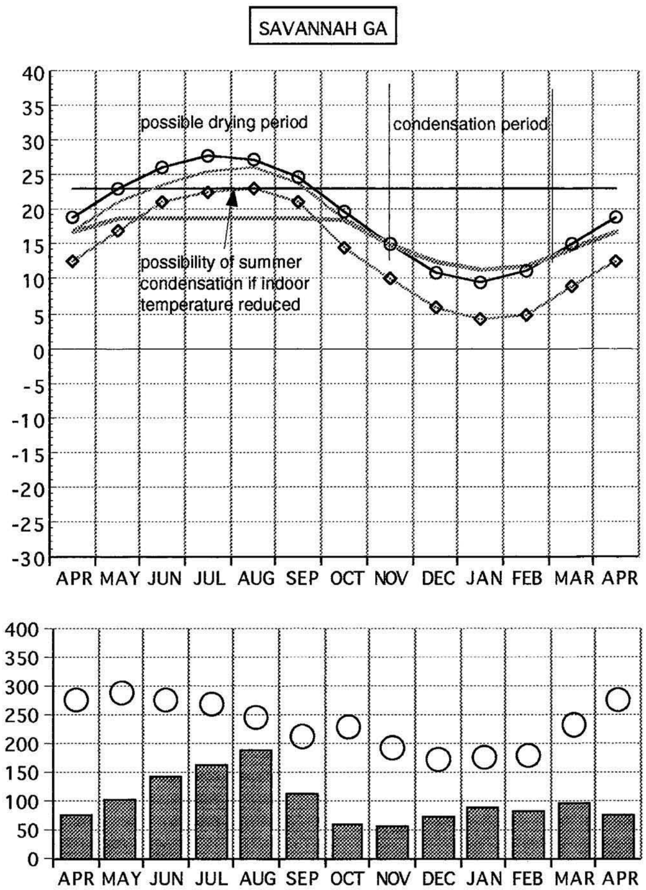


Fig. 7—Climate chart for Savannah.

Walls

There is little likelihood that condensation problems will be experienced in climates such as that of Las Vegas. Conceivably, higher rates of indoor moisture production or a significant reduction in ventilation rates in winter might raise the indoor dew point above that experienced in the outer portions of the envelope, but the drying potential would be high due to the low outdoor dew point temperature and high solar radiation conditions. The very low rainfall throughout the year might well preclude any concerns for rain penetration or rain wetting of cladding, but extensive irrigation, especially by sprinklers, could cause significant wetting of the cladding and of any concrete construction such as a slab on grade.

A Southern West Coast Example: Los Angeles, California

The climate of Los Angeles, as represented in Fig. 10, is influenced by its proximity to the Pacific Ocean, resulting in a much more moderate and more uniform conditions throughout the year. Although the indoor dew point temperature is predicted to go above the 19°C limit during the summer months, this is based on minimum ventilation and normal moisture production indoors. With increased ventilation or air leakage, or lower moisture production, indoor conditions might be acceptable without air conditioning, with proper solar shading and thermal insulation of roof areas.

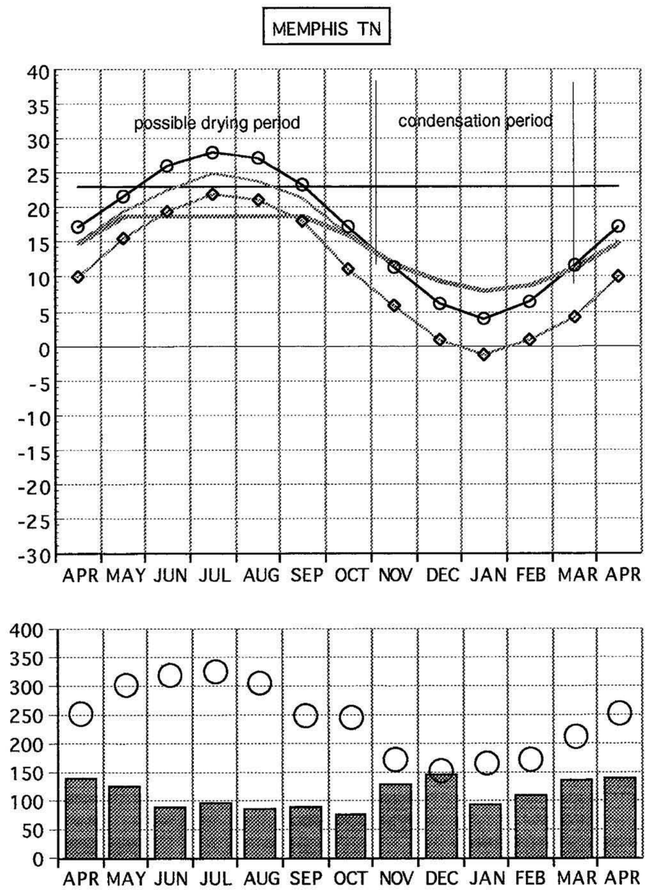


Fig. 8—Climate chart for Memphis.

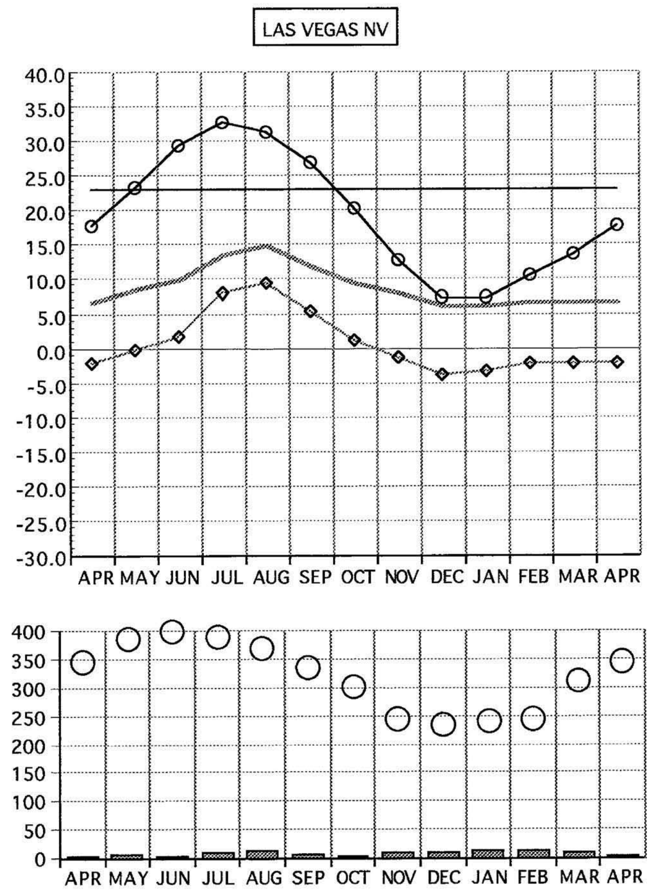


Fig. 9—Climate chart for Las Vegas.

Walls and Roofs

It is unlikely that any condensation problems will be experienced from vapor or air infiltration or exfiltration during the winter months, and rainfall during this period will not pose any long-term problems because of the substantial drying potential offered by the climate.

An Even More Moderate Climate: Honolulu, Hawaii

The climate chart for Honolulu in Fig. 11 indicates that the predicted indoor dew point temperature is above 19°C throughout the year and the monthly average outdoor dew point remains around 19°C during the year. Conventional air-conditioning systems could provide comfort conditions, but high indoor humidity might be experienced during the summer with the tendency toward lowering indoor air temperatures.

Walls and Roofs

With indoor dew point temperatures lowered to 19°C, vapor pressures outdoors would be higher than those indoors for the months of July through to November and inward vapor diffusion is possible. However, there is little likelihood that condensation will occur because the indoor and outdoor air temperature, and hence the temperature of all components of the building envelope, will be above the ambient dew point temperature.

Institutional Buildings

Educational Facilities

The indoor conditions in classrooms will be designed for human comfort so that the temperature remains relatively constant around 23°C (73°F), slightly lower in winter and higher in summer, while the relative humidity could range between 30 % and 60 %. Operable windows may often be installed to afford increased ventilation during periods of warmer weather but mechanical cooling systems may be required in more humid climates.

The indoor conditions in classrooms will involve relatively constant temperatures but the relative humidity will be greatly affected with the opening of windows when the indoor humidity will tend to equal that outdoors. This will likely occur during warm days in spring and fall, but most classrooms will not be in constant use in the heat of the summer. Estimates of the conditions as previously mentioned would likely be appropriate for design. In humid and semi-humid climates ventilation or dehumidification may be required during unoccupied periods to avoid high indoor humidity and the promotion of mold and mildew formation.

Typical wall constructions would be concrete block or brick masonry insulated on the interior or in masonry cavity walls. The use of steel-stud and brick veneer walls has also become popular for such buildings. Masonry or precast concrete cladding is preferred because of its durability and low maintenance costs and because of the possible physical

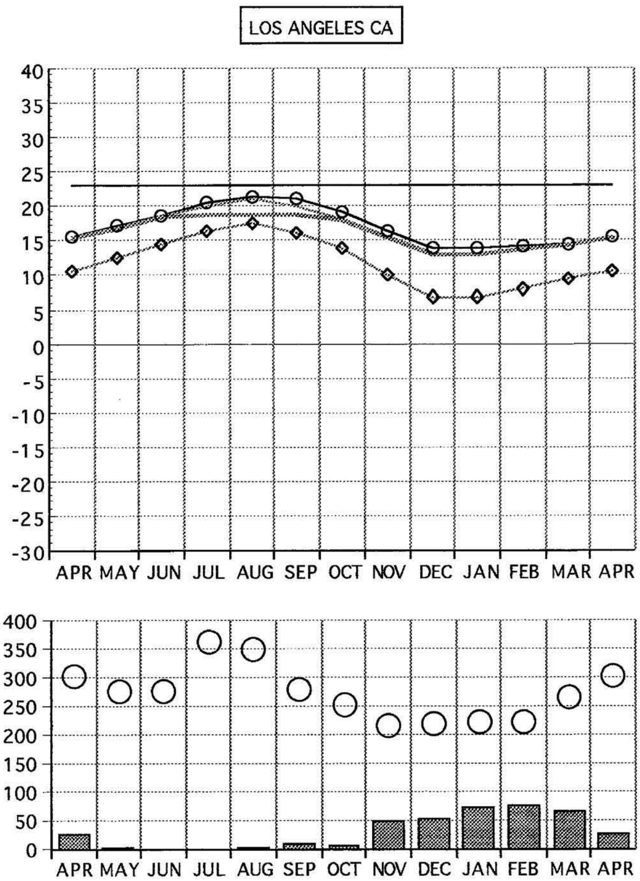


Fig. 10—Climate chart for Los Angeles.

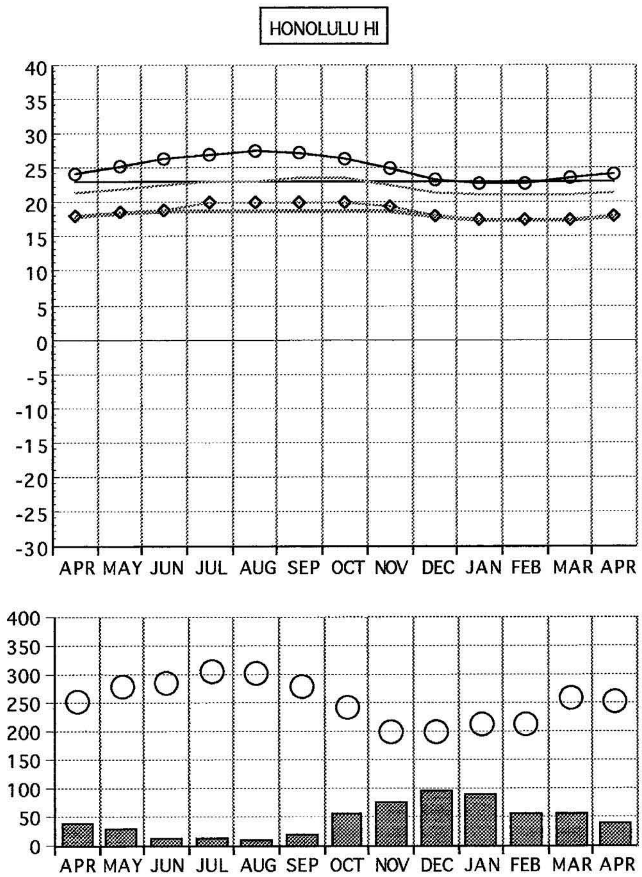


Fig. 11—Climate chart for Honolulu.

damage from sports and recreational activities around the building. Except for high-impact resistant systems, EIFS systems, although desirable from a moisture performance viewpoint, may be excluded because of possible exterior physical damage.

Roofs may be of reinforced concrete or steel decking and special wide span systems may be required over gymnasia, assembly rooms, or swimming pools. Special interior cladding may be required for sound absorption, moisture absorption, or resistance to physical damage from sporting activities in such specialty areas.

Libraries and Museums

Libraries, museums, and art galleries are primarily intended for the storage of materials that are prone to dimensional change with changing relative humidity. Temperature and relative humidity specifications for museum, library, and archival collections are listed in Table 4 of the 2003 *ASHRAE Applications Handbook* [9], indicating allowable departures from recommended values of relative humidity and temperature.

In cold climates, the possibility of condensation on windows and within the building envelope may dictate lower relative humidity levels, whereas in more humid climates higher levels may be more economical. In either case, windows may introduce significant problems because of the effect of solar radiation on the temperature of stored objects and materials. The moisture content and major dimensional changes of most of the materials involved are determined by the relative humidity, which is dependent on temperature. Solar heating of the surface of a material will decrease the relative humidity at the surface, even though the temperature and relative humidity of the space air are maintained constant. Radiation from artificial lighting can create similar situations [1].

The selection of a constant indoor dew point temperature corresponding to a relative humidity of 50 % and indoor temperature of 23 °C, for example, would provide a basis for assessing the moisture performance of the envelope for a specific locale using the climate chart approach outlined previously.

Recreational Sports and Entertainment Buildings

Ice Rink and Refrigerated Buildings

Considerable information on the design and operation of ice rinks can be found in Chapter 34 of the 2002 *ASHRAE Refrigeration Handbook* [20]. It is important to recognize that in buildings housing ice rinks, the temperature of the ice surface will influence the indoor vapor pressure or dew point and this value can be used as a basis for prediction of indoor humidity levels. The ASHRAE handbook indicates that the ice temperature will be at about −6 °C for hockey, −4 °C for figure skating, and −2 °C for recreational skating. Heating of the rink to 10 °C to 15 °C may be desirable for spectators and a maximum dew point of 7 °C may serve to lower the incidence of fogging. Choosing a constant temperature of, say, 15 °C and a dew point of 0 °C could be used for initial assessment of envelope moisture performance.

Refrigerated buildings in colder climates present a special case for condensation in the exterior envelope since the vapor pressure and air moisture content differences or the building stack effect may act in opposite directions during the year. In addition, the ice surface or the dehumidifiers in ice rinks and the cooling coils in cold storage rooms may effectively control the indoor dew point temperature [21]. Plotting of the average monthly conditions on a climate chart for the locality can provide a useful guide to the problems that might be incurred and a basis for the development of solutions.

One aspect in the design of ice rinks and cold storage buildings is the effect of below freezing indoor temperatures on the heaving of floors as discussed in CBD 61 [22].

Natatoriums (Swimming Pools)

Typical swimming pool and natatorium design conditions are listed in Table 1 of the 2003 *ASHRAE Applications Handbook* [9] and range between 24 °C to 29 °C and 50 % to 60 % relative humidity. It is suggested that air temperatures in public and institutional pools should be maintained 1 K to 2 K above the water temperature but not above the comfort threshold of 30 °C to reduce the evaporation rate and avoid chill effects on swimmers. A constant dew point and indoor air temperature throughout the year could be considered for initial assessment of envelope design. Some general comments applying to swimming pools in cold climates are presented in CBD 83 [23].

Exterior windows in swimming pool buildings are prone to excessive surface condensation in cold climates. One extreme case in western Canada resulted in interior condensation gaining entry to the lower rabbet space of sealed, double-glazed units over several winters, and the accumulated water visibly rising into the “sealed” space to a height of several inches. This phenomenon was attributed to the excessive indoor condensation being “pumped” into the lower clearance space by periodic pressure changes of the air in the sealed units because of temperature and barometric pressure fluctuations.

A progressive architect in Edmonton, Alberta arranged for the dry, heated winter air for ventilation to be delivered through a special slotted window sill so that the windows were not only warmed but blanketed with low humidity air to avoid condensation. In the colder weather, it was necessary to operate the ventilation system even during unoccupied periods.

Other High Humidity Occupancies

A unique system to avoid condensation on the windows of a printing plant built in Quebec in the 1950s was designed by another Canadian architect. An inner set of single-glazed, metal framed windows were separated from an identical outer set by a cantilevered service catwalk that incorporated the perimeter heating elements. This arrangement served to maintain the surface temperature of the inner windows well above the indoor dew point. A similar feature was incorporated in the double clerestory windows in his house in Montreal. This “buffer zone” technique has been adapted in some larger buildings in recent years. It had been suggested as one approach to wall and window design in a seminal paper by Hutcheon in 1953 [24]. The major suggestions in this paper served as the basis for CBD 48 and 50 [25,26].

The buffer zone principle was also followed in the design of a laboratory building in Ottawa, Ontario, where the laboratory spaces were to be held at room conditions and 50 % relative humidity. By placing the offices as a buffer between the interior laboratories and exterior envelope, window condensation was avoided. The windows were also positioned in the inner concrete block exterior walls with steel studs, insulated with mineral fiber insulation installed on the outside of the block over a trowelled on vapor barrier, and covered with cement stucco on self-furring lath as an exterior finish.

High-Rise Buildings

General Design and Construction Features

Modern high-rise buildings have relatively small roof areas in comparison to the exterior walls and windows, and roof decks are usually of reinforced concrete as are the individual floors between stories for fire protection. More particularly, most high-rise buildings, whether offices or residential, tend to have much greater window than wall areas in spite of the “curtain wall” classification. Insulation requirements for the smaller exterior wall areas should be discounted in favor of thermally improved windows.

The exterior walls of high-rise building are exposed to the more severe effects of higher winds and driving rain, particularly at the top and corners, leading to a greater need for designs to consider wind pressures in regard to rain penetration and air leakage. The roof/wall junction will also be the location for maximum outward acting pressure due to stack effect. The pressure difference acting across the exterior walls and windows will also tend to be greater in the case of open-plan office buildings than for high-rise residential buildings because of the lack of internal horizontal and vertical separations.

Offices and Commercial Buildings

Fixed, sealed multiple-glazed windows are almost always employed in high-rise office buildings. The fixed windows permit closer estimates of air exchange and 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 were commonly used in the past in sealed, multiple-glazed windows. 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 (CBD 129) [27], although thermal stress from solar heat gain may be more frequent cause of sealed unit breakage.

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 (CBD 40 and 55) [28,29].

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 melt-water fall free of the building facade. When employed without change as a "sloped roof," each horizontal mullion acts as a trough to collect rain or melt-water, holding it ready to be sucked into the glazing rabbet and promoting early glazing failure. Details to avoid these problems are provided in Chapter 15.

In some cold climates, excessive snow accumulation on sloped glazing at the top of buildings also leads to the problem of ice damming and "avalanching." Snow build-up insulates the underlying glass, inducing melting and promoting icicle formation at the edge of the atrium. This water build-up 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 (CBD 228) [30].

Residential Buildings

The windows employed in residential high-rise buildings are often of lower cost and quality than those used in offices or prime commercial spaces. They are usually metal-framed units incorporating operable sash, usually of the horizontal sliding, awning, or jalousie types (CBD 58) [31].

Access to balconies is usually through sliding patio doors, with the balcony formed simply by an extension of the reinforced concrete floor slab. This presents a significant thermal bridge and cold floor surfaces adjacent to the balcony. Rain and melt-water entry is possible as well as surface condensation in cold climates.

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 usually 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 beneath drapes 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 [31,32]. 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.

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 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 humidity is high and give off moisture to the air when relative humidity tends to drop. During the summer, relative humidity 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.

The Indoor Environment

The indoor environment in high-rise office and residential buildings are likely to be intended to conform to the ASHRAE Standards for human comfort and air quality as for most buildings designed for human occupancy. In office buildings, there may be areas where computers or printing processes require a higher relative humidity but the general work area conditions could be estimated as dependent on the outdoor climate since the moisture input and outdoor ventilation rates would be reasonably constant (adding 0.003 kg/kg or 0.003 lb/lb to the outdoor air moisture content). The control of conditions throughout a floor area would usually be achieved by the air-conditioning system as would any variability due to vertical air movement from floor to floor.

In high-rise apartments no such central or sophisticated air-conditioning control systems are provided; individual apartments may be served by central chilled and hot water or electrical heaters with individual or room controls but their air distribution system will be self-contained. Some apartment occupants may utilize individual humidifiers or dehumidifiers or may have different moisture sources involved such as plants, fish tanks, and other different lifestyles. In particular, apartments all have their own operable windows that are under their individual control so that ventilation rates can be variable.

In terms of estimating indoor conditions, a similar approach to that taken for low-rise buildings involving human occupants can be used and would result in similar recommendations for building envelope design in various locations. The potential for greater outward acting pressure differences to be experienced at the top of medium- and high-rise buildings in colder climates is of concern.

Walls and Roofs

The possibility of increased exfiltration into the upper walls of tall buildings has stressed the need for improved airtightness and emphasis on "improved" air barriers in the design of walls. The roofs of such tall buildings are inherently "airtight" because of the reinforced concrete deck, the nonvented insulation layer, and the impermeable upper membrane. The weak point in the assembly has long been recognized as the roof/wall junction and construction details to achieve air and vapor tightness have been suggested in Chapter 43 of the 2003 *ASHRAE Applications Handbook* [9] and *Architectural Details for Insulated Buildings*, by Brand [33].

The potential for air exfiltration and moisture accumulation in these upper walls of higher buildings is regarded by some as the cause for the observed spalling of masonry cladding at such locations. Others attribute the observed deterioration to the rain wetting of masonry at these locations. Both schools of thought accept that the deterioration is due to the freezing of wetted material (CBD 126) [34] and Canadian experience has suggested that the problem tends to occur in cities where the outdoor winter design temperature is lower than −7 °C (19 °F) [1]. In Toronto, Ontario one can observe older masonry medium- and high-rise buildings where metal cladding has been installed usually over the deteriorated cladding and often over applied exterior insulation. Some have suggested it might be an acceptable architectural feature for new buildings to avoid the wetting/spalling problem.

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 insulated masonry or steel-stud framing. Some general principles were advanced in CBD 93 and 94 [35,36].

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 the 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 for air sealing at 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 air-tight back-up wall [37].

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 [35].

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 [1]. It is this principle that led to the name "open rain screen" as a design concept [28].

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 will 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 important, 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 facade and to keep the bulk of it away from the open joint (CBD 40) [28]. 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 (CBD 97) [38].

In the case of modern designs incorporating an effective seal or air barrier on 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 that joints in precast concrete cladding cannot be left open provided that appropriate flashings or other means are provided for drainage. 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 (CBD 40) [28].

Exterior Insulation Finish Systems (EIFS)

EIFS incorporate an exterior finish of polymer-modified 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.

EIF systems 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 EIFS offer distinctive aesthetic, insulation, and weight advantages, the fire behavior characteristics of the individual system needs to be considered to evaluate its compliance with code and fire protection restrictions in more densely built office and commercial buildings.

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 moderately cold climates. There is usually no provision for drainage from the system, and as a result corrosion of the sill channel, exterior flange of studs, rusting of fasteners, mold and mildew growth, and saturation of the gypsum sheathing can all occur. As for low-rise buildings, 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 melt-water 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 EIFS. In the panel systems, the water-resistant base 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 is required in some codes, specifically in Canada.

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 as with other cladding in order to assess the magnitude of such movements [39]. 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.

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 open rain screen approach to joints in buildings.

The Effects of Wind

The air pressure differences created by wind can have a significant influence on the performance of the building and the building envelope. Flow patterns created by pressure differences around the building and over the building facades tend to concentrate rain wetting at roof edges and exterior corners and lead to the build-up of surface run-off at vertical projections such as mullions and recesses at joints. Pressure differences over a facade may also influence the lateral flow in spaces within the envelope but most significant effects will result from the pressure differences that are induced across the building envelope components.

The structural loads resulting from wind have long been a concern to structural designers and much research has been undertaken on model structures to determine coefficients for use in full scale design calculations. Most testing has been concerned with the effect of wind forces on the building as a whole, in order to provide for adequate anchoring to the foundation, suitable flexural resistance, and appropriate dynamic behavior.

When the building is considered as a whole, wind pressure variations around the building are of primary interest, and tests on solid models in wind tunnels are a suitable basis for establishing design coefficients. When the building envelope is of concern, however, the air pressures experienced within the building are a significant factor and these are difficult to determine experimentally, even in nonsolid models, particularly for any multicompartment building. In such buildings, the air pressure in any particular space will depend on the leakage characteristics of all of its enclosing boundaries and the exterior pressures acting on each of them.

In designing for envelope structural sufficiency, the structural designer is primarily concerned with the maximum pressure differences that are likely to be experienced with high winds and wind gusts. Gusts occur for only short periods, however, and other members of the design team will be more concerned with the sustained pressures acting across the building envelope and the rates of air leakage that could result over longer periods.

As examples, the HVAC designer will need to estimate the possible indoor-outdoor air exchange rates over time in order to predict energy requirements and the possible effects on indoor air quality, while the building envelope designer will need to estimate the rates of moisture transfer in and out of the building envelope. In both cases, the coincident occurrences of pressure differences, temperature and humidity will be significant.

External Pressures Created by Wind

The average wind speed for many locations in North America is about 16 k/h or 4.4 m/s measured at a height of 10 m. With a density of dry air at 20°C, this corresponds to a dynamic or stagnation pressure of:

$$p = \frac{1}{2} \times 1.2\ \text{kg/m}^3 \times (4.4\ \text{m/s})^2 = 11.6\ \text{kg/m} \cdot \text{s}^2 = 11.6\ \text{Pa}$$

The general pattern of external pressure distribution created by wind usually involves positive pressures on windward walls and negative pressures on leeward walls and low-sloped roofs. The positive pressures involved can never exceed the stagnation pressure and coefficients will vary between 0 and 1, but negative pressures may be several times the stagnation pressure at certain locations such as the leading edge of a flat roof or at exterior corners of walls.

The velocity of the wind with height above ground is a reasonably predictable value that depends on the "roughness" of the upstream terrain. This may be of significance for high-rise buildings that stand alone, but the flow patterns induced by adjacent, upstream buildings will likely have a predominant, usually unpredictable effect. For closely spaced low-rise buildings in a subdivision, it is likely that only wind pressures on roofs are reasonably predictable.

While there are many variables affecting the wind pressures on actual buildings at a particular moment in time, some appreciation of the magnitude and possible effects of wind pressures can be gained from patterns obtained for particular situations such as when the wind is blowing perpendicular to one facade (CBD 28 and 34) [40,41]. The maximum positive pressure occurs on the vertical centerline at about 75–80 % of the height with pressures decreasing toward the corners and top. Negative pressures will be experienced on the leeward face as well as over the sides of the building that are parallel to the wind and near the edges of the windward side of the building. Since these pressures can be significant, extensive wind tunnel tests may be appropriate for larger buildings.

A composite of boundary wind tunnel measurements based on a rectangular model extending at different heights above its surroundings is offered in Ref. [1], from Ref. [42].

Pressure coefficients shown are the area-weighted averages over width of the building and are referenced to the dynamic pressure of the wind at the building height. The values shown are for the wind blowing perpendicular to the face of the building.

The maximum positive pressure coefficient over the windward face is about 0.6 and occurred at 75–80 % of the height of the taller models. For a model having the same height as its surroundings, the maximum coefficient was about 0.3 at the top and 0.1 at midheight and a little over 0.2 at grade level. The leeward suction pressure coefficients were relatively uniform with height, ranging from −0.4 for the taller models and −0.2 for the low-rise models. Higher suction coefficients up to −0.7 were measured on the sides of the taller models with those for the lowest being similar to those on the leeward face at −0.2.

The coefficients for wind blowing at 45° to the facades are not shown but were between 0 and +0.4 on sides upstream sides, except for low-rise models, which showed a negative value of −0.2. Downstream sides showed values ranging from −0.2 to −0.5.

Pressure Differences Created by Wind across Exterior Walls

A building with few internal separations with a wind blowing on one facade will exhibit a pressure coefficient for the windward wall of about +0.2 and for the leeward wall about −0.2. The indoor pressures in the building will lie somewhere in between these values, depending on the size and distribution of openings through the envelope. If the envelope leakage areas of the windward and Leeward sides of the building are assumed to be about equal, the indoor pressure would be approximately halfway between the positive and negative values. If the leakage openings on the windward face happened to be larger than on the leeward side, such as if the delivery doors were all on the windward side, the indoor pressure would be closer to the windward pressure while the opposite would be the case if larger openings were on the leeward wall.

A high-rise office tower with open plan floor areas such as represented in Fig. 12 can be considered in this way since there are no internal separations between the exterior walls, only those between the office space and the central stair and elevator shafts

A high-rise apartment building plan will be markedly different however, since the floor areas will be divided into multiple compartments separating the different suites and central hallways. Many high-rise apartments are of a long, rectangular plan with rows of apartments on each side, separated by a common corridor that provides access to stairs and elevators, as represented in Fig. 12. In principle, the walls between apartments and hallways are intended to be as tight as possible for both fire safety and sound separation with the only deliberate openings being the apartment entry doors.

For all high-rise buildings, the wind velocity will increase with height as will the pressure coefficients and can be estimated. Applying the commonly accepted 1/7 power law the wind speed at the top of a twenty story building, 60 m high, based on a wind speed of 16 k/h would be:

$$p = \frac{1}{2} \times 1.2\ \text{kg/m}^3 \times (5.5\ \text{m/s})^2 = 11.6\ \text{kg/m} \cdot \text{s}^2 = 18.5\ \text{Pa}$$

From Ref. [42], for a building six times higher than its surroundings, the pressure coefficient on the windward side would be 0.7 and on the leeward side would be about −0.4.

The maximum pressure on the windward wall could be estimated as $0.7 \times 18.5 = +13$ Pa and the average suction pressure on the opposite leeward wall would be $-0.4 \times 18.5 = -7.4$ Pa.

In the office tower without internal separations and the leakage characteristics of the exterior walls were equal, the internal pressure would tend to be the average between the two external pressures or 2.8 Pa above atmospheric pressure.

Unlike the open plan buildings, an apartment building will have a central hallway separating apartments on each floor, and the hallway walls and entry doors should offer considerable resistance to the air flow through the building from windward to leeward walls.

Studies by Canada Mortgage and Housing Corporation on apartment buildings across Canada have provided information on the air leakage characteristics of representative exterior walls as well as limited information on the characteristics of interior walls and doors [43]. Based on these data, the average leakage area of exterior walls and window assemblies involved can be estimated as 10.8 cm^2/m^2. For an exterior wall/window area of 25 m^2, this would amount to a total leakage area of about 270 cm^2 per apartment.

One of the CMHC sponsored studies also reported measurements of a combined leakage through party walls and hallway partition as 54 L/s at 50 Pa pressure difference. Assuming the three partitions had equal areas of 25 m^2, the leakage area for a hallway partition would be about 33 cm^2. The leakage area around the apartment entry door was equivalent to 219 cm^2 and thus the leakage area of the halway partition and entry door combined could be estimated as $(33 + 219)$ or 252 cm^2 or about the same as the leakage area of the exterior wall.

For the apartment building in Fig. 12, the pressure difference under series flow will be about the same for each separation: equal to one-quarter of the total pressure drop across the building due to wind. If the clearance around the entry doors were reduced to provide a leakage area of 21 cm^2, as listed in the *ASHRAE Handbook of Fundamentals* [44] as that for a single non-weather-stripped exterior door, this could reduce the leakage area to the hallway to $(33 + 21) = 54$ cm^2 or about one-fifth of that of the exterior walls.

Since the pressure difference across openings in series can be considered as inversely proportional to the square of their respected areas, the hallway partitions will take most of the pressure difference acting across the building, and the pressure difference across the exterior walls could be only about 2 % of that acting across the building due to wind.

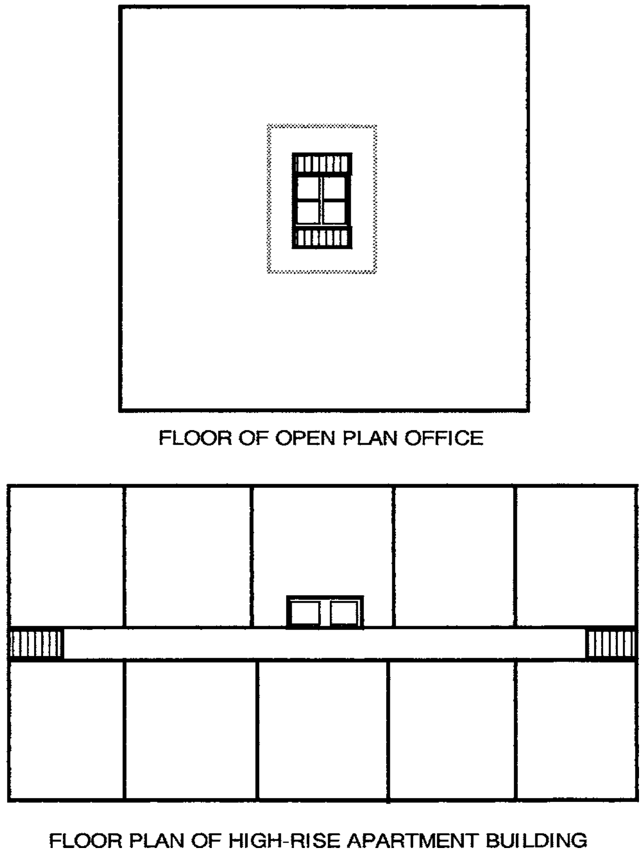


Fig. 12—Floor plans of office and apartment buildings.

These considerations illustrate the importance of considering the internal separations when estimating the average pressure differences that are likely to occur across the exterior walls. For buildings with open plan floor areas, the average rate of air leakage due to wind will depend primarily on the leakage characteristics of the exterior walls and windows. In buildings such as medium- or high-rise apartments with operable windows, the average rates of air leakage due to wind will depend primarily on the leakage characteristics of the interior separations. If these separations are tighter than the exterior walls, wind pressures may have little effect on the rates of air leakage or ventilation of the spaces involved.

The wind pressures produced during high winds and wind gusts will still be borne by the exterior envelope since the internal pressure will take time to react and this must be considered in any structural calculations. In terms of rain penetration, however, tighter interior partitions will act to reduce the sustained pressure difference acting across the envelope and consequently reduce the possibility of continued rain penetration at joints or of accumulation of water rising above the flashing or up stands in the wall or window.

In estimating the amount of condensation likely to accumulate from air leakage, a pressure difference based on the average wind velocity, and the most severe pressure coefficient to be expected might be considered for design pur-

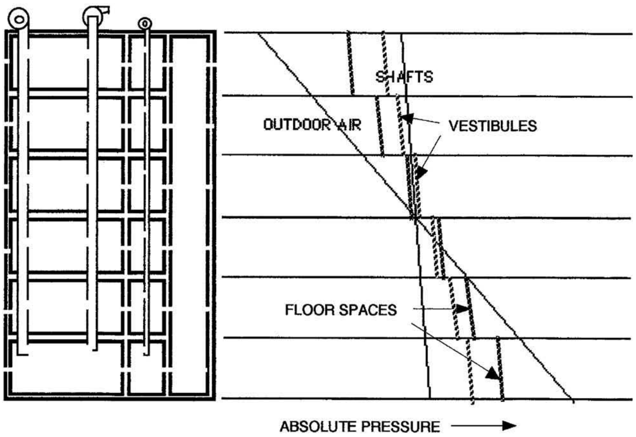


Fig. 13—Air handling systems in high-rise office buildings.

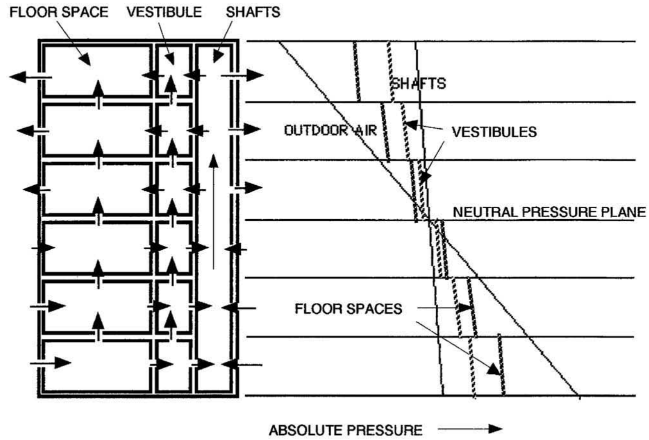


Fig. 14—Stack effect pressures in high-rise office buildings.

poses, if no measures are taken to improve the air tightness of the interior partitions.

Stack Effect in Medium- and High-Rise Office Buildings

In high-rise buildings, the pressures due to stack effect are much greater, particularly those in the stair and elevator shafts where there is no separation between stories and little resistance is offered to vertical flow. For a twenty story building with an outdoor temperature of –20°C and an indoor temperature of 23°C, the theoretical stack effect pressure for a height of 50 m can be estimated as 100 Pa, or 50 Pa operating outward at the top and 50 Pa acting inward at the bottom of the building, if the leakage openings are uniformly distributed with height.

Essentially the total building stack effect is experienced in these vertical shafts, with any reduction in in stack effect pressures in the occupied spaces due to the resistance to flow offered by the stair and elevator doors and vestibules that separate them from the shafts. "Fire stopping" is normally required around penetrations through the floor and gaps between components such as between floor edges and exterior walls, but office buildings will usually have central air supply and exhaust systems serving the occupied spaces as illustrated schematically in Fig. 13.

Air Flow Patterns Resulting From the Stack Effect in Office Buildings

These vertical ducts act as shafts interconnecting the floor spaces as well as openings through the floor systems, with the pressures and air flow patterns as illustrated in Fig. 14.

When outdoor temperatures are lower than those indoors, the tendency will be for air to flow upward from floor space to floor space through ducts and openings through the floor. Air will also flow upward in the stair and elevator shafts, with air tending to leak into the shafts from outdoors and the floor spaces below the neutral pressure level and outward through the shafts to outdoors and into the floor spaces above the neutral pressure level.

If there are no leakage openings in the floors, simple series flow can be considered and the pressure difference across the exterior walls is determined only by the relative leakage areas through the interior and exterior walls.

If a multistory building could be built with airtight separations between floors and the stair and elevator shafts isolated from the floor spaces, the vertical pressure diagram could be as shown in Fig. 15. Although complete isolation of the floor spaces from the stair and elevator shafts would be impractical if not impossible, any improvement in the airtightness of separations involved would be useful in controlling the stack effect in the occupied spaces. Such improvements, coupled with the use of floor-by-floor air handling systems to avoid openings in the floor systems, could result in reducing stack effect in the occupied spaces and enable the use of operable windows and simple through-the-wall air conditioning or ventilation systems.

As noted in Chapter 14,

> "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."

Air Flow in Multistory Apartment Buildings

The floors in multistory apartment buildings are similarly fire-stopped, but the apartments are not usually served by central air handling systems but normally have individual bath and exhaust systems connected to outdoors. Since the floor systems in modern apartments are not connected through vertical air supply or exhaust systems, they can be

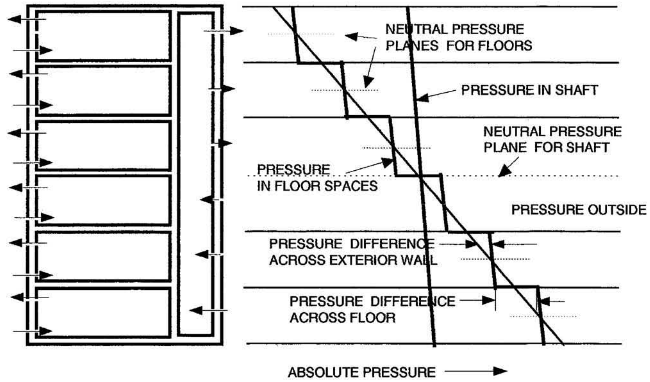


Fig. 15—Multistory building with floor spaces isolated from vertical shafts.

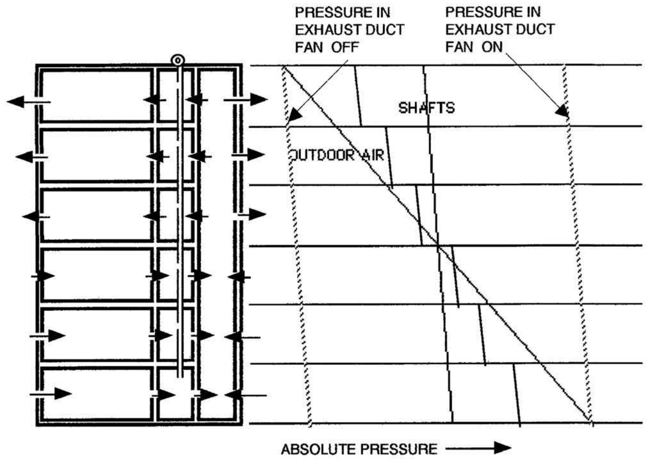


Fig. 16—Apartment building with hallway pressurization fan.

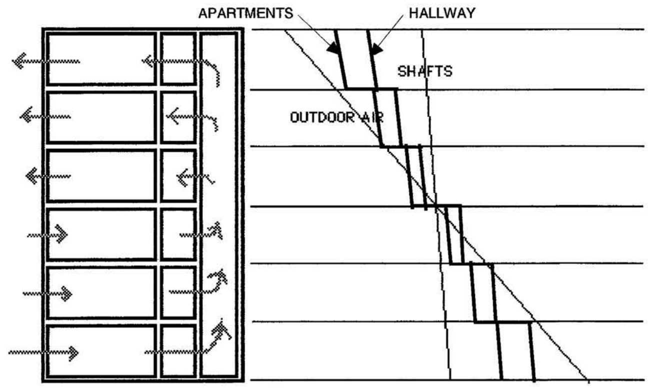


Fig. 17—Apartment building with no hallway pressurization fan.

made more airtight than the floors in office buildings. Individual apartments are also more isolated from the stair and elevator shafts by a central hallway with walls that should be tighter because of the need for fire separation, smoke control, and sound isolation.

Although the apartments are not connected through vertical air supply or exhaust ducts, the hallways are usually served by a central air supply system which was originally intended to provide a nominal amount of fresh air for the hallway. This nominal air supply, with no exhaust provisions, was thought to be capable of pressurizing the hallway to help prevent the transfer of odors between apartments. Unfortunately, it has gradually become common practice to use such a hallway "pressurization system" to deliver outdoor air to the apartments through a clearance space under the entry doors, a system which does not conform to fire, smoke, and noise requirements or the basic principles of air distribution. These approaches may have some chance of success in low-rise buildings in mild weather but not in cold climates or high-rise apartments, where significant stack effect pressures prevail.

The vertical ducts for such hallway pressurization systems have outlets on every floor and are equivalent to leakage openings through the hallway floors. As such they can act as vertical shafts in parallel to the stair and elevator shafts. The slope of the pressure line in these vertical ducts will be the same as those in the stair and elevator shafts, but the position with respect to the outdoor pressure line will depend on where the duct is open to outdoors.

The situation is represented schematically in Fig. 16.

When a rooftop supply fan is shut down, the pressure at the fan will tend to be equal to that outdoors at the top of the building, with the duct pressure line moving to the left and the pressure in the duct falling below that of other locations in the building.

The pressure in the apartments will initially be in between the stair and elevator shaft pressures and, if the hallway pressure line reaches the extreme m position indicated, the fan duct will tend to draw air from both the apartments and the shafts, particularly at the lower floors, and exhaust it at the roof. Under actual flow conditions, the position of the pressure lines will be determined by the pressure drops occasioned by the relative resistances offered by the flow paths involved.

It is not uncommon for the hallway pressurization fans to be shut off at night to conserve energy, and at least one observer has observed an inoperative rooftop exhaust fan running in reverse during very cold weather.

When the rooftop fan is turned on, it will increase the pressure in the supply duct and the pressure line will move to the right. If the fan was to pressurize the hallways to prevent odor transfer from the apartments, it would have to have sufficient capacity to overcome the entire building stack effect in order to pressurize the hallway at grade level, as indicated in Fig. 16. For the twenty story building when the outdoor temperature is −20°C, in order to pressurize the lower hallway to equal that outdoors, the hallway supply fan would create a hallway pressure of 100 Pa in the top story hallway. This could possibly prevent odor transfer between apartments, but the air flow rates through the undercut entry doors would be excessive for all of the upper apartments and would vary down the height of the building. The cost of heating the excess ventilation air, the possibility of noise generation, and the difficulty of closing doors of the upper apartments would have to be addressed.

In actuality, the installed rooftop fans are not capable of delivering such air quantities and the required hallway pressurization for odor control and delivery of required fresh air to the apartments is not achieved, except by accident, in a few apartments, and only under mild weather conditions.

Fig. 17 represents the situation for an existing building with the hallway pressurization fans shut down and the hallway outlets sealed off, or a building with no hallway pressurization system installed. A series flow pattern would be expected with outdoor air leaking inward through the openings in the exterior walls and windows of apartments below the neutral plane, then through the entry doors and hallway partitions, into the elevator and stairwell doors and upward through the stair and elevator shafts, then inward through the stair and elevator doors to the hallways, through the entry doors and hallway partitions of the apartments above the neutral plane and outward through their exterior walls and windows.

Such a flow pattern is amenable to a simple calculation based on the estimates of the leakage opening areas in series, as in dealing with pressure differences due to wind. Considering the same apartment building with a plan area as in Fig.

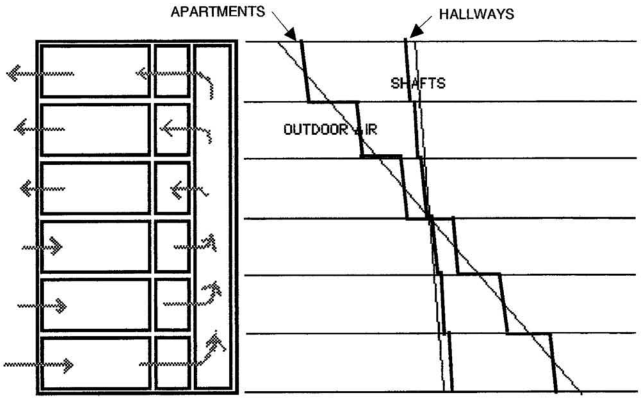


Fig. 18—Apartment building with tighter apartment entry doors.

12 with the same exterior wall leakage areas and undercut apartment entry doors, and the measured leakage areas of stairwell and elevator doors as published in the *ASHRAE Handbook of Fundamentals* [44], the pressure difference across the exterior walls and hallway separations would constitute about 21 % and 25 % of the total, with the pressure drop across the stair and elevator doors at about 54 % of the total.

If the clearance around the apartment entry door was reduced to that of a non weather-stripped exterior door (21 cm^2), the pressure difference across the exterior wall would be calculated as 3 %, the pressure drop across the hallway partition and entry door as 88 %, and that across the stair and elevator doors as 9 %, as represented in Fig. 18. Under these circumstances, there is very little pressure difference across the exterior walls, and the greatest pressure difference is across the apartment entry doors

Tightening the exterior walls will have little effect on the rate of infiltration or exfiltration, but in very cold weather or in very tall buildings, the entry doors on the upper and lower floors would be difficult to open or close.

Weather-stripping the stair shaft doors could reduce their leakage to about the same as that of the entry doors. But elevator doors require considerable clearance to operate and elevator vestibules could be used with similarly tight entry doors. Neglecting the resistance of the elevator doors themselves the resultant pressure differences would amount to 0.1 % of the total across the exterior walls, 2 % across the partition and apartment entry door, and 98 % across the stair and vestibule doors.

In many jurisdictions, the elevator penthouse is required to have intentional openings to outdoors to satisfy fire regulations or for ventilation and cooling of the installed equipment. Under such conditions and in cold weather, the elevator shaft will act as an exhaust system lowering the pressure in the hallways and increasing the potential for outdoor air infiltration into the apartments. Elevator vestibules can modify the effect, but a more satisfactory solution would be to close off all openings in the penthouse envelope and utilize a recirculating mechanical cooling system for the equipment with only minimum ventilation for servicing personnel.

Lateral movement of air and airborne contaminants between apartments may be controlled by hallway pressurization and tighter exit doors, but the stairwell and hallway air conditions will depend on the vertical air movement due to the stack effect. In general, this would suggest that in colder weather, the air conditions maintained in the apartments below the neutral pressure level will migrate upwards through the elevator and stair shafts to the hallways, and hence into the apartments above the neutral pressure level. From a moisture control point of view, it could be suggested that the upper apartments would thus tend to have air conditions, including humidity, which were the combined result of their fellow occupants activities rather than due to their own. Few measurements of indoor conditions in apartments have been reported, but one case involved measurements in several apartments on one floor above the neutral plane, which had quite different occupancies. Although the occupancies ranged between a small family to a single occupant who was seldom home, all apartments had almost identical indoor air moisture content measured over a week or two.

Summary

The first step in evaluating the moisture performance of a proposed building envelope involves an estimate of the outdoor conditions to which it will be subjected.

Summer and winter design temperatures provide an indication of the possible extremes to be expected, but solar radiation will have a marked effect on the maximum temperature reached by the exterior cladding as well as the range of temperature to which its outer surface will be exposed.

Inward of the exterior cladding, temperatures within the envelope are moderated because of the relative stability of the indoor environment and the damping effects of thermal insulation. Envelope components and materials that are outward of the thermal insulation will more closely follow the outdoor conditions, while materials inward of the insulation will tend to be at a temperature closer to the indoor conditions.

At the inner face of the building envelope, temperature and humidity conditions will depend primarily on the indoor air temperature and humidity. Indoor temperatures will usually be controlled within narrow limits and for most occupied spaces will be between 20°C and 26°C. Indoor humidity conditions will not usually require such close control and will vary throughout the year in relation to indoor moisture sources and the moisture content of the outdoor air brought in for ventilation.

The indoor humidity conditions can be predicted from the balance between moisture gains from activities within the space and the removal or addition of moisture by ventilation with outdoor air. The conditions in air-conditioned spaces will depend on the control system set points and the capability of the air-conditioning system to cope with changes in load. The humidity conditions in individual apartments in medium- and high-rise residential buildings will often depend on conditions in in adjacent hallways or in apartments at lower levels. The conditions in occupancies designed for special activities, or storage and processing of materials, may dictate a specific level or closer control of humidity.

A change of phase, that is, a change from vapor to water or ice or vice versa, offers both a complication and a simplification in predicting performance. Such changes are accompanied by an exchange of heat, the heat of vaporization or sublimation, that can effect the thermal balance, but these changes will occur at a fixed dew point temperature. Under such conditions, the steady state vapor pressure can be predicted and the tendency or direction of vapor diffusion can be estimated. The magnitude and direction of air flow through the envelope will be determined by the air pressure differences to be expected.

Air pressure differences may result from wind, the operation of the building air handling equipment, and the stack effect. Pressures on the building envelope due to wind will depend on the height and orientation of the building and on the upstream conditions, and will vary over the facade and with time. Sustained air pressure differences across the building envelope will also vary over the building facade but will also depend on the relative air leakage characteristics of the internal partitions that act as separations between the exterior walls. Pressure differences due to wind will be inward and outward across leeward walls, walls parallel to the wind direction, and flat roofs.

The pressure differences induced by the stack effect across the exterior walls will be dependent on the relative leakage characteristics of both the internal partitions and the floor separations. The air handling ducts that penetrate these partitions and interconnect compartments or stories offer leakage openings that must also be taken into consideration in estimating the stack effect pressure differences. Pressure differences across the building envelope will be inward below the neutral pressure plane and outward above it if the indoor temperature is above that indoors. The reverse situation will be experienced when the indoor temperature is below that outdoors.

Mechanical air handling systems that are operated to supply more outdoor air than the amount of air exhausted will tend to pressurize the indoor spaces they serve, while systems that exhaust more air than supplied will create a negative pressure in the space. The resultant total pressure difference across the building envelope will be the algebraic sum of those due to wind, stack effect, and mechanical systems at any given time, but average values can be estimated with due regard for the orientation of the envelope and its location with respect to the neutral pressure plane.

In designing exterior envelopes for wind loads, the influence of the interior partitions on the anticipated gust and dynamic pressure differences acting across the exterior envelope may be relatively small, but in terms of estimating sustained pressure differences that determine air leakage rates, the influence of the air leakage openings through partition walls and floor systems can be most significant. In compartmented buildings such as high-rise apartments, energy conservation and ventilation effectiveness might better be achieved by improving the airtightness of interior partitions and floor systems rather than exterior walls. The average pressure difference acting across the exterior walls on all floors and orientations would be substantially reduced, allowing operable windows to be used more effectively by the individual occupants.

In all high-rise buildings, floor-by-floor or individual compartment air handling systems would avoid duct penetrations through the floor systems and minimize the adverse influence of stack effect in cold weather, while at the same time improving sound isolation, indoor air quality, fire safety, and smoke control but add to risk of rain penetration at ventilation openings.

The air pressure differences resulting from the stack effect are the most readily predictable for a particular building and climate both in regard to magnitude and direction of flow. The direction of flow is not important in regard to energy conservation except from a system heat recovery aspect, so that airtightness and the magnitude of the pressure difference are the prime concerns.

From a moisture condensation standpoint, however, the direction of flow is most important. Infiltration is unlikely to result in condensation on heated buildings but may be of concern in cooled or refrigerated buildings. Exfiltration is unlikely to result in condensation in cooled or refrigerated buildings but can be a major contributor to condensation in heated building.

Airtightness of the building envelope may be a more important factor in regard to energy, ventilation and indoor air quality than it is in regard to moisture problems. Moisture in building envelopes can originate from other sources and moisture migration and condensation can often be more influenced by temperature changes and vapor diffusion.

Simple qualitative assessments can be based on a consideration of the monthly average indoor and outdoor conditions of temperature and dew point and on considering the anticipated extremes, bracketing the range of possibilities, and exercising judgment in what is the likely situation between these extremes. In all cases the daily and seasonal variation in outdoor climate must be considered in relation to the temperature and dew point conditions that prevail indoors. Finally, the selection and arrangement of materials and components in the building envelope itself will be the primary factors in determining performance in practice.

A graphic representation of the monthly average indoor and outdoor air temperature and dew point temperature offers a measure of the vapor pressure and moisture content of the air and a means to determine where condensation and moisture conditions are likely to occur within a building envelope during the year. With a consideration of the effect of solar radiation, rainfall and the characteristics of different buildings, several specific design principles can be suggested.

- If sufficient thermal insulation can be applied to the exterior of the stud space to raise the temperature of the sheathing above the indoor dew point temperature, accumulation of winter condensation in the stud space can be avoided and the condensation plane transferred to the inside face of the exterior cladding, where it may be more readily removed to the outdoors by drainage or evaporation.
- The exterior surface of the sheathing or of the interior masonry wythe offers a location where a more complete air barrier and vapor retarder can be applied and will reduce the rate of condensation on the exterior cladding.
- The location of the vapor retarder and air barrier on the exterior surface of the sheathing or of the inner wythe will inhibit the inward migration of water vapor from wetted cladding or humid outdoor air to the interior cladding.
- This relocation of the vapor retarder and air barrier from

the interior cladding will allow the migration of any moisture from the stud space to the indoors.

- The provision of a drainage space behind the exterior cladding and flashed drainage openings to outdoors will also serve as an inner seal of a two-stage system and allow pressure equalization to control the entry of wind-driven rain into the assembly.

When final design decisions are made, a quantitative assessment can be made utilizing the values from the graphic chart, the water vapor permeance characteristics of the significant components and assumptions regarding the air pressure differences and potential leakage characteristics of the assembly. Manual calculation procedures or computer calculations using a spreadsheet program have been employed in some building science courses at colleges and building envelope associations in Canada.

REFERENCES

[1] Hutcheon, N. B., and Handegord, G. O., *Building Science for a Cold Climate*, Institute for Research in Construction, NRCC, Ottawa, 1989.

[2] Handegord, G. O., *Moisture Considerations in Roof Design*, Can. Build. Dig. No. 73, NRCC, Ottawa, 1966.

[3] Baker, M. C., *Roofs: Design, Application and Maintenance*, Multi-science Publications Limited, Montreal, Canada, 1980.

[4] Wilson, A. G., "Condensation in Insulated Masonry Walls in Summer," Proceedings, RILEM/CIB Symposium on Moisture Problems in Buildings, Helsinki, 1965 (NRCC 9130).

[5] American Hotel and Motel Association, "Mold and Mildew in Hotel and Motel Guest Rooms in Hot, Humid Climates," Washington DC, 1991.

[6] Handegord, G., "Investigation of the Performance of Gypsum Sheathing," Can. Mortgage Housing Corp. Res. Highlights, 1993, pp. 98–114.

[7] Pressnail, K. D., et al., "Protecting Gypsum Sheathing in Insulated Steel Stud Walls," Can. Mortgage Housing Corp. Res. Highlights, 1997, pp. 98–119.

[8] ASHRAE, Standard 55, "Thermal Environmental Conditions for Human Occupancy," ASHRAE, Atlanta, GA, 2004.

[9] ASHRAE, *ASHRAE Applications Handbook*, The American Society of Heating, Refrigerating and Air-Conditioning Engineers, Atlanta, GA, 2003.

[10] World Meteorological Association publication, *Climatological Normals (CLINO) for the Period 1961 to 1990*, WMO, Geneva, 1996.

[11] Baker, M. C., and Hedlin, C. P., *Venting of Flat Roofs*, Can. Build. Dig. No. 176, NRCC, Ottawa, 1976.

[12] Stephenson, D. G., *Extreme Temperatures at the Outer Surfaces of Buildings*, Can. Build. Dig. No. 47, NRCC, Ottawa, 1963.

[13] Tibbetts, D. C., *Mineral Aggregate Roof Surfacing*, Can. Build. Dig. No. 65, NRCC, Ottawa, 1965.

[14] Garden, G. K., *Thermal Considerations in Roof Design*, Can. Build. Dig. No. 70, NRCC, Ottawa, 1965.

[15] Handegord, G. O., and Baker, M. C., *Application of Roof Design Principles*, Can. Build. Dig. No. 99, NRCC, Ottawa, 1968.

[16] Baker, M. C., and Hedlin, C. P., *Protected-Membrane Roofs*, Can. Build. Dig. No. 150, NRCC, Ottawa, 1972.

[17] Turenne, R. G., *Shrinkage of Bituminous Roofing Membranes*, Can. Build. Dig. No. 181, NRCC, Ottawa, 1976.

[18] Turenne, R. G., *Bituminous Roofing Membranes-Practical Considerations*, Can. Build. Dig. No. 211, NRCC, Ottawa, 1980.

[19] Dickens, H. B., and Hutcheon, N. B., "Moisture Accumulation in Roof Spaces Under Extreme Conditions," RILEM/CIB Symposium on Moisture Problems in Buildings, Helsinki, 1965 (NRCC 9132).

[20] ASHRAE, *ASHRAE Refrigeration Handbook*, The American Society of Heating, Refrigerating and Air-Conditioning Engineers, Atlanta, GA, 2002.

[21] Handegord, G. O., and Crocker, C. R., *Control of Condensation in Curling Rinks*, Can. Build. Dig. No. 35, NRCC, Ottawa, 1962.

[22] Brown, W. G., *Frost Heave in Ice Rinks and Cold Storage Buildings*, Can. Build. Dig. No. 61, NRCC, Ottawa, 1965.

[23] Garden, G. K., *Indoor Swimming Pools*, Can. Build. Dig. No. 83, NRCC, Ottawa, 1966.

[24] Hutcheon, N. B., *Fundamental Considerations in the Design of Exterior Walls for Buildings*, NRCC, Ottawa, 1953.

[25] Hutcheon, N. B., *Requirements for Exterior Walls*, Can. Build. Dig. No. 48, NRCC, Ottawa, 1963.

[26] Hutcheon, N. B., *Principles Applied to an Insulated Masonry Wall*, Can. Build. Dig. No. 50, NRCC, Ottawa, 1964.

[27] Sasaki, J. R., *Potential for Thermal Breakage of Sealed Double-Glazing Units*, Can. Build. Dig. No. 129, NRCC, Ottawa, 1970.

[28] Garden, G. K., *Rain Penetration and Its Control*, Can. Build. Dig. No. 40, NRCC, Ottawa, 1963.

[29] Garden, G. K., *Glazing Design*, Can. Build. Dig. No. 55, NRCC, Ottawa, 1964.

[30] Taylor, D. A., *Sliding Snow on Sloping Roofs*, Can. Build. Dig. No. 228, NRCC, Ottawa, 1983.

[31] Wilson, A. G., and Brown, W. P., *Thermal Characteristics of Double Windows*, Can. Build. Dig. No. 58, NRCC, Ottawa, 1964.

[32] Brown, W. P., and Wilson, A. G., *Thermal Bridges in Buildings*, Can. Build. Dig. No. 44, NRCC, Ottawa, 1963.

[33] Brand, and Ronald, *Architectural Details for Insulated Buildings*, Van Nostrand Reinhold, Princeton, 1990.

[34] Crocker, C. R., *Influence of Orientation on Exterior Cladding*, Can. Build. Dig. No. 126, NRCC, Ottawa, 1970.

[35] Latta, J. K., *Precast Concrete Walls—Problems with Conventional Design*, Can. Build. Dig. No. 93, NRCC, Ottawa, 1967.

[36] Latta, J. K., *Precast Concrete Walls—A New Basis for Design*, Can. Build. Dig. No. 94, NRCC, Ottawa, 1967.

[37] Perreault, J. C., "Application of Design Principles in Practice," *Construction Details for Air Tightness*, DBR Proceedings No. 3, Division of Building Research, National Research Council of Canada, Ottawa, April 1980 (NRCC 18291).

[38] Garden, G. K., *Look at Joint Performance*, Can. Build. Dig. No. 97, NRCC, Ottawa, 1968.

[39] Handegord, G. O., and Karpati, K. K., *Joint Movement and Sealant Selection*, Can. Build. Dig. No. 155, NRCC, Ottawa, 1973.

[40] Dalgliesh, W. A., and Boyd, D. W., *Wind on Buildings*, Can. Build. Dig. No. 28, NRCC, Ottawa, 1969.

[41] Dalgliesh, W. A., and Schriever, W. R., *Wind Pressures on Buildings*, Can. Build. Dig. No. 34, NRCC, Ottawa, 1962.

[42] Tamura, G. T., and Wilson, A. G., *Pressure Differences Caused by Chimney Effect in Three High Buildings*, NRCC, Ottawa, 1968; "Building Pressures Caused by Chimney Action and Mechanical Ventilation," *ASHRAE Trans.* Vol. 73, Part II, pp. 1–12.

[43] Gulay, B. W. et al., "Field Investigation Survey of Airtightness, Air Movement and Indoor Air Quality in High-Rise Apartment Buildings," Summary Report, Canada Mortgage and Housing Corporation, 1993.

[44] ASHRAE, *ASHRAE Handbook of Fundamentals*, The American Society of Heating, Refrigerating and Air-Conditioning Engineers, Atlanta, GA, 2001.

19

Recommendations for Remedial and Preventive Actions for Existing Residential Buildings

William B. Rose[1]

Existing Residential Buildings

EXISTING RESIDENTIAL BUILDINGS COMPARE well to new homes. Their performance history is evident to the trained eye of someone like a home inspector, and good diagnosis of problems helps in performance prognosis. By any measure of "sustainability," existing structures are desirable because the materials in place form a valuable repository of embodied energy. They are often in the most desirable economic locations. Existing homes have survived many of the problems that occur after construction, such as construction moisture and backfill settlement.

Existing homes are of many vintages and many types. The moisture problems that occur are strongly dependent on age, climate, condition, materials, finishes, thermal protection, foundation type, roof geometry, maintenance, use, etc. Thus it is very difficult to seek to provide a comprehensive list of possible problems, the associated factors, and recommended remedies. This chapter seeks to simply give an overview. Moisture problems may be chronic (wet basement is a common example) or catastrophic (as from a pipe burst, hurricane, or flood). This chapter addresses chronic problems. Catastrophic moisture problems require local professional care. The fire and water damage restoration industry, represented by associations such as Restoration Industry of America (http://www.ascr.org/) and the Institute of Inspection, Cleaning and Restoration Certification (http://www.iicrc.org/), has emerged to address cleanup after catastrophic problems like this.

Existing houses are not governed by the same model codes and local codes that govern new construction. The International Code Council has issued the International Existing Buildings Code [1], which describes four levels of alteration to the existing building, leading to four different levels of code compliance. In making changes to existing buildings, make sure that "bringing the building up to code" is done under the proper set of code regulations.

In the early 1950s, the National Paint and Varnish Association promoted the *Win Your War Against Water* campaign, which instilled a general fear for the invisible and damaging ways of moisture in order to encourage homeowners to adopt the then-new policies of vapor barriers and attic ventilation. This explains in part the tendency of many homeowners to imagine the worst when moisture problems arise. Some moisture problems are slow and chronic; homeowners should respond deliberatively using good diagnosis and planning. In the face of catastrophic damage, owners should respond promptly and effectively.

The historic preservation movement has developed a valuable body of knowledge to assist owners and professionals dealing with existing (not necessarily historically significant) buildings. See the Secretary of the Interior's Standards for Preservation [2], especially the series of *Preservation Briefs*. See also *Caring for your Historic House* [3]. Another valuable source of information dealing only with existing homes is from the weatherization industry. See *Home Energy* magazine [4] and local handbooks such as *Illinois Weatherization Standards* [5]. Other sources of information for building renovation include *Read This Before You Design, Build or Renovate* [6], and the HUD *Rehab Guides* [7]. Builders' guides from the time period of construction, available at many libraries, can be a good source of information about what lies beneath the surface of existing homes.

There are two sources of water that may damage homes—water from outdoors (including from the foundation) and water generated indoors. Of these two, by far the most damaging is water from outdoors, in terms of both likelihood and severity. Because of an unfortunate emphasis on water from indoors during the past 50 years, moisture control strategies such as vapor barriers and attic ventilation have received most of the attention. Rainwater management at the outside of the building deserves much greater emphasis, without losing sight of the importance of control of indoor moisture. This chapter takes a raindrop's view of a house. Water concentrations are greatest on the roof, and they have a diminishing effect as the water encounters the cladding, soil, foundation, interior of the building assembly, and interior of the house. The severity and likelihood of damage is proportional to the water—quantity, duration, and frequency—that affects the building assembly.

Table 1 provides guidance on identification and remediation of moisture problems in existing houses.

Water from Outdoors

Roof

Roofs should not leak. Roofs should discharge 100 % of the water that falls upon them outward to the roof edge, scupper

[1] *Research Architect, Building Research Council-School of Architecture, University of Illinois at Urbana-Champaign.*

TABLE 1—Inspection checklist.

Problem	Due to	Solution
Roof leaks	Workmanship, products	Roof repair
Ceiling spotting	Roof leaks	Roof repair
	Ice damming	Identify and correct vagrant heat source. Add waterproofing underlayment.
	Cathedral ceiling penetrations (e.g. recessed light fixtures)	Install fixtures designed for airtight installation.
	Duct condensation (cooling season)	Apply duct insulation with attention to vapor protection.
	Wind-blown precipitation through vents and louvers	Select vent design for snow and water exclusion.
	Discoloration where the wall meets the ceiling	Correct insulation at the top plate. Reduce indoor humidity.
Mold on exterior walls (heating season)	Closet storage, bedding, or other material against poorly insulated wall	Keep clothing, upholstered furniture, bedding, etc. away from exterior walls.
	Corner discoloration	Correct insulation if possible. Reduce indoor humidity.
	Mold beneath windows	Correct window flashing.
Mold on exterior walls (cooling season)	Negative pressure, chilled walls, impermeable finish	Replace vinyl wall covering with painted interior surface. Correct the air pressure balance, if possible.
Mold on interior walls	Basement	Remove interior basement finishes. Correct water management at exterior.
	Wet wall in bathroom	Greater care with shower curtain. Install impermeable scrubbable finish (e.g., tile) at affected wall.
Window condensation	Single pane	Install storm windows.
	Insulated glass units	Reduce indoor humidity.
	On exterior storm in late fall	Wait, or reduce indoor humidity.
Wet floor finishes on slab-on-grade	Water in the gravel base beneath	Correct the downspouts and exterior rainwater management.
	Smelly or discolored carpet	Remove carpet and clean, after correcting the water source.
Smells from crawl space	Soil gas	Install slab and sump pump with powered soil gas exhaust.
	Varmints	Call pest control.
	Plumbing	Call plumber.
Excess moisture from crawl space	Water leakage into the crawl space	Exterior rainwater management. Check if water enters through vents.
	Evaporation from soil	Provide slab or ground cover.
	Water entry despite ground cover	Install sump pump and drainage.
Wetness problem in the basement	Very local wetness	Correct the condition that is located near the problem area, such as a broken water pipe.
	General dampness in summertime	Install a dehumidifier.
	Wetness in corners or near downspout locations	Correct the grading around the house. Add splash blocks or downspout extenders.
	Wetness at the wall or the floor slab after heavy rains	Install a sump pump. Ensure that the pump water is discharged safely away from the house.
Catastrophic water entry	Storms, fire suppression, etc.	Consult professional help. Contact insurance agent.

TABLE 1— (Continued.)

Problem	Due to	Solution
"Clammy" feel during air-conditioning season	Leaky ductwork bringing humid air into the house	Test for leaks with pressure-test equipment. Contact duct or sheet-metal professionals.
	Short-cycling air conditioner	Review with air conditioning expert.

or gutter, or else inward to roof drains. Some roof sections act as funnels, concentrating water into lines (valleys or eaves) or points (drains). Water damage from roof leakage is linked to concentration and occurs almost always where rainfall amounts are concentrated. Flashing, such as chimney flashing, is a likely site of leakage. Valleys in roof systems should be designed for eventual repair. Laced and cut valleys in steep roof construction do not lend themselves to repair as well as open valleys.

Ice dams occur on roofs after snowfalls, usually when the outdoor temperature is around 20–22°F. They occur when snow is melted by heat in the attic, followed by refreezing at the eaves. If ice dams occur, the sources of vagrant heat in the attic should be identified and corrected. These often include heating equipment, chimneys or flues, poorly insulated ductwork, leaky ductwork, openings at the ceiling plane, and sections where insulation is missing. Attic ventilation may be helpful, even necessary, in arctic and subarctic regions [8], but attic ventilation is not likely to reduce ice damming in most of the United States. The reason for this is that the amount of heat that can be discharged through ventilation is much less than the amount of heat involved in snow melting in ordinary ice dam events.

Attic ventilation has been a contentious issue for several decades. Nevertheless, it can often be resolved in existing buildings. If attic sheathing shows evidence of a moisture problem (usually from darkening or mold growth on the underside of the sheathing) then the problem should be corrected. If there is no moisture problem, then no measures need to be taken—whatever the vent strategy in place, it can usually be retained at the time of renovation. This approach has been adopted by the Illinois Home Weatherization Assistance Program in 2004, which emphasizes the importance of preventing air exchange across the ceiling rather than modifying the existing venting strategy. Existing buildings showcase the fact that attics both with and without venting can perform quite well. Some may argue that additional insulation in the attic makes attic ventilation a necessity. Others may point out that material stored in attics often has a similar thermal effect as insulation, and storage has been done for decades with no change in venting strategy. For a further discussion of attic ventilation in existing buildings, see Ref. [9]. If there are moisture problems, they are most likely to occur at roof leaks, ice dams, or at sites where air leaks from below into the attic. The corrective measures should be obvious.

Houses with trusses may encounter a separation between the ceiling and an interior partition, especially during early winter early in the life of the house. This occurs with certain (relatively unpredictable) wood characteristics, where the longitudinal dimension change is greater than expected. It occurs because, during cold weather, the upper truss chords are cold while the bottom chord is warm. Since both chords are at the same vapor pressure, the upper chord tends to have a high moisture content while the bottom chord remains dry. If the top chord elongates with wetness, the geometry of the truss together with the web connections cause the bottom chord to be arched upward, sometimes by as much as 1/2 in. or 3/4 in. The condition is corrected cosmetically, using clips that keep the ceiling and partition drywall corner intact while permitting a slight rise in the truss.

Gutters

Gutters help to keep foundations dry, by permitting the management of rainwater at a few locations rather than around the entire perimeter of the building. Gutters require care and maintenance. Ladders placed against gutters can bend and damage them. In areas with trees, gutters need to be cleaned. Gutter joints, hangers, and accessories need occasional repair or reassembly.

Gutters lead to downspouts. Downspouts discharge rainwater into storm drains or onto the surface that surrounds the house. Downspouts should never discharge into water conduits that lead directly to sump pumps, as that could easily overload the pump system. Downspouts should discharge rainwater so far away from the foundation of the building that the soil in contact with the foundation is not water saturated even after a severe rainstorm. Keeping downspout extenders and splash blocks in place is often quite a challenge. Planting bushes near the discharge, or other landscaping near the downspout may help keep extenders in place, and they also provide some buffering of water content in the soil. In some areas, rainwater must be retained on site. Where this is required, information on the proper sizing and construction of cisterns is usually provided by building officials.

Walls

A wall functions as a roof when it is subject to driving rain. A wall has areas of water concentration (window sills, for example) and areas often requiring flashing (window heads, for example). The water-shedding elements of a wall should be installed shingle-style like the shingles of a roof.

A small amount of the wind-driven rain that impinges on a wall passes through the outermost cladding. With brick veneer, this may amount to 1–5 % of the applied rain load. With vinyl siding it is considerably more, but that water drains out very quickly and is dried quickly by air which moves freely along the back side of the vinyl. Massive walls of multi-wythe brick or stone may absorb some rainwater but only when the mortar has failed are channels created that allow water to pass all the way through. Wood clapboard or shingles usually require some sort of weather protection:

paint, stain, or water repellent. Paint peeling is a common complaint with wood siding, and there are many causes of paint peeling including substrate preparation, paint composition, and moisture content of the wood. Water repellents are generally not recommended for masonry construction—sorption of wind-driven rain by brick or stone is usually of little consequence so it rarely needs to be prevented or retarded.

The vapor barrier was introduced into frame construction in the late 1930s as a recommended practice to lessen the indoor moisture load upon exterior materials in insulated assemblies. The form of damage that vapor barriers were intended to minimize is the formation of water on cold sheathing materials in insulated cavity construction, where water vapor diffusion is the transport mechanism. Most researchers now admit that this form of moisture damage is extremely rare. On the other hand, moisture damage from rainwater or airflow is much more common, and vapor barriers may retard the drying capacity of wall assemblies that are wetted by these nondiffusion methods. See Chapter 16 for a discussion of vapor barriers in new construction. There is rarely any reason for existing buildings with vapor barriers to remove them, or for existing buildings without vapor barriers to install them.

Should insulation be added to the walls of existing, particularly historic, buildings? Energy conservation is increasingly desirable in buildings. Owners of existing buildings should study their own energy use. If owners wish to reduce energy consumption they should study the best and most cost-effective strategies. Usually, wall insulation is well down this list after ceiling insulation, window treatments (especially storm windows), and equipment upgrades. Insulation may be added to wall cavities or added as insulating sheathing when the house is re-sided. When insulation is added to walls in cold climates, the materials that are outboard of the insulation are subject to greater temperature swings, greater swings in moisture content, and longer periods at subfreezing temperatures. The tradeoffs between energy savings and durability deserve much more study than they have had to date. It should be noted that much of the increased wetness of exterior materials that occurs with insulation in the wall assembly is independent of the use (or not) of vapor barriers [10].

Brick exteriors have special moisture problems. Older walls with multiple wythes of brick and soft mortar usually perform well, although flashing failures often lead to efflorescence (appearance of salts on the surface) and perhaps spalling during cold wet weather. Single-wythe brick walls are typically constructed with weep holes, which help in the drying of rainwater that penetrates through the brick. Brick walls with openings at the top as well as the bottom provide for drying that is accelerated compared to walls with openings at the bottom only [11].

Windows

Window frames may leak water to the interior of the wall system. Older buildings with storm windows are rarely affected by this problem because the storm windows keep the water management plane outboard of building cavities and away from the jamb-sill joint.

Window condensation may be troublesome. Small amounts of water on the window pane do no harm unless the water begins to affect the paint or coating on the window frame, or if it leads to dirt or mold accumulation on the frame. Nevertheless, the appearance of window condensation is a good early indicator that indoor humidity levels may be too high. Window condensation is more common with interior window treatments (heavy drapes or blinds) that are thermally resistant. Late fall and early winter is a common time for window condensation in northern climates. Many building materials are hygroscopic; they take up moisture during summer and begin to discharge it at the start of the heating season. This often leads to a blush of window condensation at the start of winter. The blush is most likely to occur on exterior storm windows because they are colder, and on the upper stories of a home because of thermal buoyancy of warm air.

Surrounding Soil

Imagine the soil surface that surrounds a house as a roof. The purpose of a roof is to divert rainwater laterally so that the space below stays dry. That is true of the "ground roof" as well. Roofs require slope. The *International Residential Code* R401.3 [12] requires six inches of fall in the first ten feet of soil surface around the entire house. Unfortunately, the push for horizontality in many of the post-war ranch houses left the floor framing too close to the ground for effective correction of slope. Soil slope should be corrected, although this may sometimes involve compromise in keeping soil away from wood framing, sheathing, and siding materials. Roofs require geometry that diverts water appropriately: on a sloped lot a swale uphill from a house operates much like a water diverter (or "cricket") uphill from a chimney.

As mentioned above, extending downspouts is the principal way of ensuring that roof rainwater does not affect the building foundation. Figure 1 from *Read This* shows a supplementary strategy—the use of an impermeable "skirt" that diverts water away from the crack between the soil and the foundation. Often water problems in foundations are found where water concentration from downspouts is greatest, so a skirt may be most helpful in discrete locations such as at downspouts.

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 management of rainwater should be carefully designed to prevent water accumulation in the gravel base beneath any slab. Water should be able to drain freely away from any downspout along the soil surface. Landscaping designs sometimes include sidewalks which completely enclose a soil surface where roof rainwater is deposited; where this occurs, special provisions need to be made to drain the water past the surrounding sidewalk.

Foundation

Basement

Basements should be dry. Current code [*IRC*406.2] requires dampproofing (which inhibits moisture diffusion) of all residential foundations, and requires waterproofing (which in-

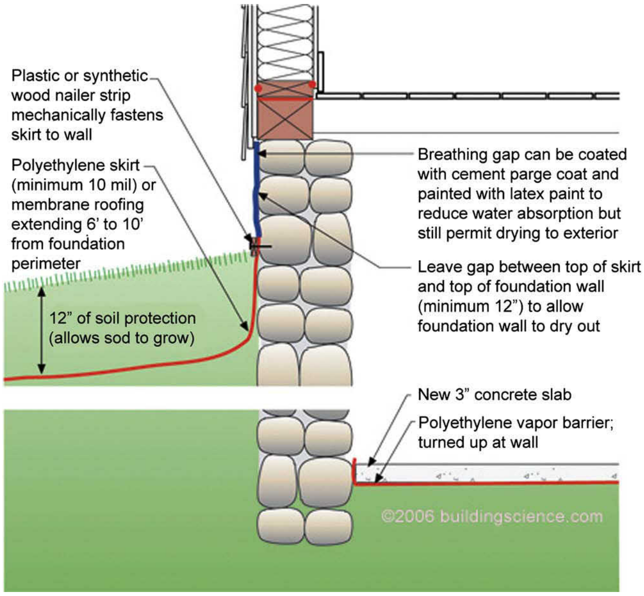


Fig. 1—*Shows impermeable skirt for building foundations. Published with permission from Building Science Corp.* [*6*].

hibits 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 or spray-applied to the foundation. Waterproofing requires the treatment of the joints and surfaces to resist a head of liquid water. 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. Any buildings that are subject to rising groundwater up to the level of the basement slab must be protected from water entry by the use of drainage piping and sump pumps.

However, there are many structures which lack effective exterior dampproofing or waterproofing, and which lack operating foundation drainage. Leaking and seepage of water into such basements is a common problem. If leakage occurs within hours after heavy rains, or from high on the basement wall, 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.

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 necessary. Excavation is often considered for the purpose of adding exterior thermal insulation. which may itself contain spacing for vertical drainage. Many foundation wall drainage mats are being marketed, including dimpled mats and rigid insulation with drainage channels. These prevent the build-up of water pressure against the insulation or foundation wall. Adding a drainage mat increases the importance of providing dependable foundation footing drainage.

Perhaps the most convenient way to address minor dampness problems is from within the basement. Certain paints, including epoxy-based paints, may reduce moisture evaporation from wet walls. Any paint for this purpose must not only reduce the overall water transmission 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 de-watering 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. Below grade insulated interior assemblies were studied by Forest and Ackerman for Canada Mortgage and Housing Corporation [13], which found that the water load from flooding and behind interior finishes leads to mold growth in the assembly, except for assemblies that are designed to withstand occasional liquid wetting. The research found that the assemblies using conventional construction (wood and metal framing, insulation, gypsum wallboard, and polyethylene) permitted mold growth after water loading; proprietary systems with prefinished insulated panels and supports did not show mold growth after water loading.

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 for easy access, good lighting, and adequate clearance (32 in. or 0.8 m with 18 in. or 0.5 m clearance at beams and ducts). The soil surface should be level and free of debris.

Crawl spaces should be inspected regularly—at least once a year. 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 growth on

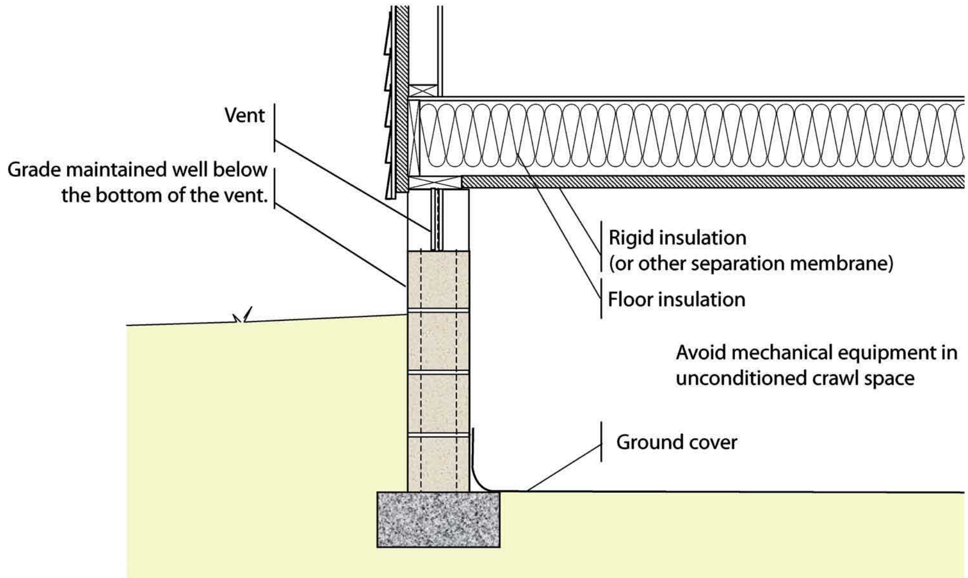


Fig. 2—*Idealized crawl space that uses venting. Note that the vent is elevated well above exterior grade. This design advises against use of mechanical equipment in the crawl space because the space is unconditioned and because of the likelihood that equipment installers will leave openings between the crawl space and the living space.*

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.

Building codes have historically required crawl spaces to be vented. The most commonly cited requirement [*IRC*R408.2] is for a total vent area of at least 1/1,500 of the covered crawl space floor area, with vents located within 3 ft (1 m) of the corners of the foundation. For background information on crawl space venting, see Advanced Energy [14].

Figure 2 shows a vented crawl space that is coupled to the outdoors, and isolated from the indoors. Note the insulation in the floor plane, the moisture protection afforded by rigid insulation on the underside of the floor framing, and the absence of any mechanical services in the crawl space itself. This approach is modeled on manufactured housing, where the building itself is effectively isolated from the air beneath. This is an idealized approach—crawl spaces are rarely fully open to the outdoors and closed to the indoors. Note in Fig. 2 that the vent is located high, so that the bottom of the vent is well above the surrounding soil surface. In many existing crawl spaces the vent is located at grade or below grade. Low openings should not be called "vents," they should be called "sluices" because they are often the openings that may cause flooding of the crawl space.

Figure 3 shows a crawl space that is coupled to the indoors and separated from the outdoors. Rainwater management around the building must be sufficient to keep surface water away from the foundation. Any rainwater that might enter the crawl space should be collected by a drain system and directed toward a sump pump. In the past, a polyethylene ground cover was considered a satisfactory surface for the bottom of the crawl space. However, if the crawl space is, in effect, a room in the house, then it should be cleanable like other rooms in the house. A concrete slab is a much more cleanable surface than polyethylene sheet material. In this approach, the insulated envelope is at the outside of the crawl space walls, so mechanical equipment can be placed in the crawl space and openings between the crawl space and the living space are not restricted.

The *IRC* permits several exceptions to the venting requirement for crawl spaces [R408.2] including where climatic conditions warrant, and openings are provided to the interior space.

Most existing crawl spaces, in fact, are hybrids with the crawl space air being neither completely within the conditioned envelope nor being completely outside. This lack of consistent strategy spells trouble for many crawl spaces. The trouble can be minimized by ensuring a good ground cover and good rainwater management at the exterior, and by making sure that no water enters through the "vent" openings. Once such a crawl space establishes a track record of dryness, then the vents are often shut and insulated with tight-fitting blocks of rigid insulation. If the crawl space remains wet despite water management efforts at the outside, then a sump pump should be installed, together with regrading or drainage tile installation inside, as necessary. The crawl space vents may be helpful in the event of accidental water accumulation in the crawl space.

The band joist is the outside perimeter floor framing member. Because it is chilled by the outdoors, 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 joist by insulating with a rigid insulating material, foamed in place.

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

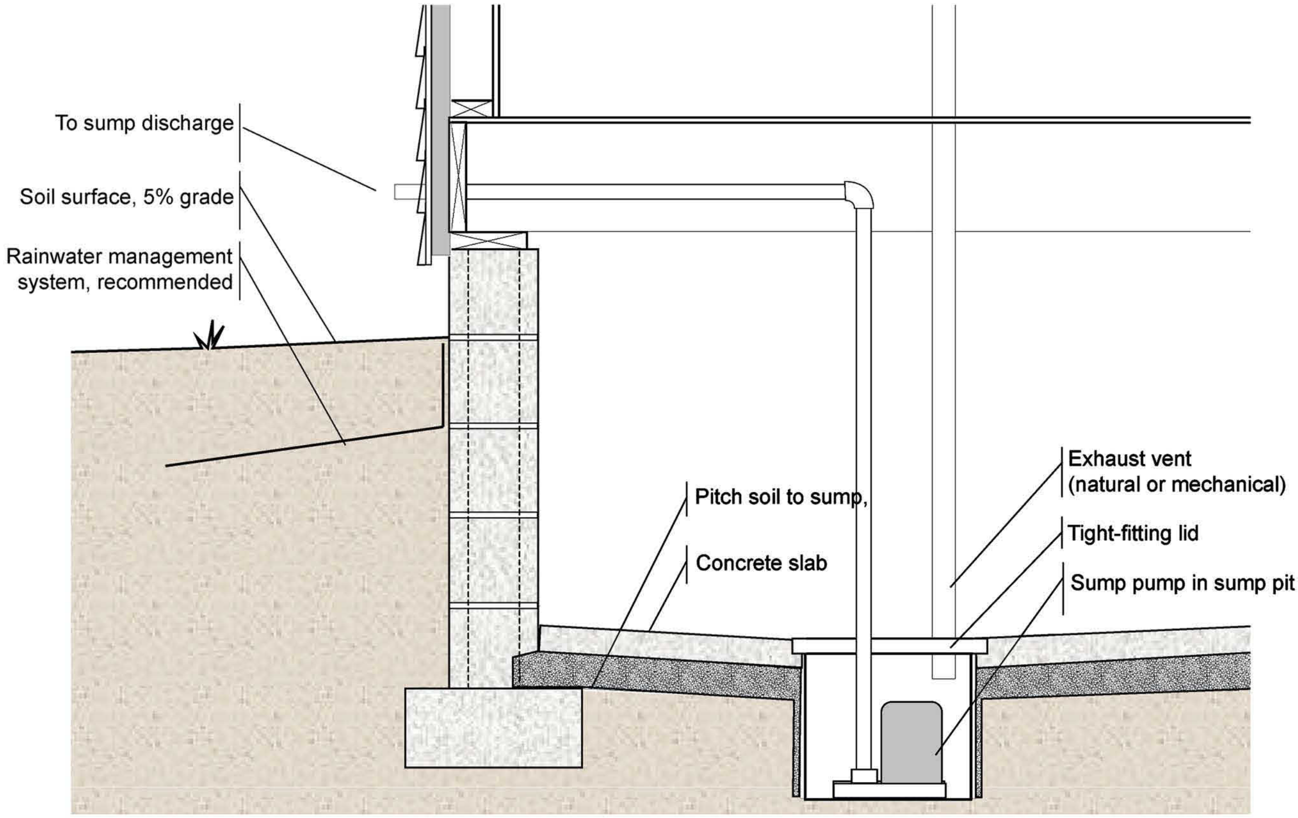


Fig. 3—*Idealized crawl space without venting. Note that the crawl space floor is designed to drain to a sump pump, and the sump pit may be used to evacuate soil gas from beneath the slab.*

crawl space involves blocking air flow through these chases. Home inspectors often cite the finding that damage to attic sheathing occurs almost uniquely on houses with wet crawl spaces, usually with vent openings in the crawl space and attic, alloying a strong buoyant flow. This finding was first reported by Britton in 1949 [15]. To date, systematic details for achieving airtightness in the floor framing above basements and crawl spaces have not been presented.

Slab

Slab floors should remain dry. They are usually poured on a gravel or sand base for leveling and capillary break. When the slab floor is too close to the surrounding soil grade, water may enter into the gravel base beneath the slab and lead to wetting of the slab. This may cause damage to floor finishes and cause mold growth on carpets and rugs. Figure 4 shows an air gap that ensures that water that lands on the site can never engage the underside of the slab.

Some slabs in the 1950s and 1960s were cast with below-grade ductwork usually lined with galvanized metal. Most of these have rusted severely by now. A common problem is rainwater entry into these ducts, leading to humidified air being supplied to the house. In most cases, the best solution is to abandon the sub-slab ductwork and install another means of heating and cooling distribution.

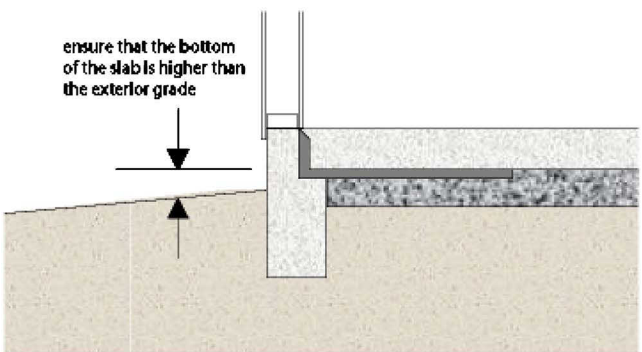


Fig. 4—*Soil surrounding a slab should be kept lower than the height of the underside of the slab. If the surrounding soil is too high, the water level could reach the slab, leading to excess moisture.*

Sump Pump

Sump pumps may be very helpful in solving water problems in wet basements and crawl spaces. They collect water at the base of the sump pit and provide for discharge. In many cases, the discharge site is poorly thought out—it may discharge at the building foundation leading water right back to the sump pit, or it may discharge to an unsightly hose or pipe away from the foundation. It is preferable to provide a drain that is open outdoors near the foundation, and which leads to an appropriate outlet such as daylight to a retention pond or a storm drain. Sump pumps should be designed with a tight-fitting lid so that radon or soil gas can be evacuated from the sump pit if necessary.

Water from Indoors

When outdoor water affects part of the building envelope, it does so in the vicinity of the water entry. High indoor humidity can cause problems distant from the source of water vapor. Houses must be designed to withstand and eventually dilute the moisture contribution from occupants and normal use—around 20–30 lb per day from a family of four. Normal frame construction through the several eras of house construction in the United States meets this requirement easily. If the moisture contribution rate is higher, however, interior surfaces, especially cold spots, can begin to show discoloration. Generally speaking, there are four sources of chronic (not catastrophic) high humidity that lead to distress on interior surfaces:

- Wet crawl space, either with uncovered soil or standing water on top of the ground cover,
- Poorly controlled humidifier,
- Backdrafting or unvented combustion appliance, or
- Severely overcrowded conditions.

Note that the first three of these are problems that lie within the domain of the builder or mechanical equipment installer. In the past, high indoor humidity has often been blamed on "lifestyle" of occupants. The high humidity sources could contribute as much as 100 lb per day into the living space; it is unlikely that a "lifestyle" source could contribute as much.

Plumbing

Water supply systems operate under pressure, so even small leaks can lead to large quantities of water entering the structure. Water supply systems should be plumbed so that joints are at least as strong as the straight runs of piping. Newer systems using crosslinked polyethylene (PEX), often called home-run systems because each fixture is served from a central manifold, show much promise. Gordon [16] has shown that bursting of water pipes under freezing conditions is due to elevated fluid pressures downstream from an ice blockage, and is not due to forces acting radially outward as water turns to ice. This leads to several approaches such as the inclusion of pressure relief devices in plumbing groups that permit water supply to turn to ice and back to water without rupture. A common site of catastrophic water supply rupture is at washing machine hookup hoses. These should be inspected and changed regularly.

Plumbing fixtures are designed with nonporous surfaces so that they can be wetted and dried and leave no stored water that could support mold growth. Surfaces near plumbing fixtures may be affected by splash. A common site of moisture problems occurs on the wet wall of a small bathroom containing a sub/shower, toilet, and lavatory. The small wall area between the tub and the lavatory is difficult to clean. This area should be designed or fitted with a surface such as concrete board that can be easily scrubbed and is less likely to be damaged by retained water.

Plumbing drains should be kept in good repair. Drains in crawl spaces should be inspected as often as drains in basements, though this is rarely the case. The site where service lines such as main plumbing drains pass through foundation walls is a common site for rainwater entry, especially after repair to the line. Soil should be tamped tightly to all below-grade service lines.

Air Conditioning

Air conditioners provide a chilled coil, and house air passes over the coil. The coil first lowers the sensible temperature of the air. When the coil reaches the dewpoint of the air, droplets form on the coil fins. These coalesce and then drain by gravity to the condensate pan. If the condensate pan is dirty, water will first saturate the dirt in the pan; otherwise it fills the pan until water begins to drain out through the condensate line. Only at that point has water been removed from the house air. If the unit is large, it may satisfy a thermostat quickly, sometimes even before any water has been removed from the air stream. Henderson et al. [17] estimate that water removal begins late in the cycle—from 13 to 32 minutes under their test conditions. A smaller a/c unit satisfies a thermostat more slowly, and so it can be more effective at dehumidification. If an a/c unit provides sensible cooling while providing little or no moisture removal (latent cooling) the result is higher relative humidity, higher moisture content on surfaces, and a cold clammy feel. A more recent study by Parker [18] showed that downsized air conditioners did not lead to lowered humidity in the homes that they studied, because leaky ductwork and extended run times led, in fact, to higher humidity. Leaky ductwork should be repaired.

A dehumidifier is essentially an air conditioner with both the evaporator unit and the condensing unit indoors. Humidifiers add heat to the space as they remove moisture. Humidifiers are rated for their strength in removing water. If the moisture source strength is high—for example from a wet crawl space—the dehumidifier may not be able to compensate. Buildings with basements that are mildly damp and perhaps smelly may benefit from the use of dehumidifiers. Buildings that rely on dehumidification, whether from air conditioners or dehumidifiers, should be tightened against excessive air change. It is very difficult to dehumidify a leaky building.

Humidifiers are occasionally provided to add humidity to the indoor air during winter. Relative humidity below 25 % may lead to skin cracking, sparks, and discomfort for contact lens wearers. During cold weather, average indoor humidity should not be allowed to drift too high—window condensation is often used as a first sign of excess indoor humidity. Automated controls may be installed to desired levels of humidity with changing outdoor conditions. Humidifiers require regular cleaning and maintenance. Humidity controls for humidifiers may require calibration. They should never be used where there are signs of excess humidity indoors, such as mold spotting or window condensation. Piano manufacturers and distributors provide humidifiers which can be installed near the soundboard to keep it from cracking from excess dryness. In general, the use of humidifiers is discouraged except where they are rigorously maintained.

Human Sources of Moisture

(See Chapter 7 on sources of moisture.) Only at very low air change rates, or in particularly dense conditions can the moisture generated by occupants be considered to contribute to moisture problems. Of course, solving moisture problems in houses should never involve discouraging occupants from normal habits of hygiene and cleaning. Almost all moisture problems lend themselves to corrective measures in the construction, repair, maintenance, or operation of equipment.

Research indicates that there is a correlation between self-reported dampness in buildings and respiratory health effects. See *Damp Indoor Spaces and Health* [19]. When is a building "too damp?" During winter the indoor moisture concentration can be approximately calculated from the outdoor moisture concentration, the amount of moisture generated and the amount of infiltration or ventilation dilution (see below). This incremental indoor moisture above the outdoor ambient moisture has been termed the "moisture balance" [20]. In most evaluations, a "damp" building is one with a high moisture balance, that is, with a high moisture generation that is not sufficiently diluted by ventilation or infiltration. Correlations between quantified indoor humidity (for example, using moisture balance) and respiratory health must await future research.

Ventilation

House occupants need fresh air, of course. Kitchen exhaust devices have been used for decades to remove cooking odors and to dilute moisture generated by cooking. Bath fans were installed originally to remove bathroom odors, but they serve as well to dilute moisture spikes and help dry out the bathroom surfaces following showering. Infiltration is ventilation (or air exchange with the outdoors) under natural conditions. Existing homes vary widely in their natural airtightness and background ventilation rate. Reducing infiltration is beneficial for energy conservation. Occasionally (indeed rarely), during winter, houses may be so tight and occupation so dense that additional whole-house ventilation is called for in order to reduce high moisture levels. During air-conditioning season, airtightness is an overall benefit. Generally it is good to identify large holes and cracks in the building envelope, and close them.

Homes may outgas contaminants, though the quantity outgassed is finite and older homes should be effectively free from this problem. Reducing contaminant concentrations indoors through ventilation is desirable. ASHRAE Standard 62.1 imposes ventilation requirements for public buildings, and for commercial and industrial construction, and it has been widely adopted. ASHRAE Standard 62.2 was created to regulate ventilation requirements for residential buildings; it is rarely applied to existing houses.

Do vents significantly reduce moisture in buildings? During summer, ventilation rarely reduces indoor humidity. Bathroom ventilation may help reduce the local and temporary humidity shock associated with taking showers, especially in residences of high occupancy. Controls should be designed to run bathroom fans for a period of time after the last shower is taken in order to help dry water from walls. Kitchen ventilation may exhaust odors, contaminants (when gas is the cooking fuel), and local high humidity. Using heat exchangers or enthalpy exchangers may lessen the space-conditioning cost of ventilation air. In summary, ventilation should not be seen as a cure-all, but as an effective means of reducing local and temporary high humidity and high concentrations of unwanted gases.

Combustion Appliances

Any appliance that burns fuel produces combustion by-products. These include carbon dioxide, nitrogen oxides, carbon monoxide, water vapor, and particulates, depending on the fuel and the quality of combustion. In general, combustion by-products should be extracted from the air near the source of production of these by-products with a flue or chimney.

Naturally-vented appliances (including furnaces, boilers, and hot water heaters) discharge their combustion products to a chimney that operates by buoyancy of heated combustion gases. These appliances may have small amounts of combustion products discharged into the house when they fire up, but after a few moments, essentially all of the combustion products should move with ease up the chimney. Appliances with sealed combustion (condensing appliances) discharge their products outdoors with assistance of a blower. Most furnaces and boilers available are sealed combustion units, and these are strongly recommended.

In most states in the United States, the sale and use of certain ventless gas appliances is permitted. Two types are hearth appliances and "supplementary heating" appliances. These appliances have no chimney, and all of the combustion products are delivered to the indoor air. At the time these appliances were adopted by state codes, there was one report [21] that offered support for claims of safety for these appliances. Recent research indicates that the resulting concentrations of combustion gases remain below guidance thresholds in many cases, except for NO_2, which is often in excess of guidance thresholds [22].

In existing homes, ductwork can pass through unconditioned spaces such as attics and crawl spaces. If that ductwork is leaky, the consequences may be significant. Leaky supply and return ductwork may waste considerable amounts of energy. Leaky returns during summertime may lead to high humidity being brought into the house air.

Summary

Existing houses have the benefit of experience over new houses that moisture problems can be observed and fixed. Worries about moisture were fostered during the early 1950s. Those who live in existing houses, and those who work on them, should recognize that moisture worries can be overcome and set aside, following the modest list of precautions presented here.

References

[1] International Code Council, *International Existing Building Code*. www.icsafe.org, 2003.

[2] Secretary of the Interior's Standards for The Treatment of Historic Properties, http://www2.cr.nps.gov/tps/secstan1.htm. See also the National Park Service series of *Preservation Briefs* available online http://www2.cr.nps.gov/tps/briefs/presbhom.htm, 1995.

[3] *Caring for Your Historic House*, Charles E. Fisher and Hugh Miller, Eds., Harry N Abrams, New York, 1998.

[4] Home Energy magazine. www.homeenergy.org

[5] IWHAP (Illinois Home Weatherization Assistance Program), *Illinois Weatherization Standards*, Springfield, IL, 2004.

[6] Building Science Corporation, *Read This Before You Design, Build or Renovate*, http://www.buildingscience.com/resources/mold/Design_Build.pdf, 2004.

[7] HUD, (U.S. Department of Housing and Urban Development) (nine volumes), *The Rehab Guides*, HUD, Washington DC, http://www.huduser.org/publications/destech/rehabgds.html, 1997–2000.

[8] Tobiasson, W., Buska, J., and Greatorex, A., 1994, "Ventilating Attics to Minimize Icing at Eaves," *Energy Build.*, Vol. 21, 1994, pp. 229–234.

[9] Rose, W. and TenWolde, A., "Attic Ventilation for Historic Buildings: Background and Current Developments," *The Roofing Handbook for Historic Buildings*, D. Slaton and C. E. Fisher, Eds., Historic Preservation Education Foundation and the National Park Service, Washington DC, 1999.

[10] Rose, W., "Should the Walls of Historic Buildings be Insulated," *APT Bull.*, Special issue on sustainability and preservation, Vol. XXXVI, No. 4, 2005.

[11] VanStraaten, R. and Straube, J., "Field Study of Airflows Behind Brick Veneers: ASHRAE 1091—Development of Design Strategies for Rainscreen and Sheathing Membrane Performance in Wood Frame Walls," Report #6 Final Report, ASHRAE (American Society of Heating Refrigerating and Air-Conditioning Engineers), Atlanta, GA, 2004.

[12] International Code Council, *International Residential Code*, www.icsafe.org, 2003.

[13] Forest, T. and Ackerman, M., "Basements that Dry," Canada Mortgage and Housing Corporation, http://www.cmhc-schl.gc.ca/publications/en/rh-pr/tech/99–109_e.pdf, 1999.

[14] Advanced Energy, Technology assessment report. A. field study comparison of the energy and moisture performance characteristics of ventilated versus sealed crawl spaces in the south., U.S. Department of Energy, Washington, DC. 2002. http://www.advancedenergy.org/root/buildings/crawlspaces/reports/tech_assess.pdfEnergy.

[15] Britton, R. R., "Crawl Spaces: Their Effect on Dwellings—An Analysis of Causes and Results—Suggested Good Practice Requirements," Housing and Home Finance Agency Technical Bulletin No. 2, Jan. 1948. Housing and Home Finance Agency, Washington, DC, 1949.

[16] Gordon, J. R., "Preventing of Bursting in Water Pipes," Research Report 96-1, Building Research Council, University of Illinois at Urbana-Champaign, Champaign, IL, 1994.

[17] Henderson, H. I., Shirey, D. B., and Raustad, R. A., 2003, "Understanding The Dehumidification Peroformance of Air Conditioning Equipment At Part-Load Conditions," *CIBSE/ASHRAE Proceedings*, http://www.cdhenergy.com/presentations/CIBSE–ASHRAE%20Scotland%202003%20Part-Load%20Dehumidification.pdf, 2003.

[18] Sonne, J. K., Parker, D. S., and Shirey, D. B., "Measured Impacts of Proper Air Conditioning Sizing in Four Florida Case Study Homes," Florida Solar Energy Center Report FSEC CR-1641–06. http://www.fsec.ucf.edu/en/publications/pdf/FSEC-CR-1641–06.pdf, 2006.

[19] IOM, *Damp Indoor Spaces and Health*, National Academy of Science Institute of Medicine, 2004.

[20] Rose, W. and Francisco, P., "Field Evaluation of the Moisture Balance Technique to Characterize Indoor Wetness," *Proceedings of Performance of the Exterior Envelopes of Whole Buildings IX*, 2004.

[21] DeWerth, D. W., Borgeson, R. A., and Aranov, M. A., "Development of Sizing Guidelines for Vent-Free Supplemental Heating Products," by American Gas Association Research Division, GRI 96–0093, 1996.

[22] Francisco, P. W., Gordon, J. R., and Rose, W. B., "Indoor Combustion Product Concentrations Resulting from the Use of Unvented Gas Fireplaces," *IAQ2007: Sustainability and Human Health*, Baltimore, MD, Oct. 2007.

MNL18-EB/Oct. 2009

20

Evaluation and Remediation of the Building Envelope for Existing High-Rise Buildings

Warren R. French P.E. RRC, RWC[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 for 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, such as the special exterior design wind pressures and internal pressurization arising from mechanical equipment or partially enclosed fenestration arrangements (Figs. 1–3).

The best time to deal with moisture-related problems is during design and original construction using good design and construction practice related to 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 *2005 Handbook of Fundamentals* [3].

Troubleshooting

Before being able to develop remedial recommendations for the 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 to identify the moisture source, the general mechanisms and paths of its migration, as well as secondary 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. ASTM International has developed and promulgated E2128 for evaluating water leakage in building walls, which may provide some guidance with respect to conducting such investigation [4]. In addition, pertinent magazine articles and compilations of technical papers have been written on this subject as well [5–10].

It should be noted that the scope and extent of exterior building envelope investigations for most high-rise buildings will preclude a *quantitative* evaluation due to limitations of access, manpower, time, and resources. In addition, a building evaluation based on a strict quantitative analysis would require a statistically significant sampling of the exterior building envelope for examination, and perhaps destructive testing, which is based on a strict random selection of the sample specimens throughout the building envelope. For practical building evaluations, there are at least two major problems with this approach. First, due to the tens of thousands, and in some cases hundreds of thousands, of square meters (square feet) of building envelope surface area, a quantitative evaluation could require the disruption of hundreds of samples interposed on the fenestration of a physical asset that is presumably under investigation in an attempt to *preserve* the asset. The potential damage to the facility (for instance, a historically significant structure) and the excessive costs involved in the investigation and repair at each test location would be prohibitive. Second, if a strictly random selection process is utilized to choose the locations to be investigated, it is possible many “random” locations could be chosen that would not manifest the problem being investigated, or else could “miss” the key areas exhibiting such anomalies just a short distance away. Under strict random selection, an investigator would not be free to concentrate his investigative efforts on the more promising investigation locations of a building envelope without corrupting the random process. Accordingly, it is generally adequate for experienced investigators to implement a well planned *qualitative* evaluation, consisting of a “directed” investigative approach involving information rich investigation sites that representatively describe the assemblies or processes being evaluated [11,12]. Such investigations may result in fewer locations on the building being investigated to the fullest, but, using information from leak histories and interior observations, the qualitative evaluation would concentrate on those areas that would most likely yield the greatest amount of data about the problem being experienced in the

[1] *President, French Engineering, Inc., 4201 FM 1960 West, Ste. 300, Houston, TX 77068, USA.*

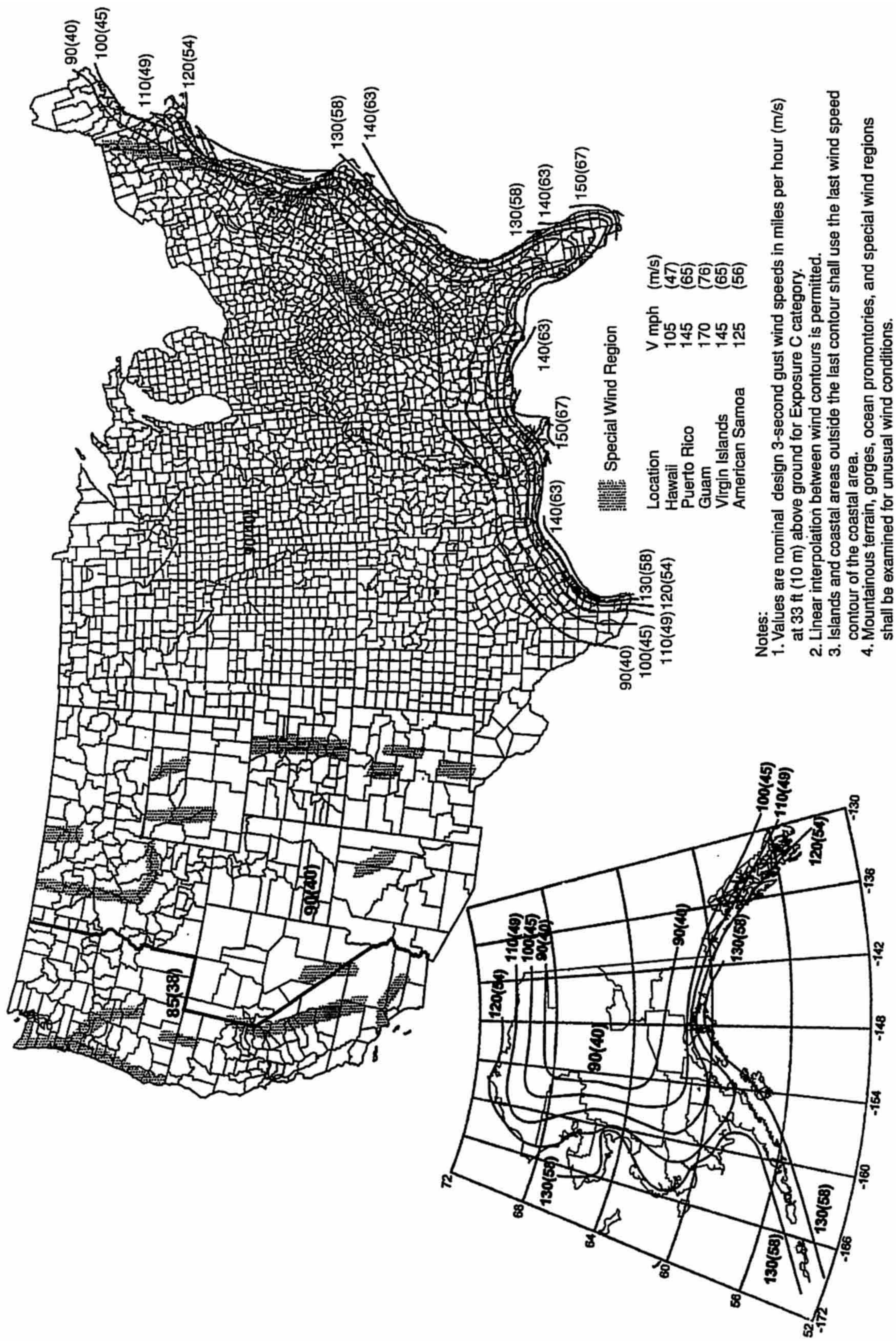


Fig. 1—Basic Wind Speed in miles per hour (m/s), corresponding to 3 s gust 10 m (33 ft.) above ground for Exposure C. (Adapted from ASCE7-05.)

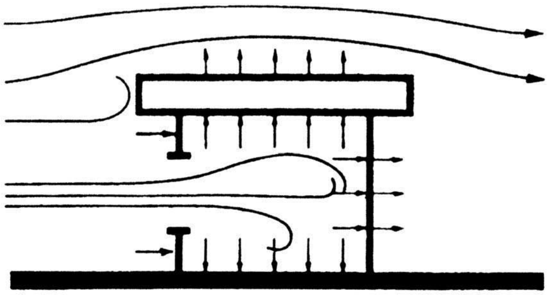


Fig. 2—Wind striking a building causes pressure differentials.

effort to understand and correct the problem. Obviously, an investigative approach may be developed that represents a hybrid of the quantitative and qualitative evaluation techniques.

From the building testing and evaluation, a proper diagnosis of the problems and their cause may be derived; information provided in Chapter 14 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, but not always practical, 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 re-evaluation 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 physical space with respect to water leakage. At present, it would be beneficial to consider how the operation of building mechanical systems affects the space enclosure.

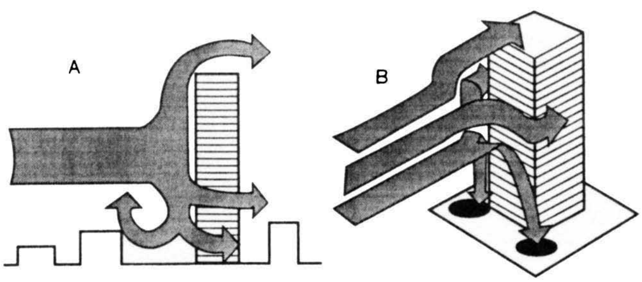


Fig. 3—Wind effects on tall buildings.

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 systems. 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 8 and 9, 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 HVAC 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 the possibility 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. In addition, proper operation and performance of the HVAC system is dependent on an appropriate program of regularly scheduled maintenance, cleaning, balancing, and adjusting. For older buildings, changes in the ownership, occupancy, and usage of interior spaces may have occurred since original construction without corresponding revisions to the HVAC systems. Each of these conditions could adversely affect the HVAC system capability of controlling the building environment, including temperature, humidity, moisture balance, ventilation air exchange, and interior/exterior pressure differences.

For these reasons, sizing and performance of the building mechanical equipment for the interior spaces involved may have to be reviewed during a thorough investigation of the building envelope. 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 may 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. It is important that the HVAC systems be 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 an 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 their products. In some cases, it is prudent to obtain this data in order to assist with the forensic 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, then 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 [13] (see also Chapter 8). 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 is 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. If the building interior inadvertently becomes "negative" with respect to the exterior, the pressure differential can increase infiltration of unconditioned outside air, as well as result in increased water penetration through any incidental openings occurring within the building envelope.

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 have a deleterious effect on interior humidity levels. Therefore, mechanical means of removing moisture from the air, or dehumidification, is commonly required to bring exterior air in under 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 psychrometrics of moist air when it is sufficiently cooled from a previously existing condition (see Chapter 9). Typically, sufficient dehumidification will occur due to room air passing through the coil to shed sensible heat and is usually adequate for most buildings. However, it has been well established that air conditioned buildings located in hot humid climates require special considerations, particularly hotels and apartment buildings with individual fan coil units or packaged terminal air conditioners, which usually operate intermittently under the control of the occupant [14]. 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). When related to absorption and capillary action of water within building components in contact with the ground (i.e., foundations), this condition 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. In addition, kitchen activities such as continuous cooking or boiling water in apartment buildings with limited ventilation can result in excessive interior condensation against cool surfaces (aluminum windows, single pane glass, etc.) during winter months.

Building Pressurization/Depressurization

As stated previously, 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 be-

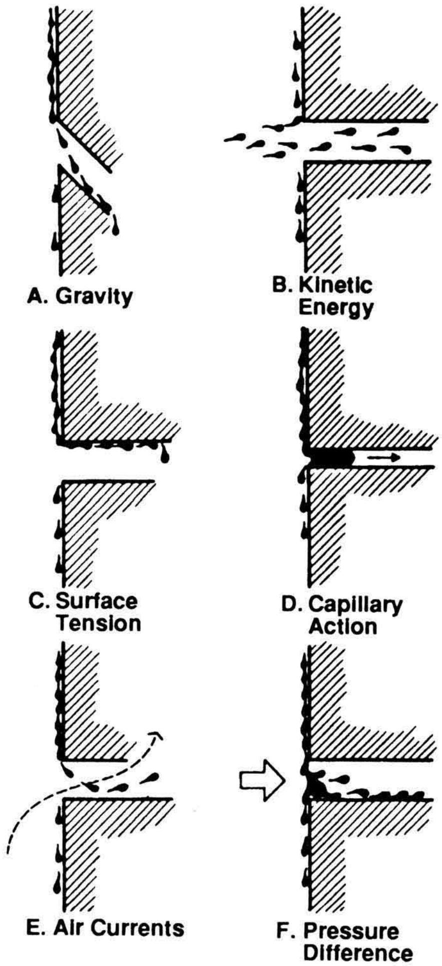


Fig. 4—Forces acting to move water through an opening.

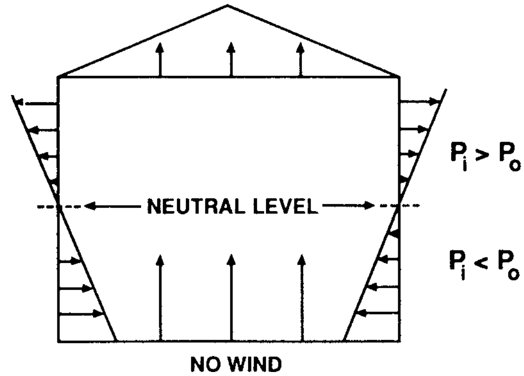


Fig. 5—Pressure differences caused by stack effect for a typical structure (heating). (Arrows indicate magnitude and direction of pressure difference.)

ing 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, once again, the building investigator should be aware of the particular HVAC design aspects of the project in order to evaluate their effects on moisture migration and balance within the building envelope.

It is as important to achieve a proper pressure balance within the controlled space as it is to achieve proper temperature 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 by the use of appropriate 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 air moves due to a change in elevation and atmospheric air density within the enclosed space. It is particularly prevalent when air can leak between floors at floor 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 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 affect 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.

Design Wind Pressures

History and Development

One of the first codes widely used to estimate design wind pressures on buildings was developed by the American National Standards Institute (ANSI) in 1972, which was later revised and utilized throughout the United States until the late 1980s [15]. This code included wind speed maps based on fastest mile wind speed and a 50 year mean recurrence interval. After 16 years of use, the American Society of Civil Engineers (ASCE) undertook the task of updating and completely revising the ANSI A58.1 standard, which resulted in ASCE 7-88. A number of modifications and improvements were made based on contemporary research, however, the wind speed maps were still based on fastest mile. In 1993,

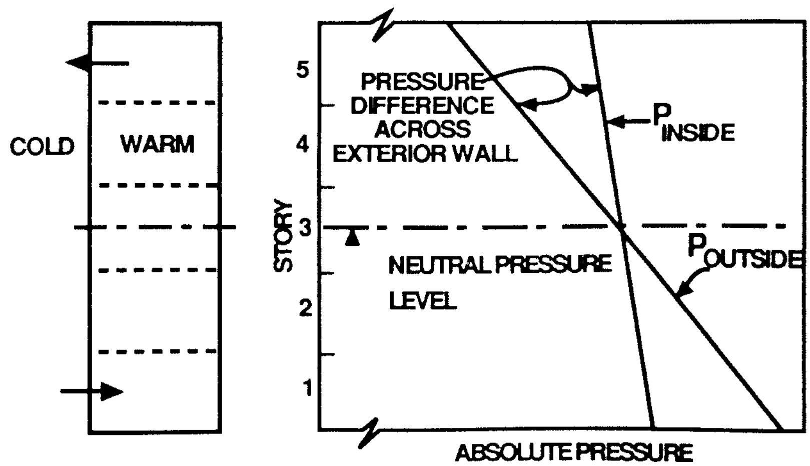


Fig. 6—Stack effect for an idealized building with no internal partition.

ASCE 7 was revised, but the changes were primarily related to seismic requirements, and wind provisions stayed essentially the same. The most extensive revisions to ASCE 7 were published in 1995 and included wind speed maps based on three second gusts, revision of terrain and height factors, gust effect factors, and pressure coefficients for components and cladding. Building classifications and importance factors were revised, as were internal pressure coefficients for enclosed, partially enclosed, and open structures. The cladding and roofing special wind pressure areas (zones) were also reduced from seven to five. ASCE 7-95 also introduced topographic factors for hills and escarpments and provided clarification of building shape factors for hipped, stepped, and saw-toothed roofs. ASCE 7 was once again revised in 1998, which included the introduction of directionality factors, and redefined terrain exposure categories. In addition, the internal pressure coefficients were revised and Exposure "D" was eliminated for buildings located in hurricane prone areas and within 1500 ft of open water. Based on research presented to the committee, Exposure "C" was stipulated as being utilized in such cases due to increased ocean roughness that simulated buildings and trees approximately 30 ft high. After 1998, ASCE 7 restricted Exposure "D" to buildings located near inland water ways and large lakes not occurring near hurricane prone coasts. ASCE 7-02 was published in 2003 and ASCE 7-05 was published in 2006.

High-Rise Building Envelopes

A particular area of concern regarding high-rise buildings is related to the special fastening, adhesion, and ballasting requirements accruing from increased wind exposure and roof uplift at specific portions of the building envelope. 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). In addition, similar concentrations of wind forces occur within the walls of building at building corners and other "hot spots" that may be deduced by experience or determined by wind tunnel testing. As previously described, the American Society of Civil Engineers [16] has developed minimum design guidelines for wind loads. In addition, Factory Mutual (FM) [17,18] 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. Cladding systems for high rise buildings will require specific analysis and design in order to achieve fastening systems and assemblies that meet or exceed the wind pressure requirements in the corners. Window or door systems located in these areas may require modifications or reinforcement of typical components in order to accommodate the design wind pressure in these localized areas. A more complete understanding of these phenomena and specific construction requirements can be achieved from a thorough study of these reference standards.

Structural Systems

Consideration of design wind pressures on the components and cladding of high rise buildings requires a fairly comprehensive evaluation and assessment of cladding connections, load paths, and continuity of restraint systems. The evaluator of these types of systems must first determine appropriate design pressures, then make certain the component is adequately secured against those forces. Finally, the forces must be properly transferred from component to component until the forces are completely absorbed into the main structural framing. Accordingly, the "load paths" from each element of the cladding system to the main wind frame resisting system must be continuous in the sense that there is no weak link that would fail prematurely. An example would be a roof membrane and roof deck designed to meet required design wind pressures, but constructed over open web bar joists that have been secured to the underlying structural framing with inadequate welds. In such a case the roof membrane and roof deck would be acceptable, but the roof assembly would fail due to the weakness in the bar joist welds and may be subject to catastrophic failure.

Special Considerations

When evaluating cladding systems for high-rise buildings consideration should be given to special conditions or factors that may adversely affect or magnify other wise normal design wind pressures imposed on a building. For example, although the code does not typically allow a designer to *reduce* wind effects due to shielding from other buildings, the effects from surrounding buildings and structures should be taken into account regarding how it may *increase* the mini-

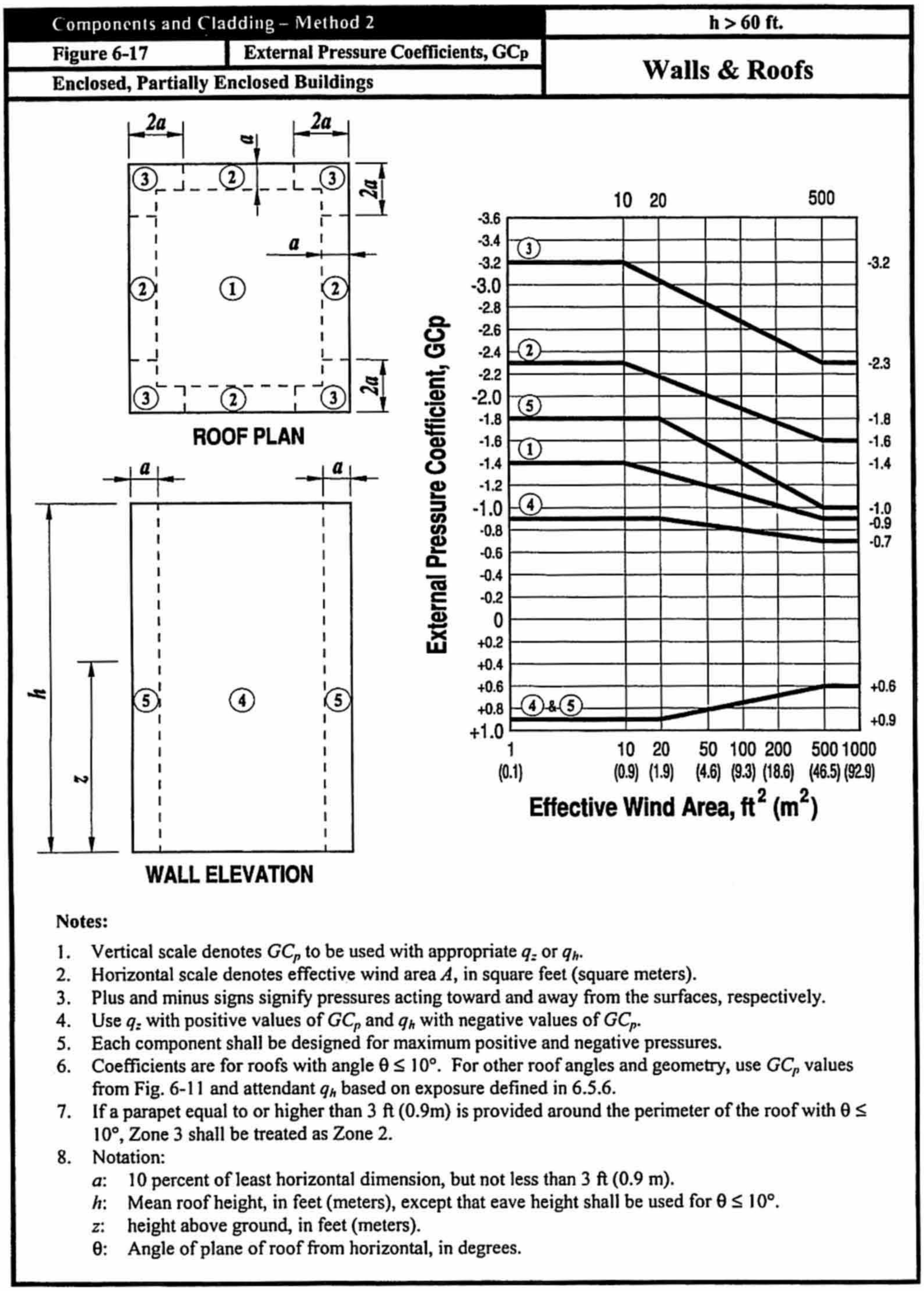


Fig. 7—External pressure coefficients GC_p, for loads on building components and cladding for buildings with mean roof height h greater than 60 ft. (Adapted from ASCE7-05.)

mum wind pressure under certain conditions. Accordingly, adjacent high rise buildings on two sides of a lower building could direct and concentrate winds into a more narrow space, resulting in a venturi effect where the wind temporarily speeds up between the buildings, increasing the wind coefficients over the lower building. Should this condition occur, the wind pressures "felt" by the lower roof would be higher than those normally predicted using the lower wind speed.

Another example involves the somewhat innovative use of topographic effects (provided in ASCE 7 since 1995) based on structures or building configurations that would not normally be considered as "hills or escarpments." For instance, lower set-back portions of a building surrounding a higher portion of the same building could make the wind flow behave similar to that flowing over a hill or escarpment with the same increase in wind speed and wind pressure for the higher building portion. Once the "minimum" design wind pressure for any building has been established, the experienced building investigator should critically evaluate the building for areas that may have such special configurations or surrounding structures.

Roof Systems

While roof areas typically make up a much smaller percentage of the building envelope for high-rise structures, recent litigation indicates that it remains an important building component. In general, common roofing principles also 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. Periodic inspection and appropriate maintenance are also critical in order to achieve maximum effectiveness from the roofing system. Of particular concern for high-rise buildings is the need for the roof membrane and flashings to resist the wind uplift pressures. Deficiencies in the design, manufacture, or installation of these components could result in delamination or ballooning of the membrane, and even catastrophic removal of the roof system in extreme cases. Once properly analyzed and designed, strict compliance with the roof manufacturer's installation requirements and Factory Mutual recommendations will usually go a long way to assure a construction assembly that will meet these criteria.

Obviously, all of the elements discussed above that make up proper roof design may have to be investigated for building envelopes where suspected roof problems exist. Accordingly, a systematic program should be developed that is designed to eliminate various components of the roof systems as being contributory to the observed problem. As more potentially contributory components are eliminated as being deficient (by observation, testing, or rational analysis), the cause of any performance problems may usually be narrowed down and ultimately discerned within a reasonable degree of certainty.

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 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) [19]. 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) [20–22] and ASTM International [23–31]. The most definitive volumes on the subject to date are probably the *Aluminum Curtain Wall Design Guide Manual*, *Aluminum Store Front and Entrance Manual*, and *Metal Curtain Wall Manual* published by AAMA [32–34]. These manuals deal with the design, fabrication, testing, and erection of all types of glass and metal curtain wall systems and storefronts.

Masonry Cladding

Due to its long-term serviceability and low maintenance, masonry is still used on buildings of considerable height. Instead of load-bearing masonry designs as utilized in the first part of the twentieth century, contemporary designs typically incorporate a true masonry curtain wall which is generally supported from 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. The principles regarding proper design and construction of a brick veneer cladding system for a multiple story building are fairly well known, specifically, (a) gravity support at each floor level, (b) lateral support from properly spaced wall ties to an appropriate substrate, (c) clear drainage cavity with properly sized and spaced weep holes, (d) effective weather resistive barrier at the face of the exterior sheathing, and (e) adequate flashings that are continuous at corners and changes in direction, as well as provisions for terminations using proper end dams. These principles, as well as many others, are elaborated on within a number of technical bulletins and construction information from the Brick Institute of America [35]. In addition to information on brick construction from professional and trade organizations, there are also several good technical references that have been authored by knowledgeable individuals [36].

Modern masonry may use brick, concrete masonry units (CMUs), 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* [37], providing information on CMU and stone, and. The "renaissance" of natural stone has been covered in a previous ASTM technical publication, STP 996, which is a collection of contemporary papers on this subject [38]. In addition, the Marble Institute of America also has well-established details and technical data for hand set and thin veneer stone [39].

Once again, all of the elements discussed above that make up proper masonry design may have to be investigated for building envelopes where suspected leakage or structural problems exist. Accordingly, a systematic program should be developed that is designed to eliminate various components of the wall system as being contributory to the observed problem. As more potentially contributory components are eliminated as being deficient (by observation, testing, or rational analysis), the cause(s) of any performance problems may usually be narrowed down and ultimately discerned within a reasonable degree of certainty.

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) [40,41], the Post-Tensioning Institute [42], and the Precast/Prestressed Concrete Institute (PCI) [43]. 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. The technical information provided in these references may be helpful in understanding the "state-of-the-art" design and construction of such systems, as well as in diagnosing the causes for any performance problem observed.

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. Another synthetic stucco system would be the various types of Direct Applied Finish Systems or Decorative Exterior Finish Systems, although these materials generally have less applicability to high-rise structures.

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 the last 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 *Portland Cement Plaster* (*Stucco*) *Manual* [44], the American Concrete Institute (ACI) *Guide to Portland Cement-Based Plaster* [45], as well as a number of specific standards and guides produced by trade organizations and ASTM [46–52].

For high-rise structures, the primary considerations for Portland cement plaster systems would, again, be the attachment or securement of the system to the substrate or structure, and accommodation of building movement such as thermal expansion and contraction, as well as lateral drift or "racking" at the upper floors of the structure causing elastic shortening and extension of the cladding. As a collection and drainage system, Portland cement plaster applications for multi-story buildings should have an effective weather resistive barrier at the exterior sheathing and floor-to-floor flashings that evacuate the water from the system. One of the most prevalent problems associated with investigating plaster cladding is the presence and propagation of cracks within the system. Before implementing a repair, it will generally be necessary to determine the cause of the cracking, which could be due shrinkage, thermal expansion and contraction,

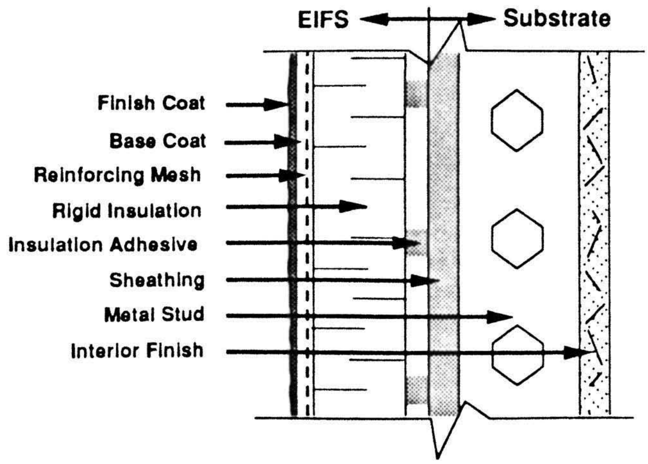


Fig. 8—Components of EIFS construction.

restraint conditions, or excessive structural movement that exceeds the anticipated movement accommodated by the system.

Exterior Insulation and Finish Systems

Synthetic stucco, or exterior insulation and finish systems (EIFS), were developed in Europe approximately 60 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, extruded expanded polystyrene, and certain types of fiberboard insulations. Over this base, one or more layers of a proprietary, acrylic-modified cement are applied 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 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 [53]. The two categories are polymer-based systems, which are typically thinner, more flexible and generally adhesively secured, as well as polymer-modified systems, which are usually thicker, more rigid, and generally mechanically fastened. In addition, the development of EIFS over the years includes water management systems, which incorporate means to collect and drain incidental water infiltration occurring within the EIFS or at penetrations. 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 only a limited number of widely accepted general industry standards regarding design, fabrication, installation, and maintenance of EIFS materials. An industry organization has adopted a few standards [54–57], and a task force of ASTM Committee E-06 has been working on this subject in a number of areas, although it may still be several years before this work is complete and a full range of appropriate standards

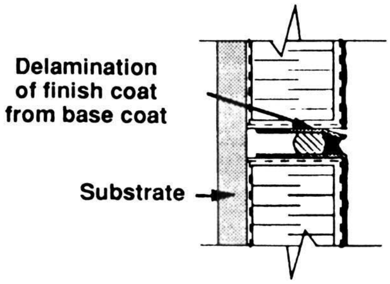


Fig. 9—EIFS cohesive failure.

are established. Some of the changes occurring in regard to EIFS over the years were related to 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 [58] (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.

Experience with EIFS in recent years has resulted in a number of developments, including material and performance standards established through the International Code Council (ICC) and ASTM [59–61]. In addition, one ASTM standard has been developed to forensically evaluate EIFS assemblies that have been in place and subjected to weather exposure for some period of time after installation [62]. One area of intense scrutiny over the years is the relationship between the EIFS assembly itself and openings and penetrations through the EIFS, such as windows and doors. Residential type windows with fastening flanges, although more prevalent in residential construction (both single-family and multi-family), have been utilized within high-rise installations with mixed results depending on the capacity and integrity of the windows provided. For more information on this topic as it relates to all cladding systems, see the section on window installation below. With respect to EIFS, all of the issues related to overall window performance, as well as proper installation with head and sill flashings, also apply to EIFS applications.

Water management EIFS applications have gained popularity over the last few years and have been mandated as the only acceptable EIFS-type installation in some jurisdictions. However, water management systems are not a panacea and simply eliminate the traditional "barrier wall" aspects of traditional EIFS installations. In addition, there are the extreme variations that are available between manufacturers, including both mechanically fastened and adhered systems, systems that require a separate weather barrier and those that utilize integral weather barriers, weather barriers that consist of sheet membranes and those that employ fluid-applied membranes, as well as those that require a separate drainage layer or composite, etc. These systems can be very intricate in their design and implementation, particularly with respect to integrating the specialized EIFS with the penetrations and openings in order to achieve an acceptably performing overall cladding system. Particular care must be taken to achieve an integrated assembly, and the different roles and responsibilities for the various interfaces must be clearly delineated within the construction documents or carefully worked out during construction in order to avoid problems. Only now are standards beginning to be developed for this type of assembly [63]. When investigating these types of systems, a comprehensive understanding of the issues involved in each of these components, as well as these roles and relationships, will be required.

One other issue related to EIFS design and construction is worth mentioning for those involved in investigation of such assemblies for high-rise buildings. Although more associated with residential type construction, the use and proper installation of kick-out flashings where a steep-sloped roof eave may terminate against a rising vertical wall has been problematic over the years. This problem occurs due to the fact that the substrate to which the EIFS assembly is applied is positioned as much as $1\frac{1}{2}$ to 2 in. behind the front plane of the EIFS finish. When metal flashing is installed along the rake of a steep sloped roof where it is adjacent to a vertical wall and the eave terminates within the "field" of the wall, the flashing installed between the substrate and the back of the EIFS foam insulation will direct water runoff into or behind the EIFS assembly if the flashing is not provide with a deflector, or "kick out" at the flashing termination occurring at the roof eave. One of the issues involved here is that neither architectural designers nor the manufacturer's details anticipated the conditions described above, particularly for multi-story construction. It was not until 1996 that these types of details began appearing in manufacturer's details and EIMA literature. By that time, millions of square meters (square feet) of EIFS cladding had been installed on thousands of projects, resulting in significant localized damage where the water intrusion was incurred. Whenever these types of systems are investigated, the structure should be checked for this type of anomaly.

Evaluation of 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 investigating problems and developing 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.

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.

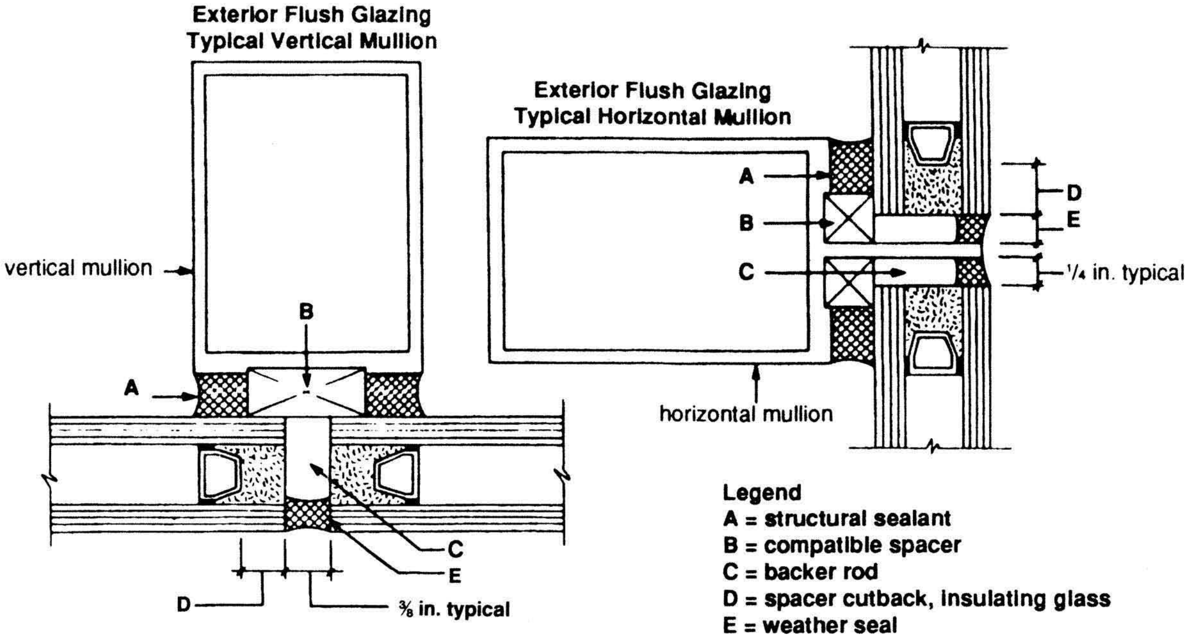


Fig. 10—Structural glazing.

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 properly spaced weep holes. Other versions of this concept are recommended for plaster and stucco constructions in which special drainage accessories 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 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 [64,65].

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 monolithic surface is attempted, with high-performance elastomeric 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

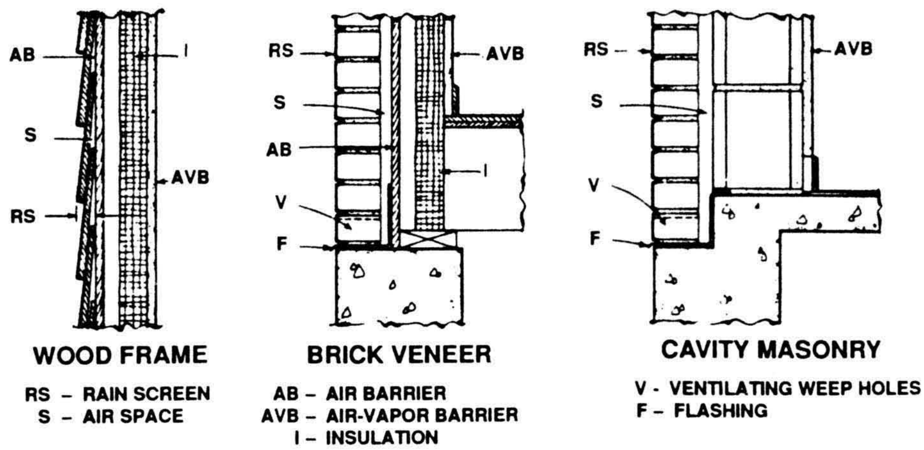


Fig. 11—Traditional walls that resist rain penetration.

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 isolated chambers constructed over an interior wall that is sealed against air leakage. The exterior wall is designed to shed water (the rain screen), but not necessarily be air or 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 that 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 [66,67] (see Fig. 14).

Climate and Weather Conditions

One of the principal 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 [68]. This subject is too broad to be fully covered in this chapter. Chapter 6 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.

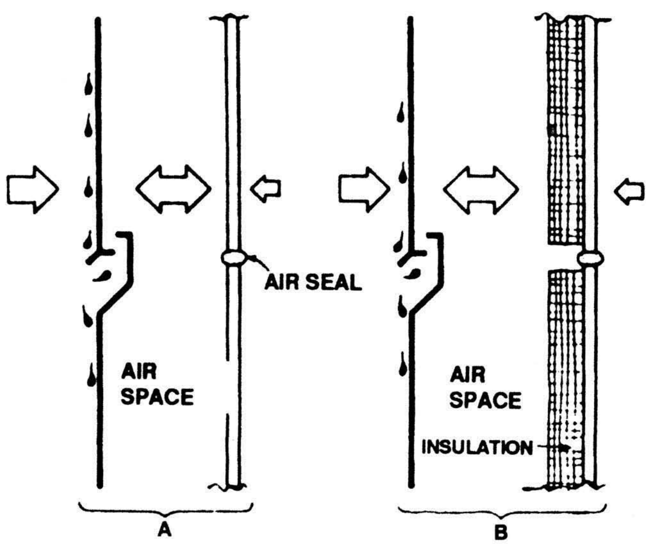


Fig. 12—Essentials of the rain screen and a pressure-equalized wall construction.

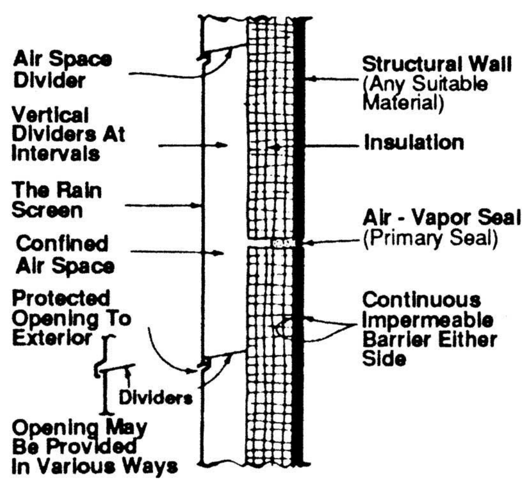


Fig. 13—Typical dividers for confined air spaces (pressure-equalized design).

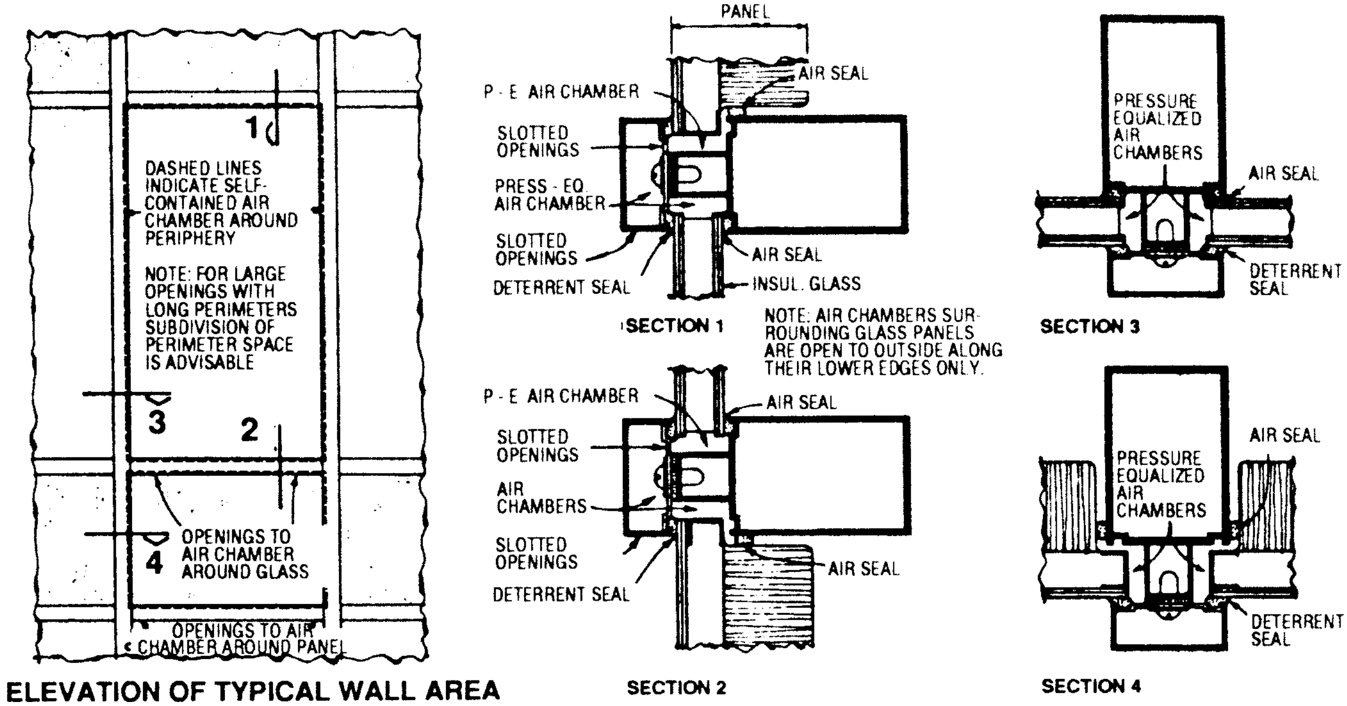


Fig. 14—Pressure-equalized standard wall system.

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* [69], 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 joints that allow for relative movement for portions of 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 and 16), as well as the characteristics described in Table 1. 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 the ASTM "Guide for Use of Joint Sealants" (C1193).

Design of Joints

The primary method of accommodating thermal expansion and contraction within materials of wall-cladding systems is to provide preplanned joints in regular patterns and appropriate 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. When the design of these components and their incorporation into the wall cladding are left up to tradesmen without proper training and construction administrators in the field under the duress of a compressed time schedule, failures of the building envelope can often result. Appropriate care

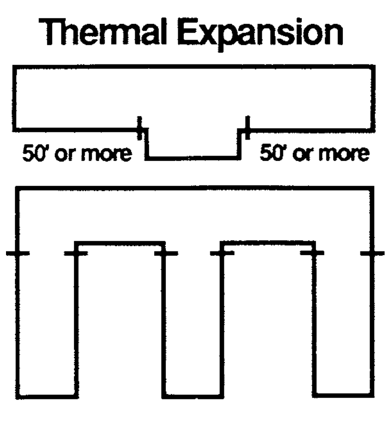


Fig. 15—Location of expansion joints.

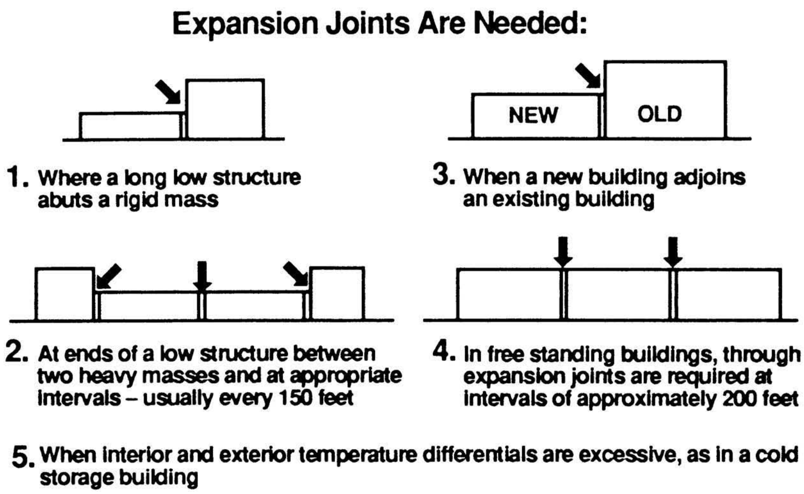


Fig. 16—Typical locations for building expansion joints.

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 [70], which should be used whenever possible.

Another consideration with regard to joint design is whether to utilize one-stage or two-stage sealant applications (Figs. 17 and 18). Although more expensive to install initially, two-stage sealant joints can provide benefits due to their 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. In both new construction and existing buildings, it is particularly helpful to pay careful attention to special conditions, such as internal pressurization, partially enclosed configurations, the effect of large volume buildings, as well as missile impact affecting cladding systems. Recent developments regarding impact resistance cladding components include test methods for large and small missile impact on windows, shutters, and other cladding materials. 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 [71], and today virtually all monumental or high-rise buildings of note are modeled using this procedure to assist in structural design for the main force resisting frame, as well as for components and cladding. 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 [72]. 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 or-

TABLE 1—Characteristics of common elastomeric sealants.

	Acrylic (Solvent Released)	Polysulfide		Polyurethane		Silicone
	(One-Part)	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, and plasticizers, accelerators, activators, and extenders	Polyurethane prepolymer, inert fillers, pigment, and plasticizers	Siloxane polymer, pigment, and selected fillers
Percent solids	60–85	90 min.	90 min.	90 min.	90 min.	94 min.
Curing process	Solvent release and very slow chemical cure	Chemical reaction with moisture in air	Chemical reaction with curing agent	Chemical reaction with moisture in air	Chemical reaction with curing agent	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	Manufacturer's approved primer required for most surfaces
Application temperature (°F)	40°–122°, must be heated	40°–122°	40°–122°	40°–122°	40°–122°	–20° –122°
Tackfree time	24–72 hr	<72 hr	Variable <24 hr	<72 hr	<24 hr	<1 hr
Hardness, Shore A, Cured 1 to 6 mos.,	40–70	25–30	20–35	20–50	0–50	25–50
Aged 5 years	20–90	25–30	20–35	30–40	30–40	No change
Toxicity	Nontoxic	Curing agent is toxic	Contains toxic ingredients	Toxic; Gloves recommended for handling	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

der 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 Chapters 3 and 17). In addition, performance of the thermal insulation may have to be restored by providing a means to dry the insulation (if possible), or else removal and replacement of the insulation material.

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 psychrometric properties of the roof and 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,

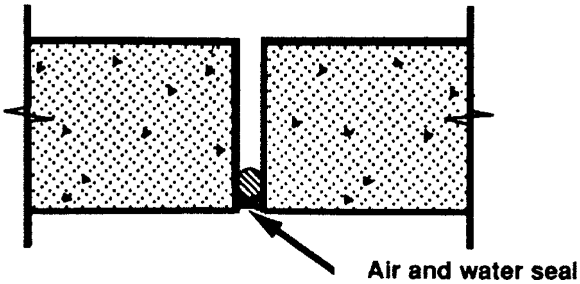


Fig. 17—Section of vertical, one-stage joint.

which are typically utilized for HVAC design. This latter data is commonly available from recognized sources such as *ASHRAE Fundamentals* [73], but to obtain the average dry bulb and wet bulb temperature it is necessary to refer to Chapter 6 of this book or to utilize other sources, such as the "Facility Design and Planning—Engineering Weather Data" (NAVFAC P-89) [74], 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 through 3 of this manual for more details on this process and the procedures involved).

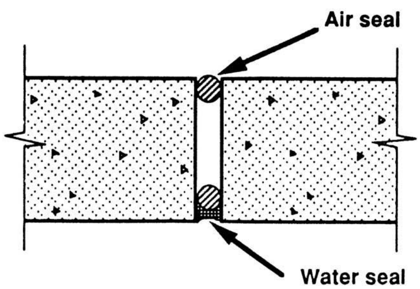


Fig. 18—Section of vertical, two-stage joint.

Proper Selection and Installation of Windows

One of the most important aspects of achieving a comprehensive and functional design regarding the exterior cladding system of any building is to properly size, select, and install the various openings within the fenestration, including windows and doors. Windows and doors must be selected with performance capabilities that "match" or exceed the estimated load requirements derived from codes and standards that attempt to predict or anticipate wind loads. As it currently stands, there are no prescriptive requirements within the codes for water infiltration performance of windows. However, the codes are typically clear with respect to requirements for structural loading, both gravity (usually self-weight) and lateral (seismic and wind). For wind load, this performance requirement is generally a design wind pressure (DWP) expressed as a resistance to wind-generated pressures, such as newtons per square meter (N/m^2) or pounds per square foot (PSF). The "proof" of structural adequacy is typically achieved by laboratory testing of representative mock-ups at both the DWP, as well as the structural test pressure, which has traditionally been 150% of the DWP. Historically within the industry, the water infiltration performance of windows was typically taken as resisting a specific amount of water spray impinging on the unit, while applying a pressure difference across the unit equivalent to some percentage of the DWP, usually 10, 15, or 20%, depending upon performance classifications. Requirements for air infiltration/exfiltration, as well as thermal and condensation performance, may also be important to the overall success of any cladding system.

Many forensic investigations and design reviews of modern buildings have established that the design process described above is often faulty in one aspect or another. Typically these deficiencies are related to a misunderstanding or a misapplication of the wind loads required, as well as a failure to secure or fasten the window or door unit into the sur-

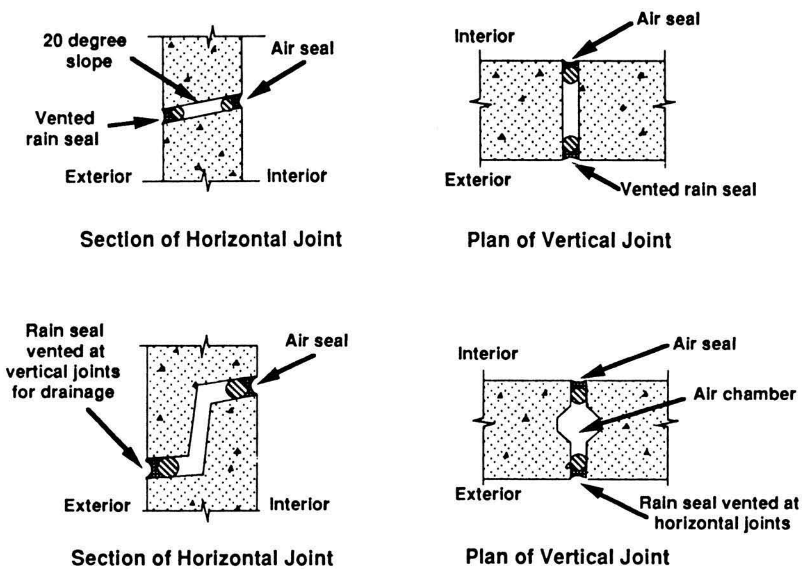


Fig. 19—Two-stage pressure equalized joints.

rounding structure and integrate it with the surrounding construction assemblies to achieve a design that adequately resists the imposed loads. In addition, the window and door openings may be specified correctly, but a lack of understanding of the intricacies of these components may result in "compliance" data that are inadequately or improperly evaluated by the designer-of-record, allowing units that actually do not comply with the specifications to be inadvertently approved for use. Finally, properly designed and fabricated window units may be improperly installed and not adequately integrated with required flashings to the surrounding cladding components.

The investigator of these types of systems for buildings that are experiencing performance problems must methodically investigate each aspect of the window selection and installation, starting with a thorough review of the design and specification, proceeding through an evaluation of the compliance submittals and available data, and including a comprehensive site investigation of the installation and workmanship utilized during construction. The "failure" of any window system may occur along any of these avenues, and only a thorough understanding of these issues will result in an appropriate diagnosis of the problems and proper development of a remediation program.

In general, the glazed openings for high-rise buildings will consist of "high end" commercially available windows or curtain all systems offered by various manufacturers, and may involve systems that are completely custom designed and fabricated for a specific project. There may also be hybrid systems, consisting of a manufacturer's standard system that has been modified to meet project requirements. Particular care should be taken to adequately evaluate the custom and hybrid system due to the unintended consequences that can occur due to the newly designed or modified system.

It has also been observed that more recent designs may rely on lower performance windows for multi-family residential and office installations. These types of units may incorporate features of residential type windows, such as nailing flanges and perimeter extrusions having minimal, or even insufficient, bond lines for sealant applications. Once again, incorporation and integration of these types of window systems into the surrounding substrates and weather resistive barrier (WRB) is crucial in order to achieve a successful installation. In 2001, ASTM promulgated a "Standard Practice for Installation of Exterior Windows, Doors and Skylights" (ASTM E2112) [75]. This rather comprehensive guide has a stated purpose of providing "technical guidance to organizations that are developing training programs for installers of fenestration units," but includes recommendations and details that can be incorporated into new construction designs, as well as designs for remedial and corrective work. In addition, while compliance with the recommendations of this practice cannot be extended before 2001, those involved in forensic investigations may evaluate an existing construction or assembly in comparison to the recommendations outlined in ASTM E2112 as a guide to where the existing installation may be exhibiting problems or deficiencies. The standard practice deals with the concepts of Barrier Systems and Membrane/Drainage Systems, and covers the proper use of a WRB, continuity of the fenestration units with the WRB, joints and anchorage, flashing requirements, and water shedding strategies. Its recommendations apply to windows, sliding glass doors, swinging patio doors, and skylights. One of the best features of the practice is the clear distinctions drawn between the various types of window products, as well as the sequencing of the installation of these products with the surrounding construction. The practice outlines different methods of flashing these assemblies and integrating them with the surrounding WRB, making a difference for windows in walls utilizing a Membrane/Drainage System and windows in walls utilizing a Surface Sealed Barrier Wall System. In addition, the ASTM guide provides different methods of flashing both windows that include a perimeter mounting flange, or nailing fin, as well as nonfinned windows. Suffice it to say that this practice essentially represents the "state-of-the-art" regarding window installations for the types of fenestration products that it applies to and can be a valuable tool in evaluating existing buildings, as well as remediating buildings with problems.

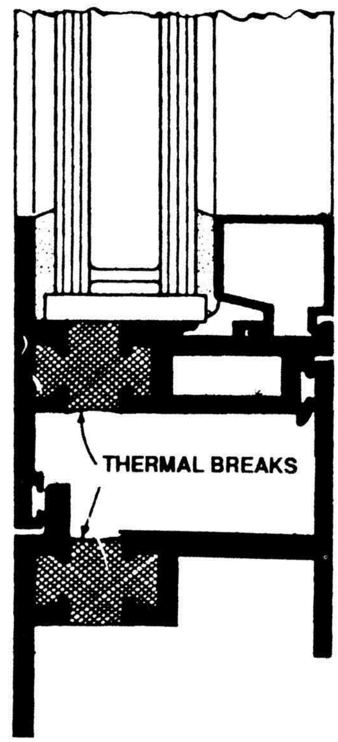


Fig. 20—Typical thermal break for curtain wall.

Air Barriers

The use of air barriers is probably one of the most misunderstood concepts in construction today. Although utilized fairly extensively in the single-family residential market [76], 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 psychrometric 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

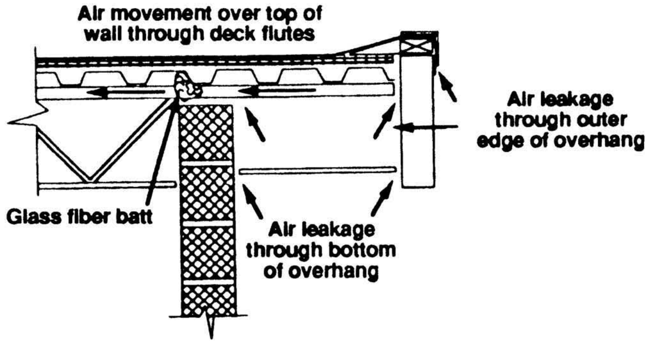


Fig. 21—Air leakage at roof overhang.

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 [77]. 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, condensation, 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 8 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. [78] 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 through 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 evaluate 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 have been generally covered in Chapters 12 through 14 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 and lateral movement. In addition, the level of required 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, metal panels, 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, and water leakage through a barrier wall design or by through-wall collection and drainage. It is particularly relevant to pay attention to the evaluation of the 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. 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 large sums of capital 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 analysis can be a useful tool in developing information to present to building managers in order for them to make a decision [79].

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 [80,81]. 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 [82] and ASTM STP 1069 [83], the Sealant and Waterproofing Institute's *Sealants: The Professional's Guide* [84], Panek and Cook's *Construction Sealants and Adhesives* [85], as well as numerous technical articles and papers [86,87].

Expansion Joints

Particular care should have been given to the design, function, and aesthetics of building expansion joints during the original construction. However, this aspect of the building envelope design may be deficient and can cause, or at least contribute to, the water infiltration occurring within the building. In most investigations, an estimate of thermal expansion and contraction should be made and an evaluation made of the existing layout and size of joints previously designed. Appropriate correction or repair of the building joints may have to be implemented within any remediation project. Consideration should also 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 effect original problems or deficiencies may have had on sealant failures in order to avoid repeating the same mistakes. 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 the top surface of a building segment does not project above grade and is "buried," horizontal waterproofing is also often required.

Design Concepts

Several key design concepts should be understood prior to proceeding with the investigation of materials for use on below grade construction. These concepts relate to (1) water environments (2) membrane placement and protection, and (3) substrate design. The water environment of the waterproofing would consist of 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 [88]. 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

Substrates to be waterproofed should consist of hard, dense materials that are not porous and are not susceptible to moisture deterioration, such as gypsum or wood-based materials. Based upon the experience of this author, concrete masonry units (CMUs) 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 horizontal waterproofing substrates 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 a waterproofing membrane which has been punctured during backfilling operations and rendered ineffective.

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 on the concrete with this type of design, the investigator must be careful to evaluate the presence of any water migrations paths into or through 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, sheet 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 [89,90] and certain ASTM special technical publications [91]. 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 because 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 [92] and the NRCA *Roofing and Waterproofing Manual* [93].

Fluid-applied waterproofing materials may be hot-applied in some applications, but cold-applied materials are more common for vertical applications because 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 [94–96]. 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, such as crystalline capillary waterproofing materials, 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 else provided in pre-formed panels with the bentonite "captured" between either two layers of filter fabric or a layer of filter fabric and a layer of high density polypropylene drainage board. Bentonite clay in a granular form has previously been packaged in degradable cellulose panels in which the "cardboard" corrugations were filled with the bentonite granules. It is possible the investigator of waterproofing problems may come across this type of application; however, marketing and use of this material is currently limited. Bentonite waterproofing is generally 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 and is one of the few materials appropriate for "blind side" waterproofing against piles and lagging; however, it is imperative that the materials be continuous, 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

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 investigation, 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 [94]. 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 implement a speedy and appropriate repair is an advantage offered by a paver/pedestal type system. For a good discussion regarding design principles for waterproofing of plaza decks with a particular focus on loose-laid membranes, the reader is referred to "Principles of Design and Installation of Building Deck Waterproofing" by Ruggiero and Rutila [95]; 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) and can have the advantage of segmenting potential leaks into discreet areas, 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.

Once again, it is incumbent upon the investigator of plaza deck waterproofing to be familiar with the design principles discussed above in order to properly evaluate and diagnose water leakage problems within these systems. Techniques utilized to investigate problems would include a review of original construction documents and waterproofing submittals, a review of the project construction history and sequencing, a review of the leak history, and any correlation to ground water and rainfall conditions, as well as a visual examination of existing topographic conditions and any exposed areas of waterproofing. Where the waterproofing applications are not generally accessible, it will be necessary to obtain at least qualitative sampling of typical installations by removing the wearing surface to gain access to the waterproofing membrane. For paver and pedestal systems, this is a relatively easy process; however, for cast-in-place concrete topping slabs and pavers or tiles set in a cementitious setting bed, this will involve judicious selective demolition at appropriate locations to gain access. Although it is highly dependent on circumstances related to each project, the experienced investigator will typically select locations that will provide information on both the most common waterproofing installation, as well as at special locations pertaining to penetrations, terminations, and flashings. Investigation techniques could also involve flood testing, other types of leak testing, as well as geotechnical investigations related to soil gradation and conditions, soil compaction, and the presence of ground water. In addition, it may be possible under certain circumstances to utilize more sophisticated investigation techniques, such infrared thermography to determine where moisture may be adversely affecting thermal differences within the structure. All of these investigation techniques may be helpful in determining whether the "failure" is systemic, requiring comprehensive remediation, or else localized in which discreet repairs may be developed and implemented.

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 plaza deck 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 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 issues to consider when remediating the roofing and waterproofing of existing high-rise buildings. 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 when determining the required renovation of high-rise buildings.

General Remedial 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 happen. In virtually all conceivable cases, it will be more cost effective to provide up-front resolutions as opposed to performing after the fact remediation of the deficiency.
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 in-

vestigated 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 previously performed 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 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 remedial work, from planning and scheduling of the remedial work to progress 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. After acceptance of the project, 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, specify that 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.

Remedial Concepts 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, endeavor to 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.

Remedial Concepts 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, infrared thermography, and nondestructive testing.
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 the existing wall systems in the past or will have on the 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 re-establish 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 Standard Guide for Use of Joint Sealants (C1193-09). 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.

Remedial Concepts Related to Waterproofing

1. Investigation of suspected waterproofing problems should, if possible, include a visual inspection of a qualitative sampling 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, determine if 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 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 de-watering practices.
5. During remediation, follow good waterproofing techniques and practices in accordance with recognized wa-

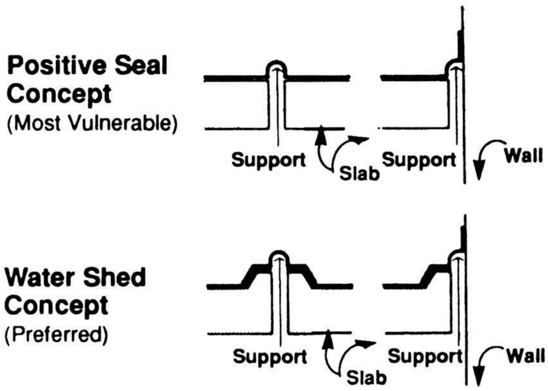


Fig. 22—Schematic expansion joint concepts at membrane level.

terproofing industry standards, as well as material manufacturer's requirements for the systems being installed. Require that membranes be 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 substrate with no intermediate layers in between. Notwithstanding recommendations from some designers related to loose-laid and segmented plaza deck waterproofing, these membranes should also be fully adhered where adequate substrate conditions 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, 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 that would impose large live loads, always check with the structural engineer-of-record 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.
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 may 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 may be required. Use proprietary drainage composites or aggregate layers with filter fabric (or both) directly on top of the membrane and protection course to achieve 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.

REFERENCES

[1] NRCA, *The NRCA Roofing and Waterproofing Manual*, 5th ed., National Roofing Contractors Association, Chicago, IL, 2001.

[2] SMACNA, *Architectural Sheet Metal Manual*, 5th ed., Sheet Metal and Air Conditioning Contractors National Association, Inc., Merrifield, VA, 1993.

[3] ASHRAE, *2005 Handbook of Fundamentals*, American Society of Heating, Refrigerating and Air Conditioning Engineers, Inc., Atlanta, GA, 2005.

[4] ASTM, Standard E2128-01a, "Standard Guide for Evaluating Water Leakage of Building Walls," *Annual Book of ASTM Standards*, ASTM International, West Conshohocken, PA, 2001.

[5] Nicastro, D. H., "A Scientific Approach to Water Infiltration," *Walls and Ceilings Magazine*, July 1991, pp. 20–36.

[6] "Water in Exterior Building Walls: Problems and Solutions," T. A. Schwartz, Ed., *ASTM STP 1107*, ASTM International, West Conshohocken, PA, 1991.

[7] "Water Leakage Through Building Facades," R. J. Kudder and J. L. Erdly, Eds., *ASTM STP 1314*, ASTM International, West Conshohocken, PA, 1998.

[8] "Water Problems in Building Exterior Walls: Evaluation, Prevention, and Repair," J. M. Boyd and M. J. Scheffler, Eds., *ASTM STP 1352*, ASTM International, West Conshohocken, PA, 1999.

[9] "Performance of Exterior Building Walls," Paul. G. Johnson, Ed., *ASTM STP 1422*, ASTM International, West Conshohocken, PA, 2003.

[10] "Building Façade Maintenance, Repair, and Inspection," J. L. Erdly and T. A. Schwartz, Eds., *ASTM STP 1444*, ASTM International, West Conshohocken, PA, 2004.

[11] Murphy, C., and Haughton, L., "ERD Manual and Protocol for Building Envelope Surveys at the Exterior Wall and Low Slope Roof," RCI Building Envelope Technology Symposium, 2003.

[12] Patton, M. Q., *Qualitative Research and Evaluation Methods*, 3rd ed., Sage Publications, California, 2002.

[13] ASHRAE Standard 62.1, "Ventilation for Acceptable Indoor Air Quality," ISSN 1041–2336, American Society of Heating, Refrigerating and Air Conditioning Engineers, Inc., Atlanta, GA, 2007.

[14] ASHRAE, "Humidity Control Design Guide for Commercial and Institutional Buildings," American Society of Heating, Refrigerating and Air Conditioning Engineers, Inc., Atlanta, GA, 2001.

[15] ANSI A58.1-1982, "Minimum Design Loads for Buildings and Other Structures," American National Standards Institute, Inc., New York, 1982.

[16] "Minimum Design Loads for Buildings and Other Structures," ASCE 7-05, American Society of Civil Engineers, New York, NY, 2005.

[17] FM, *Loss Prevention Data for Roofing Contractors*, Factory Mutual Engineering Corporation, dates vary.

[18] FM, *Approval Guide*, Factory Mutual Research Corporation, periodically updated.

[19] NAAMM Standard TM-1-68T, "Methods of Test for Metal Curtain Walls," The National Association of Architectural Metal Manufacturers, Chicago, IL, 1968.

[20] AAMA 501-05, "Methods of Test for Exterior Walls," American Architectural Manufacturers Association, Schaumburg, IL, 2005.

[21] AAMA 502-08, "Voluntary Specification for Field Testing of Newly Installed Fenestration Products," American Architectural Manufacturers Association, Schaumburg, IL, 2008.

[22] AAMA 503-03, "Voluntary Specification for Field Testing of Storefronts, Curtain Walls, and Sloped Glazing Systems," American Architectural Manufacturers Association, Schaumburg, IL, 2003.

[23] ASTM, Standard E283-04, "Standard Test Method for Determining Rate of Air Leakage Through Exterior Windows, Curtain Walls, and Doors Under Specified Pressure Differences Across the Specimen," *Annual Book of ASTM Standard*, ASTM International, West Conshohocken, PA, 2004.

[24] ASTM, Standard E330-02, "Standard Test Method for Structural Performance of Exterior Windows, Doors, Skylights and Curtain Walls by Uniform Static Air Pressure Difference," *Annual Book of ASTM Standard*, ASTM International, West Conshohocken, PA, 2002.

[25] ASTM, Standard E331-00(2009), "Standard Test Method for Water Penetration of Exterior Windows, Skylights, Doors, and Curtain Walls by Uniform Static Air Pressure Difference," *Annual Book of ASTM Standard*, ASTM International West Conshohocken, PA, 2000.

[26] ASTM, Standard E547-00(2009), "Standard Test Method for Water Penetration of Exterior Windows, Skylights, Doors, and Curtain Walls by Cyclic Static Air Pressure Difference," *Annual Book of ASTM Standard*, ASTM International, West Conshohocken, PA, 2000.

[27] ASTM, Standard E783-02, "Standard Test Method for Field Measurement of Air Leakage Through Installed Exterior Windows and Doors," *Annual Book of ASTM Standard*, ASTM International, West Conshohocken, PA, 2002.

[28] ASTM, Standard E997-01, "Standard Test Method for Structural Performance of Glass in Exterior Windows, Curtain Walls, and Doors Under the Influence of Uniform Static Loads by Destructive Methods," *Annual Book of ASTM Standard*, ASTM International, West Conshohocken, PA, 2001.

[29] ASTM, Standard E998-05, "Standard Test Method for Structural Performance of Glass in Windows, Curtain Walls, and Doors Under the Influence of Uniform Static Loads by Nondestructive Method," *Annual Book of ASTM Standard*, ASTM International, West Conshohocken, PA, 2005.

[30] ASTM, Standard E1105-00(2008), "Standard Test Method for Field Determination of Water Penetration of Installed Exterior Windows, Skylights, Doors, and Curtain Walls by Uniform or Cyclic Static Air Pressure Difference," *Annual Book of ASTM Standard*, ASTM International, West Conshohocken, PA, 2000.

[31] ASTM, Standard E1233-06, "Standard Test Method for Structural Performance of Exterior Windows, Doors, Skylights, and Curtain Walls by Cyclic Static Air Pressure Differential," *Annual Book of ASTM Standard*, ASTM International, West Conshohocken, PA, 2006.

[32] AAMA, *Aluminum Curtain Wall Design Guide Manual*, American Architectural Manufacturer's Association (formerly Architectural Aluminum Manufacturer's Association), Palatine, IL, 1979.

[33] AAMA, *Aluminum Store Front and Entrance Manual*, American Architectural Manufacturer's Association (formerly Architectural Aluminum Manufacturer's Association), Palatine, IL, 1987.

[34] AAMA, *Metal Curtain Wall Manual*, American Architectural Manufacturer's Association (formerly Architectural Aluminum Manufacturer's Association), Palatine, IL, 1989.

[35] "Technical Notes on Brick Construction," Brick Institute of America, Reston, VA., (available online; www.gobrick.com).

[36] Beall, C., *Masonry Design and Detailing for Architects, Engineers, and Contractors*, 4th ed., McGraw-Hill, New York, 1997.

[37] *Concrete Masonry Design & Construction*, National Concrete Masonry Association (available online: www.ncma.org).

[38] "New Stone Technology, Design, and Construction for Exterior Wall Systems," *ASTM STP 996*, ASTM International, West Conshohocken, PA, 1988.

[39] Marble Institute of America, Washington, DC.

[40] "Specifications for Structural Concrete," ACI 301–05, American Concrete Institute, Farmington Hills, MI, 2005.

[41] "Building Code Requirements for Structural Concrete and Commentary," ACI 318–08, American Concrete Institute, Farmington Hills, MI, 2008.

[42] *Post-Tensioning Manual*, Sixth Ed., Post-Tensioning Institute, Phoenix, AZ, 2006.

[43] *Architectural Precast Concrete*, 3rd ed., Precast/Prestressed Concrete Institute, Chicago, IL, 1999.

[44] PCA, *Portland Cement Plaster* (*Stucco*) *Manual*, 5th Ed., Portland Cement Association, Skokie, IL, 2003.

[45] ACI 524R-04, "Guide to Portland Cement-Based Plaster," ACI Committee 524, American Concrete Institute, Farmington Hills, MI, 2004.

[46] NAAMM, "Specifications for Metal Lathing and Furring," National Association of Architectural Metal Manufacturers, Chicago, IL, 1989.

[47] ASTM, Standard C1177-06, "Standard Specification for Glass Mat Gypsum Substrate for Use as Sheathing," ASTM International, West Conshohocken, PA, 2006.

[48] ASTM, Standard C847-04, "Standard Specification for Metal Lath," ASTM International, West Conshohocken, PA, 2004.

[49] ASTM, Standard C897-05, "Standard Specification for Aggregate for Job-Mixed Portland Cement-Based Plasters," ASTM International, West Conshohocken, PA, 2005.

[50] ASTM, Standard C926-06, "Standard Specification for Application of Portland Cement-Based Plaster," ASTM International, West Conshohocken, PA, 2006.

[51] ASTM, Standard C955-06, "Standard Specification for Load-Bearing (Transverse and Axial) Steel Studs, Runners (Tracks),

and Bracing or Bridging for Screw Application of Gypsum Panel Products and Metal Plaster Bases," ASTM International, West Conshohocken, PA, 2006.

[52] ASTM, Standard C1063-08, "Standard Specification for Installation of Lathing and Furring to Receive Interior and Exterior Portland Cement-Based Plaster," ASTM International, West Conshohocken, PA, 2003.

[53] Gorman, J. R., Jaffe, S., Pruter, W. F., and Rose, J. J., *Plaster and Drywall Systems Manual*, 3rd ed., McGraw-Hill Book Co., New York, 1988, pp. 70–77.

[54] "EIMA Guideline Specification for Exterior Insulation and Finish Systems, Class PB," Exterior Insulation Manufacturers Association, Clearwater, FL, June 1991, Revised August 1995.

[55] "EIMA Guideline Specification for Exterior Insulation and Finish Systems, Class PM," Exterior Insulation Manufacturers Association, Clearwater, FL, June 1991, Revised May 1995.

[56] "EIMA Guideline Specification for Expanded Polystyrene (EPS) Insulation Board," EIFS Industry Members Association, Clearwater, FL, August 1992, Revised August 1995.

[57] "EIMA Guide for Use of Sealants with Exterior Insulation and Finish Systems, Class PB," EIFS Industry Members Association, Clearwater, FL, March 1992, Revised May 1994.

[58] Kenny, R. J., and Piper, R. S., "Factors Affecting the Durability of Sealants in Contact with the Finish Coating of EIF Systems," *Science and Technology of Building Seals, Sealants, Glazing, and Waterproofing, ASTM STP 1168*, C. J. Parise Ed., ASTM International, West Conshohocken, PA, 1992, pp. 117–127.

[59] ICC-ES AC24—"Interim Criteria for Exterior Insulation and Finish Systems," 2003.

[60] ICC-ES AC212—"Acceptance Criteria for Water-Resistive Coatings Used as Water-Resistive Barriers Over Exterior Sheathing," 2005.

[61] ICC-ES AC219—"Acceptance Criteria for Exterior Insulation and Finish Systems," 2003.

[62] ASTM, Standard E2359-05, "Standard Test Method for Field Pull Testing of an In-Place Exterior Insulation and Finish System Clad Wall Assembly," *Annual Book of ASTM Standard*, ASTM International, West Conshohocken, PA, 2005.

[63] ICC-ES AC235—"Acceptance Criteria for EIFS Clad Drainage Wall Assemblies," 2008.

[64] *Time-Saver Standards for Architectural Design Data*, 6th ed., J. H. Callender Editor-in-Chief, McGraw-Hill Book Co., New York, 1982, pp. 321–332.

[65] *Ramsey/Sleeper Architectural Graphics Standards*, 7th ed., R. T. Packard, Ed., John Wiley & Sons, New York, 1981, pp. 210–212, 217, 387–392.

[66] AAMA, *Aluminum Curtain Wall Design Guide Manual*, American Architectural Manufacturers Association (formerly Architectural Aluminum Manufacturers Association), Chicago, IL, 1979.

[67] *Time-Saver Standards for Architectural Design Data*, 6th ed., J. H. Callender, Editor-in-Chief, McGraw-Hill Book Co., New York, 1982, pp. 3–100 to 3–101.

[68] *Moisture Control Handbook: New, Low-rise, Residential Construction*, ORNL/Sub/89-SD350/1, Oak Ridge National Laboratory, Oak Ridge, TN, October 1991.

[69] *ASHRAE 2005 Fundamentals*, ASHRAE, Atlanta, GA, Chaps. 23–25.

[70] ASTM, Standard C1193-05, "Standard Guide for Use of Joint Sealants," *Annual Book of ASTM Standard*, Appendix, ASTM International, West Conshohocken, PA, 2005.

[71] AAMA, "Design Windloads for Buildings and Boundary Layer Wind Tunnel Testing," American Architectural Manufacturers Association, Chicago, IL, 1985.

[72] ASCE 7–05, Commentary Section 8.2, p. 337.

[73] *ASHRAE 2005 Fundamentals*, ASHRAE, Atlanta, GA, Chap. 28.

[74] NAVFAC P-89, "Facility Design and Planning—Engineering Weather Data," National Technical Information Services, Defense Publications Branch, Springfield, VA.

[75] ASTM, Standard E2112-07, "Standard Practice for Installation of Exterior Windows, Doors and Skylights," *Annual Book of ASTM Standard*, ASTM International, West Conshohocken, PA, 2007.

[76] Conners, S., "Housewrap Acts as Wind Barrier," *RSI Magazine*, August 1990, pp. 42–45.

[77] AAMA 1503–98, "Voluntary Test Method for Thermal Transmittance and Condensation Resistance of Windows, Doors and Glazed Wall Sections," American Architectural Manufacturers Association, Chicago, 1998.

[78] ORNL/Sub/88-SA407/1, "Catalog of Thermal Bridges in Commercial and Multi-Family Residential Construction," Oak Ridge National Laboratory, Oak Ridge, TN, December 1989.

[79] ASTM, Standard E917-05, "Standard Practice for Measuring Life-Cycle Costs of Buildings and Building Systems," *Annual Book of ASTM Standard*, ASTM International, West Conshohocken, PA, 2005.

[80] ASTM, Standard C510-05, "Standard Test Method for Staining and Color Change of Single—or Multicomponent Joint Sealants," *Annual Book of ASTM Standard*, ASTM International, West Conshohocken, PA, 2005.

[81] ASTM, Standard C719-05, "Standard Test Method for Adhesion and Cohesion of Elastomeric Joint Sealants Under Cyclic Movement (Hockman Cycle)," *Annual Book of ASTM Standard*, ASTM International, West Conshohocken, PA, 2005.

[82] "Building Seals and Sealants," J. Panek, Ed., *ASTM STP 606*, ASTM International, West Conshohocken, PA, 1976.

[83] "Building Sealants: Materials, Properties, and Performance," T. F. O'Conner, Ed., *ASTM STP 1069*, ASTM International, West Conshohocken, PA, 1990.

[84] *SEALANTS: The Professional's Guide*, Sealant and Waterproofing Institute, Glenview, IL, 1984.

[85] Panek, J. R., and Cook, J. P., *Construction Sealants and Adhesives*, 2nd ed., John Wiley & Sons, New York, 1984.

[86] Francis, G. V., "A Practical Approach to Sealant and Joint Design," *Exteriors Magazine*, Spring 1987, pp. 64–71.

[87] Nicastro, D. H., "Parameters for Comparing High-Performance Sealants," *The Construction Specifier*, April 1989, pp. 122–127.

[88] ASTM, Standard D1079-08a, "Definitions of Terms Relating to Roofing, Waterproofing, and Bituminous Materials," *Annual Book of ASTM Standard*, ASTM International, West Conshohocken, PA, 2005.

[89] ASTM, Standard C898-01, "Standard Guide for Use of High Solids Content, Cold Liquid-Applied Elastomeric Waterproofing Membrane With Separate Wearing Course," *Annual Book of ASTM Standard*, ASTM International, West Conshohocken, PA, 2001.

[90] ASTM, Standard C1127-01, "Standard Guide for Use of High Solids Content, Cold Liquid-Applied Elastomeric Waterproofing Membrane With an Integral Wearing Surface," *Annual Book of ASTM Standard*, ASTM International, West Conshohocken, PA, 2001.

[91] "Building Deck Waterproofing," *ASTM STP 1084*, ASTM International, West Conshohocken, PA, 1990.

[92] ASTM, Standard C981-05, "Standard Guide for Design of Built-Up Bituminous Membrane Waterproofing Systems for Building Decks," ASTM International, West Conshohocken, PA, 2005.

[93] NRCA, *The NRCA Waterproofing and Dampproofing Manual*,

5th ed., National Roofing Contractors Association, Chicago, IL, 2001.

[94] Henshell, J., and Buccellato, P., "Precast Concrete Pavers for Parking Decks," *Building Deck Waterproofing, ASTM STP 1084*, L. E. Gish, Ed., ASTM International, West Conshohocken, PA, 1989, pp. 83–94.

[95] Ruggiero, S. S., and Rutila, D. A., "Principles of Design and Installation of Building Deck Waterproofing," *Building Deck Waterproofing, ASTM STP 1084*, L. E. Gish Ed., ASTM International, West Conshohocken, PA, 1990, pp. 5–28.

[96] *Below Grade Waterproofing Manual*, Sealant, Waterproofing & Restoration Institute, Kansas City, MO, 1999.

21

Manufactured Housing

Francis Conlin[1]

Preface

IN THE PREPARATION OF THIS CHAPTER, THE CON-tents of the first edition were drawn upon. The author acknowledges the author of the first edition, Michael F. Werner [1]. The new current edition will review and update the topics as addressed by the previous author, introduce new technology that has been developed, and include up-to-date references.

Moisture Dynamics in Manufactured Housing

(See Ref. [2].) According to the 2005 American Housing Survey there are nearly nine million occupied manufactured homes in the United States [3], with half of these homes built prior to 1988. Manufactured housing is the largest subset of homes that are built in factories and is distinguished by a Federal law that provides these homes with an exemption from compliance with state building codes. In place of this preemption, however, is a requirement that manufactured housing comply with national standards set forth by the Manufactured Housing Division of the U.S. Department of Housing and Urban Development (the Manufactured Housing and Construction Safety Standards MHCSS)—often referred to as the HUD Code. This law provides a means for manufacturers to produce homes for a number of states without having to satisfy multiple, and sometime conflicting, state building codes and is a significant factor in preserving the affordability of these homes. Over 25 % of the 2005 manufactured home stock was built prior to 1976, when these national construction standards were first introduced, and an additional 34 % were built prior to the first major update of these standards in 1994. Amendments and revisions to the HUD Code are considered through petitions made to the Secretary of HUD through specific rulemaking procedures [4]. In 2000 the MHCSS Act was amended to add a standards and regulatory "Consensus Committee" in an effort to effect more timely revisions of the HUD Code [5].

The goal of moisture management in housing is to maintain an acceptable balance between moisture addition, storage capacity, and moisture removal that preserves the durability of the home. The HUD Code contains several specific requirements regarding moisture management; however, since moisture in buildings is ubiquitous, provisions that affect the dynamics of moisture are found throughout the Code. Major provisions of the HUD Code that impact moisture management are outlined in another section of this chapter and referred to as warranted.

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 on-site. Thus, moisture control issues for manufactured housing tend to be much the same as for site-built, single-family dwellings. There are, however, some differences, including construction methods, which need to be considered.

Factory Assembly and Construction Aspects of Manufactured Homes

Both the HUD Code and circumstances generated from being assembled in a factory create unique differences between manufactured homes and site-assembled structures. Although the physics of moisture dynamics are obviously the same, methods of moisture transport and sites that are prone to moisture accumulation are sometimes different. A comparison of site-built and factory-built housing codes suggests that the codes are in fact quite similar. It is not accurate to assume that site-built codes are more progressive. For example, the HUD Code allowed single-section homes to use unvented attic systems years before this became an advanced technique for site-built homes; and fresh air ventilation requirements that are standard in manufactured homes are just beginning to surface in site-built homes. Significant changes in manufactured housing over the past 20 years have resulted in structures that are hardly recognizable as traditional manufactured homes. Arguably, the most significant change has been the rise of the multi-section home. In the 1980s multi-sectional manufactured homes were little more than two single-section homes joined at the midline and captured only 20 % of the market; now, however, multi-section homes are 80 % of the market and have evolved to look sometimes indistinguishable from a site-built home.

The current manufactured home product varies considerably depending upon the region of the country it is made and upon the local market. In parts of the country where basements are demanded, manufactured homes are built over basements; where site-applied exterior stucco is common, it is found also on manufactured homes. The new manufactured home product can satisfy whatever housing opportunity is unfilled by site-assembled homes; where the median price of housing is high, manufactured homes rise to meet the challenge and two-story, highly appointed manufactured homes have evolved. Older manufactured homes are also addressed in this chapter; these homes, by their abil-

[1] *Senior Engineer, ComfortWorks Engineering, consultant to manufacturers and agencies regarding building performance issues in factory-built housing including moisture management, Durham, NC.*

ity to endure long years of sometimes minimal maintenance, have both proven their worth as a housing resource and show clearly how much progress has been made in this industry in a relatively short period of time. Older homes are still in service that were made when the industry was building "transportable" homes. Market forces behind the make up of new manufactured homes are: affordability, local demand, the HUD Code, site installation, and historic conventions.

Unique Aspects of Manufactured Housing that Affect Moisture Management

There are several unique aspects to manufactured housing that can affect moisture management strategies. In manufactured housing, building cavities such as the attic and below-floor assemblies are enclosed. Indeed, access to these cavities would be of limited use because space is generally not available for movement. Often these cavities are never again viewed once they leave the manufacturing plant [6]. If excess moisture gains access to these cavities, they can act as hidden pathways for moisture transport both concentrating moisture within a small volume and directing moisture towards surfaces where it may accumulate. Other unique aspects of manufactured housing include specifics of the HVAC and building ventilation systems.

Manufactured Housing Floors

Manufactured homes typically make use of a conditioned floor cavity [7]; this is because the floor insulation is located adjacent to the exterior plastic floor liner (referred to by the industry as the "bottom board or belly"). As typically installed, the liner establishes an air barrier and vapor retarder surface directly below the floor insulation. Building science supports such placement of the air barrier, vapor retarder, and thermal barriers immediately adjacent to one another for optimal performance [8]. The HUD Code, by its emphasis on sealing this bottom liner rather than the floor plane, promotes the bottom board as the primary air pressure boundary. Historic field-testing of the plastic liner typically used for the bottom board material has demonstrated mixed success in its effectiveness as a durable air barrier. Air barrier effectiveness may be affected by lack of complete sealing of the bottom board in the field or sometimes due to incomplete sealing where the liner is connected at the perimeter joists.

When holes are present in the bottom liner, moist crawl space air can bypass the vapor retarder and insulation layers and come into contact with floor joists, floor sheathing, and the HVAC ducts. Excess moisture in the floor cavity can result in warping of the lumber and floor sheathing and condensation—particularly on cold metal supply air ducts. For example, in hot, humid climates where overhead ducts are becoming more popular, floor moisture problems are sometimes observed where cold air is directed on top of a vapor retarding floor covering [9]. Elsewhere, manufactured homes have heating and cooling ducts located in the floor cavity above the insulation layer and bottom board. This arrangement both promotes a conditioned floor cavity and inadvertently causes the floor cavity to operate at a slight positive pressure due to inevitable leaks in the air distribution ducts (provided the home has a moderately well-sealed bottom liner). Small duct leaks in floor cavities may be beneficial with regards to moisture management. Humid air present in the floor cavity is diluted and entry of outside air is repelled by conditioned air leaking into the floor cavity from the ducts. As duct leakage is reduced to improve energy saving goals, bottom board sealing should likewise improve to prevent an increase in floor moisture problems.

No provision is made in the HUD standards for water vapor control through the floor. Although older homes used an asphalt-treated paper for the "bottom board," since the 1980s, the typical bottom board has consisted of a woven or single-ply polyethylene liner. This liner is located between the metal chassis and the wood frame and is often stapled to the perimeter rim joists to form the enclosure for the bottom side of the floor cavity. The present standard requires only that the material be evaluated for puncture resistance; thus measured permeance of materials used as bottom floor closures is not typically identified [10]. Permeance of polyethylene is typically very low; however, the permeance may be affected when a woven product is used. Vapor permeance of typical oriented strand board (OSB) sheathing products often used for interior flooring is also relatively low; and when used under vinyl or tile flooring covering the combined permeance is even lower, potentially creating a vapor retarder above and below sections of the floor cavity.

Plumbing is also typically located in the floor cavity. Leaks in the plumbing and spills from inside the home often find their way into the floor cavity. Bottom liner materials have no provision to allow accumulated water to drain away and may hold many gallons of water. Any such water that accumulates in a bottom board floor cavity may be present for long periods of time before it is able to dry out. Inspection and repair of any spill or plumbing leak should always include inspection of the bottom plastic for accumulated water.

Manufactured Housing Walls

A primary function of a wall is to prevent the passage of water into the wall cavity and home. This is largely achieved by preventing bulk and capillary water entry into the wall at the cladding level and then the sheathing level. Chief among water entry prevention strategies are window and door flashings and the sealing of penetrations. For example, manufactured homes have been relatively successful using "self-flashing" windows. When weather-resistive exterior sheathings such as exterior grade OSB is used, windows may be sealed directly to the OSB without secondary drainage protection such as pan flashings. With other sheathing materials, such as when blackboard is used, a secondary drainage plane consisting of asphalt-impregnated paper is typically placed behind the vertical window flange and extends below the bottom of the wall to reject any water to the outside. Capillary moisture is typically less of a problem in manufactured homes because the homes rarely are close to the ground. However, interior spills, adjacent decks and porches, and excessive berming around the home may cause water to contact porous wall materials.

Exterior wall coverings for manufactured homes traditionally were made with corrugated metal siding, which, when assembled, provide a water-shedding siding with a ventilated cavity. These metal-sided walls still exist in single-section homes. Currently walls typically include some type of exterior sheathing covered by vinyl siding. Ventilation, when incorporated in a sheathed wall, is provided by drilling various size holes into the sheathing material. With the advent of wider homes, maximizing the living space has become less critical such that full 2 by 6-in. exterior walls are not uncommon. Penetrations in any exterior wall cladding should be sealed to prevent water entry, particularly when the penetration extends into the wall cavity such as around electrical outlets. Manufactured homes using ventilated metal siding (single-section homes) typically have no exterior sheathing behind the metal—in these homes it is critical that any holes in the metal siding be sealed to prevent water entry. When any type of ventilated wall system is used, it is important also to air-seal the interior wall surfaces.

When the HUD Code was developed, central air conditioning was far less common as it is today and, like all housing construction codes at the time, requirements for moisture vapor management for walls focused more on wintertime, cold climate issues. Now that central air conditioning has become the norm, it is important that wall construction designs apply additional strategies to address the possibility of moisture vapor movement into the wall cavity from the outside air, both because the interior wall surface is increasingly at risk of condensation formation as space cooling temperatures are lowered, and because negative pressure imbalances may draw excessive amounts of humid air into the wall cavity. There are two basic strategies to prevent excess moisture vapor accumulation: (1) prevent moisture entry, and (2) promote moisture removal.

Moisture vapor can enter a wall cavity by air movement and by diffusion. Experts estimate that the amount of moisture vapor transported by air leakage can be up to 200 times higher than the amount transported by vapor diffusion and can account for more than 98 % of all water vapor movement through a building enclosure [11]. Thus, moisture control via air movement is key—and this can be addressed in a number of ways including: infiltration control at the exterior sheathing, preventing negative pressures by improving duct and bottom liner leakage, improving return air flow pathways, proper sizing of cooling equipment, and taking measures to improve comfort that result in less inclination to overuse air conditioning and overcool the home such as: minimizing moisture under the home and reducing infiltration throughout the home by improving the effectiveness of the marriage gasket seal.

When air transported moisture is controlled, water vapor entry by diffusion may remain a concern. Like other types of housing codes, manufactured home regulations have until recently encouraged the use of an interior-side vapor retarder even in hot, humid climates. Although it is recognized that an interior-side vapor retarder does not remove moisture from a wall cavity as well as a more permeable wall cover, moisture is still removed towards the inside and towards the outside depending on the specific conditions. Several home manufacturers report that measures taken to control moisture entry have all but eliminated wall moisture problems.

The HUD Code offers four specific options to choose from to build exterior walls. These options include for both ventilated and nonventilated wall cavities and vapor retarder locations on either side of the wall insulation. These options are listed in the standards and regulations section of this chapter. The newest HUD Code wall construction option was only made available in May 2006 and allows a wall to be constructed with the dominant vapor retarder on the exterior provided that a 5-perm or greater interior wall covering is used on the interior [12]. Several manufacturers are reportedly beginning to explore this option to provide an additional moisture management approach for humid climates [13]. The ventilated metal wall used by some single-section homes relies on passive ventilation of the wall cavity to the outside to remove any moisture build-up in the wall cavity. This option does not specify any vapor retarder conditions.

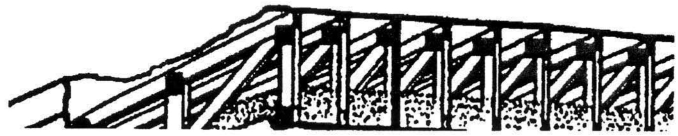


Fig. 1—Typical roof cavity.

During conditions where the water vapor pressure outside is high, there is a concern that achieving a moisture balance in a wall cavity is more difficult. Internal-side vapor retarders in hot, humid climates will limit drying towards the interior of the home. However, some drying does occur and other measures to limit moisture entry into the wall cavity help to maintain this balance. Virtually all multi-section manufactured home walls since 1976 have been built with interior-side vapor retarders and since the mid 80s a majority have been built with vinyl wallboard; and since relatively few homes have exterior wall moisture problems [14], it can be concluded that walls exhibiting moisture problems in humid climates have other contributing factors such as excessive negative pressures. Indeed, although building science discourages use of an interior vapor retarder in hot humid climates, in a study by Florida Solar Energy Center of 25 manufactured homes with moisture problems, no homes were found that cited only the vapor retarder location as the cause of the moisture problem [15]. Interior side vapor retarders are recommended in colder climates to help slow moisture diffusion into the walls from inside the home.

Manufactured Housing Attics

Attic designs for manufactured homes are somewhat limited by over-the-road transportation height restrictions. Double-section homes typically feature 32/12 and 4/12 roof profiles; higher roof profiles are available by incorporating hinged roof sections that are raised at the site. Higher roof profiles are sought primarily to achieve aesthetic effects and to meet zoning requirements. Attic cavities in older manufactured homes are relatively small [16]. Figure 1 is a view showing roof covering, trusses, and insulation at the peak of the attic of a typical double-section home. Figures 2 and 3 depict typical single-section roof profiles; typical double-section roof profiles are depicted in Fig. 4. Attics tend to have ample room for insulation at the midpoint, but are more constrained

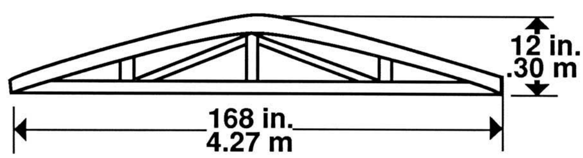


Fig. 2—Single-section with metal roof.

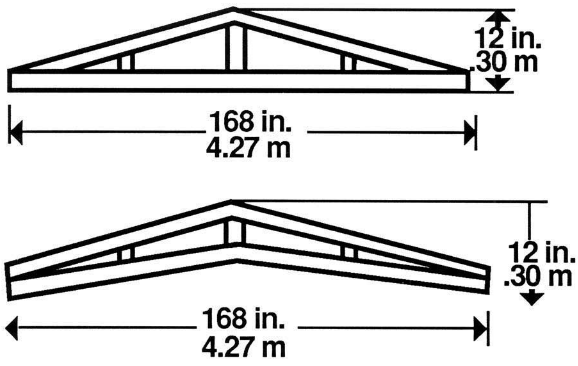


Fig. 3—Single-section with shingle roof.

near the exterior walls. In this case, the balance of insulation is redistributed towards the center of the home to maintain air space for ventilation near the soffit vents.

Manufactured home roof systems designed for cooler regions as defined by HUD Code Thermal Zones 2 and 3 are required to have a vapor retarder of not greater than 1 perm on the living space side of the roof cavity; the vapor retarder may be omitted in homes designed for warmer regions as defined by Thermal Zone 1 [17]. The popularity of factory-applied textured surface finishes has made spray application of vapor retardant undercoatings on the ceiling economical. Attics are almost all built using $1\frac{1}{2}$ to 2-in. engineered trusses adhered to the gypsum ceiling material. This provides for a monolithic gypsum ceiling and truss structure, which is then finished with interior-side vapor retarder and finish coatings prior to being placed on top the home.

Attic cavity moisture incorporates passive or active ventilation, or in some cases is unventilated. Passive attic ventilation must have a minimum free ventilation area of not less than 1/300 of the attic area with at least half of the vents provided near the peak. To provide for ventilation, a minimum height of 1 in. is required between the top of the insulation and the bottom of the roof sheathing or roof covering. A mechanical attic ventilation system that provides a minimum air change rate of 0.02 (cfm) per sq ft of attic floor area may be installed instead of providing passive ventilation.

Several producers of home heating equipment offer ventilation systems that are designed to introduce fresh air into

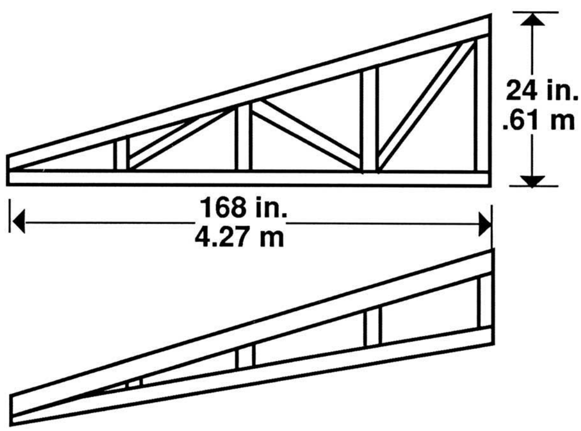


Fig. 4—Double section (showing only one half).

the attic to provide attic ventilation. This, in combination with eave, ridge, and gable vents, accomplishes air changes in the attic that, during the heating season, serves to move moist attic air out of the attic. These systems have been proven successful in preventing condensation from forming in attics [18]. The HUD Code requires ceiling vapor barriers [19] in Thermal Zones 2 and 3 whether or not the attics are ventilated. Single-section manufactured homes constructed with metal roofs and having no sheathing or underlayment are not required to be provided with attic or roof cavity ventilation provided that the air leakage paths from the living space to the roof cavity are sealed [20].

All roofs should be periodically inspected for flashing and sealant performance around penetrations through the shingles. Regular maintenance should include inspection for damage to the shingles. Many manufactured homes have shipping plastic tacked onto the roof to prevent water entry during transport. These need to be sealed during installation after the plastic is removed.

Duct Systems in Manufactured Housing

Virtually all manufactured homes in the nation use forced air systems for heating and cooling distribution. These systems are arranged in a wide array of designs from simple, single trunk systems to looped trunks with perimeter supplies. Duct materials are made of aluminum, fiberboard, and flexible duct. Ducts are most commonly located in the floor cavity but may also be located in the attic. Return ductwork in the home is rare, although some manufacturers continue to use the conditioned floor cavity as a return plenum. Door undercuts are specified to provide for return air or, where this is not sufficient, return air transfer grilles through the wall are dictated [21]. Connections between trunk ducts in each half of a multi-section home are made by means of "crossover" ducts. These connections can be made with a single round flexible duct or using multiple crossovers sometimes connecting through chases cut through the rim joists.

Duct leakage is a known contributor to moisture problems both from the diminished ability to properly heat and cool the home and also as a result of negative home pressures created by lost supply air duct leakage that draws in humid outdoor and crawl space air into building cavities [22].

The HUD Code requires only that ducts be "substantially airtight" and defines this as a duct system that can maintain at least 80 % of the static pressure developed in the furnace housing [23]. The specified HUD airtightness test also allows measuring equipment with a resolution of 1/10-in. of water column, which is not precise by today's standards. Passing this test does not ensure that duct leakage is within current good building science practice. Simple duct systems, with their fewer connections, seem to perform best; duct systems with many perimeter connections, branch ducts, and crossovers provide many more potential openings in the duct system and are sometimes found to have more leakage. Although floor ducts located above the bottom board liner are considered to be within the conditioned space, some portion of the total duct leakage may make its way to the outside through leaks in the bottom board and other pathways [24]. When the bottom plastic is breached by ruptures, it cannot provide a pressure boundary, and all duct leakage goes outside rather than being contained in the floor cavity and redirected towards the interior. In spite of opinions to the contrary, testing has not demonstrated that ducts become more leaky during transportation; it is rather during construction and home installation that duct tightness is often severely affected.

More recently and particularly in response to the interest in building homes that qualify as an "Energy Star Home," a significant number of plants have drastically reduced duct leakage. Where 10 to 15 % duct leakage was common only a few years ago, now it is common to find manufactured homes with 3 % or less duct leakage. Many plants now routinely conduct actual duct leakage tests in addition to the HUD required pressure test [25].

Fresh Air Ventilation in Manufactured Housing

Following changes in the HUD Code in 1994, each manufactured home is equipped with a fresh air ventilation system that is based on the ASHRAE recommended 0.35 air changes per hour [26,27]. The ventilation may be provided by either a mechanical or a combination mechanical and passive system that meets the HUD prescription—passive only systems are no longer allowed. The ventilation system is further prohibited from creating a positive pressure if the home is located in Thermal Zones 2 and 3 or a negative pressure if located in Thermal Zone 1. Combination mechanical and passive systems must demonstrate through testing that sufficient make-up air is available to effectively prevent unbalanced pressures from the ventilation system. In most homes field testing results indicate that any pressure difference caused by the ventilation system is negligible. Some fresh air ventilation systems are incorporated into the furnace blower, these inlets are required to be moved when any cooling coils are added. If the inlets are not moved, the outside air may be directed into the cooled side of the air handler risking condensation in the blower cabinet and ducts from unconditioned air.

Several ventilation systems are incorporated with the air distribution blower. However, during days when the heating or cooling system runs long hours, excessive outdoor air intake may increase the humidity in the home. Particularly in humid climates, care should be taken to provide for the minimum ventilation rate but no more. Some sophisticated controls are available that provide a prescribed runtime for ventilation regardless of demand for heating or cooling [28].

Infiltration Control

Because manufactured homes are constructed under controlled conditions and rely on large expanses of sheathing materials, a properly installed manufactured home typically has low levels of infiltration, particularly for single-section homes. The HUD Code specifies that the envelope be constructed to "limit air infiltration to reduce heat loss/heat gain due to infiltration without impinging on health and comfort [29]." Some design details, however, are prone to shell leakage. The junction between a cathedral ceiling and the top plate of the exterior wall are occasionally problematic as are air by-passes created by unintended gaps in the marriage line and through the bottom board material in multi-section homes. Manufactured homes can achieve low levels of infiltration; however, proper installation steps must be taken during set-up to prevent significant shell leakage. Infiltration into cavities can still be a moisture concern in homes with good overall infiltration control; even small overall infiltration levels can cause damage if negative pressures bring humid air into an isolated area such as behind crown moldings.

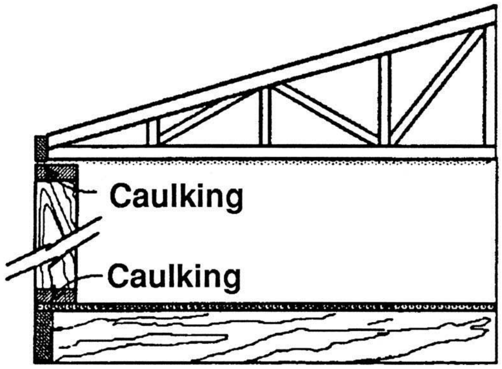


Fig. 5—Construction joints.

In-Plant Construction Environment

Manufactured homes leave the plant with over 95 % of the construction work complete. Home assembly in the plant provides the optimal construction working environment and the potential to bring significant quality control to the manufactured housing product. Homes are built without the risk of rain, excessive cold, mud, or other elements that often result in moisture damage. Factory assembly of the open roof/ceiling structure [30] enables close attention to the quality of the application of vapor retardant and ceiling insulation. Tightness of construction joints, attributable to the accuracy of production cut framing and the factory-controlled application of caulking and sealing, can consistently be attained in manufactured housing. Factories use moveable scaffolding to provide critical access to accomplish air sealing and other tasks without strain or safety risks. Both plant supervisors and third party quality assurance staff are present during construction to ensure methods and materials meet the requirements of the HUD Code [31]. Wall, floor, ceiling, and window assemblies are connected using methods to reduce air infiltration at the intersections including the application of caulking, gaskets or putty tape, and fillers as is illustrated in Figs. 5–7. Factory construction, however, is not without challenges. Turnover rates often require constant training and a culture of getting

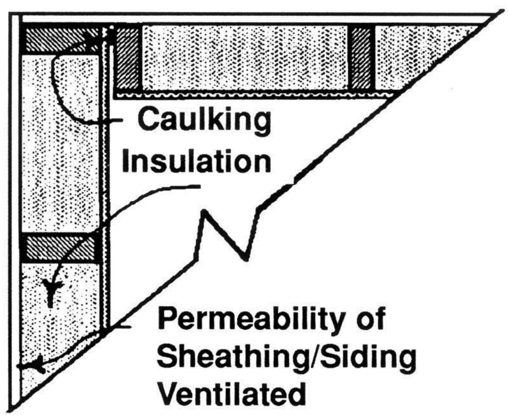


Fig. 6—Typical wall construction.

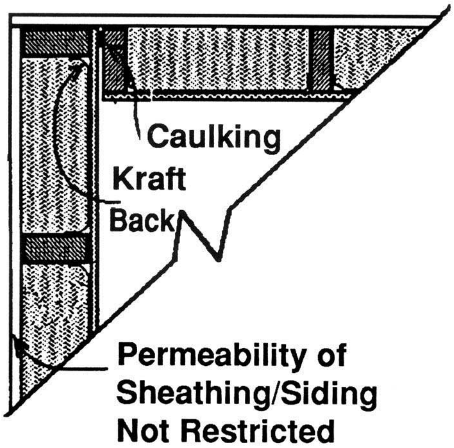


Fig. 7—Wall Kraft back insulation vapor retardant.

tasks done quickly can be at odds with goals for high-quality construction.

Installation On Site

Installation is one of the most important moisture management events for a manufactured home. Installation specifications vary among HUD, manufacturers, and the state or local building officials having jurisdiction over installation. HUD has issued installation instruction guidelines in a "consumer manual" since 1977, also the ANSI [32] Standard A225 set specifications for installation. More recently, model installation standards have been drafted and accepted by HUD [33]. Typically each state will elect to adopt or reject portions of the model standard for their state standard. Often the manufacturers' installation manual will also dictate certain specifications of the installation that take precedence over a model or state standard.

Set Up

Manufactured homes are moved to a building site where the home is placed on the foundation, the utility connections are made, and all finish details are completed. Several key aspects of the site installation affect successful moisture management. Effective site drainage is crucial. Significant damage may result from grading that permits standing water to accumulate beneath the home. Manufacturer's installation instructions most often recommend but do not require the application of a polyethylene film ground vapor barrier. The application of the ground vapor barrier in combination with effective site drainage will create a barrier system that minimizes moisture entry and accumulation in the crawl space.

Another important installation aspect is ventilation of the crawl space. Crawl space ventilation has been traditionally relied upon to remove excess moisture that may develop under the home. Maintaining dry air under the home will benefit overall moisture control as damp crawl space air is in position to infiltrate into the home [34]. Crawl space ventilation is typically accomplished by using prefabricated vinyl skirting with engineered perforations or with traditional foundation vents for brick skirting (see Fig. 8). Crawl space ventilation is usually obtained with the application of foundation wall vents with a net free ventilation area equal to 1/150 of the crawl space area, but codes may allow different

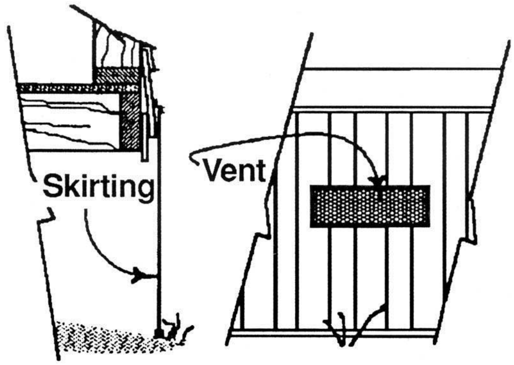


Fig. 8—Crawl space ventilation.

ventilation area when coupled with a ground vapor barrier. Vents should be four or more in number and installed at or near each corner to maximize the effectiveness of cross ventilation [35]. Sealed crawl spaces are coming in vogue in site-built homes and may indeed provide more consistently dry crawl space environments in humid climates where ventilation offers less drying benefit during humid weather.

The installer is typically responsible to assure that the crossover duct is properly and durably installed and adequately sealed and supported. The installer has the last view into the attic and should replace or redistribute any insulation that may have shifted as a result of transportation. The installer also must ensure that the marriage gasket is present, properly located, and creates a continuous perimeter air sealed joint. The marriage gasket is typically a nonporous 2 to 3-in. continuous flexible rubber or foam strip intended to seal the interior of the home from the exterior. This key installation requirement was traditionally put in place by the installer using materials shipped with the home; however, it is sometimes improperly or incompletely made in the field. Tests of homes set with and without the marriage gasket have demonstrated a 75 % reduction in infiltration by proper placement of a nonporous marriage gasket [36]. Currently, many manufacturers are installing marriage gaskets to one side of the home at the factory; regardless, installers must ensure such gaskets remain in position during installation. Some installers are misinformed that they can seal the marriage line with expandable foam from the roof after the home is pulled together; this technique often provides little if any benefit. Failure to effectively seal the marriage wall coupled with house depressurization resulting from supply duct leakage may lead to moisture problems in marriage walls.

The installer is also responsible to make durable repairs to the bottom board liner. On occasion the installer also encounters structural members that inadvertently interfere with the crossover duct location. The installer must, in such a situation, get specific authorization from the manufacturer to move the structural member to complete the duct connection. During the site installation the dryer exhaust, HVAC condensate line, and other drains should be routed to the outside of the home perimeter.

Mechanical Equipment

Manufactured homes are required to provide a functioning heating system from the factory, and the majority of manu-

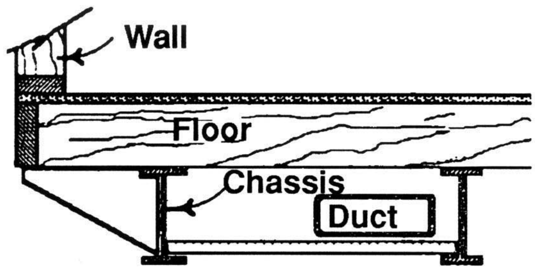


Fig. 9—Air duct in floor.

factured homes are sold with an electric or combustion furnace. Manufactured housing using combustion furnaces (and water heaters) are required to separate the combustion air supply from the interior atmosphere of the home [37]. Air for combustion and for draft hood dilution is ducted in from outside the home into sealed combustion equipment. This eliminates the risk of back drafting, and contributes to fewer air changes in the living space by eliminating the need for house air to provide make-up combustion air. Plant installed HVAC equipment are either down-flow units to supply duct systems located in the floor system, as illustrated in Fig. 9, or homes with supply ducts located in the attic will have plant-installed upflow equipment or site-installed outdoor packaged HVAC systems.

The vast majority of new homes are set up with central air conditioning equipment either as a split system or packaged air conditioners or heat pumps. Nearly all of the air conditioning equipment for manufactured housing is sold by the retailer and installed in the aftermarket. The sizing of air conditioning equipment is considered during the design phase for manufactured housing. Historically only the capacity of the ducts to accommodate air conditioning has been specified by the manufacturer. However, several manufacturers now provide sizing recommendations for the air conditioning system. Due to the variance in installation quality, considerable load can be added to the home from shell and duct leaks and installers have, in the past, oversized cooling equipment to compensate for these losses. Over sizing decreases the ability of the cooling equipment to remove moisture from the air; equally risky from a moisture management perspective is that oversized units allow the occupant to significantly lower the indoor cooling temperature. Excessively low set point temperatures during summer months result in increased cold envelope surfaces, which are at risk from condensation and moisture damage, particularly for homes located in humid climates.

HUD Regulations Affecting Moisture Managment

Since June 1976, manufactured housing has been regulated in the United States by the Federal Government under the HUD Manufactured Home Procedural and Enforcement Regulations [38] and the HUD Manufactured Home Construction and Safety Standards [39] with revisions made in May 2006.

Major provisions of the HUD Code that impact moisture management in manufactured homes are outlined below. Code provisions that are similar to site-built codes (such as a requirement for bathroom ventilation) are not highlighted. For a more complete description of the provisions, one is directed to read the entire section of the HUD Code. The Uo Zone Map (Thermal Zone Map) is referred to in some climate-specific requirements such as ventilation and vapor retarder specifications.

Excerpts from the HUD Code:

Subpart B—Planning Considerations

§ 3280.103 Light and ventilation

(b) Whole house ventilation. Each manufactured home must be provided with whole house ventilation having a minimum capacity of 0.035 $ft^3/min/ft^2$ of interior floor space or its hourly average equivalent. This ventilation capacity must be in addition to any openable window area. In no case shall the installed ventilation capacity of the system be less than 50 cfm nor more than 90 cfm. The following criteria must be adhered to:

(1) The ventilation capacity must be provided by a mechanical system or a combination passive and mechanical system. The ventilation system or provisions for ventilation must not create a positive pressure in Uo Value Zones 2 and 3 or a negative pressure condition in Uo value Zone 1. Mechanical systems must be balanced. Combination passive and mechanical systems must have adequately sized inlets or exhaust to release any unbalanced pressure. Temporary pressure imbalances due to gusting or high winds are permitted.

Subpart D—Body and Frame Construction Requirements

§ 3280.305 Structural design requirements

(g) Floors

(2) Wood, wood fiber, or plywood floors or subfloors in kitchens cbathrooms (including toilet compartments), laundry areas, water heater compartments, and any other areas subject to excessive moisture shall be moisture resistant or shall be made moisture resistant by sealing or by an overlay of nonabsorbent material applied with water-resistant adhesive.

(6) 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 Standard Test Methods for Puncture and Stiffness of Paperboard, and Corrugated and Solid Fiberboard, ASTM D781-1968 (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.

Subpart F—Thermal Protection

§ 3280.504 Condensation control and installation of vapor retarders

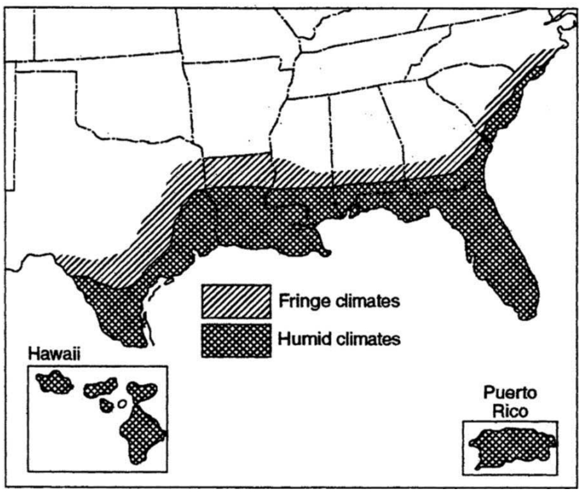
(a) Ceiling vapor retarders.
  (1) In Uo Value Zones 2 and 3, ceilings must have a vapor retarder with a permanence of not greater than 1 perm (as measured by ASTM E96-93 Standard Test Methods for Water Vapor Transmission of Materials) installed on the living space side of the roof cavity.
  (2) For manufactured homes designed for Uo Value Zone 1, the vapor retarder may be omitted.
(b) Exterior walls.
  (1) Exterior walls must have a vapor barrier not greater than 1 perm (dry cup method) installed on the living space side of the wall; or

(2) Unventilated wall cavities must have an external covering and/or sheathing that forms the pressure envelope. The covering and/or sheathing must have a combined permeance of not less than 5.0 perms [40]. In the absence of test data, combined permeance may be computed using the following formula: $\mathbf{P_{Total}} = (\mathbf{1}/[(\mathbf{1}/\mathbf{P_1}) + (\mathbf{1}/\mathbf{P_2})])$, where P_1 and P_2 are the permeance values of the exterior covering and 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 must be constructed so that ventilation is provided to dissipate any condensation occurring in these cavities; or

(4) Homes manufactured to be sited in "humid climates" or "fringe climates" as shown on the Humid and Fringe Climate Map in this paragraph are permitted to have a vapor retarder specified in paragraph (b)(1) of this section installed on the exterior side of the wall insulation or be constructed with an external covering and sheathing with a combined permeance of not greater than 1.0 perms, provided the interior finish and interior wall panel materials have a combined permeance of not less than 5.0 perms. The following need not meet the minimum combined permeance rating of not less than 5.0 perms for interior finish or wall panel materials:

Humid and Fringe Climate Map



(i) Kitchen back splash materials, less than 50 square feet in area installed around countertops, sinks, and ranges;
(ii) Bathroom tub areas, shower compartments;
(iii) Cabinetry and built-in furniture;
(iv) Trim materials;
(v) Hardboard wall paneling of less than 50 square feet in area under chair rails.

(5) The following areas of local governments (counties or similar areas, unless otherwise specified), listed by state are deemed to be within the humid and fringe climate areas shown on the Humid and Fringe Climate Map in paragraph (b)(4) of this section, and the vapor retarder or construction methods specified in paragraph (b)(4) of this section may be applied to homes built to be sited within these jurisdictions: (*See the HUD Code for specific counties in each state: Alabama, Florida, Georgia, Hawaii, Louisiana, Mississippi, North Carolina, South Carolina and Texas*).

(c) Attic or roof ventilation.

(1) Attic and roof cavities shall be vented in accordance with one of the following:

(i) A minimum free ventilation area of not less than 1/300 of the attic or roof cavity floor area. At least 50 percent of the required free ventilation area shall be provided by ventilators located in the upper portion of the space to be ventilated. At least 40 percent shall be provided by eave, soffit or low gable vents. The location and spacing of the vent openings and ventilators shall provide cross-ventilation to the entire attic or roof cavity space. A clear air passage space having a minimum height of 1 inch shall be provided between the top of the insulation and the roof sheathing or roof covering. Baffles or other means shall be provided where needed to insure the 1-inch height of the clear air passage space is maintained.

(ii) A mechanical attic or roof ventilation system may be installed instead of providing the free ventilation area when the mechanical system provides a minimum air change rate of 0.02 cubic feet per minute (cfm) per sq.ft. of attic floor area. Intake and exhaust vents shall be located so as to provide air movement throughout space.

(2) Single-section manufactured homes constructed with metal roofs and having no sheathing or underlayment installed, are not required to be provided with attic or roof cavity ventilation provided that the air leakage paths from the living space to the roof cavity created by electrical outlets, electrical junctions, electrical cable penetrations, plumbing penetrations, flue pipe penetrations and exhaust vent penetrations are sealed.

(3) Parallel membrane roof section of a closed cell type construction are not required to be ventilated.

§ 3280.505 Air infiltration

(a) Envelope air infiltration. The opaque envelope shall be designed and constructed to limit air infiltration to the living area of the home. Any design, material, method or combination thereof, which accomplishes this goal may be used. The goal of the infiltration control criteria is to reduce heat loss/heat gain due to infiltration as much as possible without impinging on health and comfort and within the limits of reasonable economics.

(1) Envelope penetrations. Plumbing, mechanical and electrical penetrations of the pressure envelope not exempted by this part, and installations of window and door frames shall be constructed or treated to limit air infiltration. Penetrations of the pressure envelope made by electrical equipment, other than distribution panel boards and cable and conduit penetrations, are exempt from this requirement. Cable penetrations through outlet boxes are considered exempt.

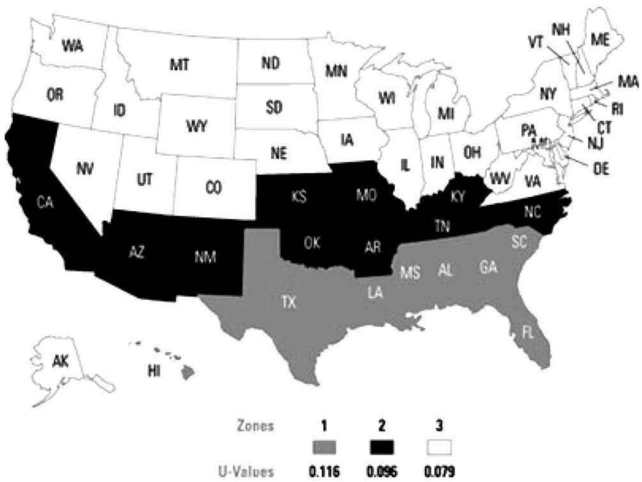
(2) Joints between major envelope elements. Joints not designed to limit air infiltration between wall-to-wall, wall-to-ceiling and wall-to-floor connections shall be caulked or otherwise sealed. When walls are constructed to form a pressure envelope on the outside of

the wall cavity, they are deemed to meet this requirement.

§ 3280.506 Heat loss/heat gain

The manufactured home heat loss/heat gain shall be determined by methods outlined in sections 3280.508 and 3280.509. The Uo (Coefficient of heat transmission) value zone for which the manufactured home is acceptable and the lowest outdoor temperature to which the installed heating equipment will maintain a temperature of 70 F shall be certified as specified in section 3280.510 of this subpart. The Uo value zone shall be determined from the U/O Value Zone Map.

Thermal Zone Map



(a) Coefficient of heat transmission. The overall coefficient of heat transmission (Uo) of the manufactured home for the respective zones and an indoor design temperature of 70 F, including internal and external ducts, and excluding infiltration, ventilation and condensation control, shall not exceed the Btu/(hr.) (sq. ft.) (F) of the manufactured home envelope as tabulated.

(b) To assure uniform heat transmission in manufactured homes, cavities in exterior walls, floors, and ceilings shall be provided with thermal insulation.

(c) Manufactured homes designed for Uo Value Zone 3 shall be factory equipped with storm windows or insulating glass.

Subpart H—Heating, Cooling and Fuel Burning Systems

§ 3280.707 Heat producing appliances

(b) Fuel-burning heat-producing appliances and refrigeration appliances, except ranges and ovens, shall be of the vented type and vented to the outside.

§ 3280.715 Circulating air systems

(a) Supply system

(4) Airtightness of supply duct systems. A supply duct system shall be considered substantially airtight when the static pressure in the duct system, with all registers sealed and with the furnace air circulator at high speed, is at least 80 percent of the static pressure measured in the furnace casing, with its outlets sealed and the furnace air circulator operating at high speed. For the purpose of this paragraph and section 3280.715(b) pressures shall be measured with a water manometer or equivalent device calibrated to read in increments not greater than 1/10 inch water column.

(b) Return air systems

(1) Return air openings. Provisions shall be made to permit the return of circulating air from all rooms and living spaces, except toilet room(s), to the circulating air supply inlet of the furnace.

(3) Sizing. The cross-sectional areas of the return air duct shall not be less than 2 square inches for each 1,000 Btu per hour input rating of the appliance. Dampers shall not be placed in a combination fresh air intake and return air duct so arranged that the required cross-sectional area will not be reduced at all possible positions of the damper.

(4) Permanent uncloseable openings. Living areas not served by return air ducts or closed off from the return opening of the furnace by doors, sliding partitions, or other means shall be provided with permanent uncloseable openings in the doors or separating partitions to allow circulated air to return to the furnace. Such openings may be grilled or louvered. The net free area of each opening shall be not less than 1 square inch for every 5 square feet of total living area closed off from the furnace by the door or partition serviced by that opening. Undercutting doors connecting the closed-off space may be used as a means of providing return air area. However, in the event that doors are undercut, they shall be undercut a minimum of 2 inches and not more than 2 1/2 inches cas measured from the top surface of the floor decking to the bottom of the door and no more than one half of the free air area so provided shall be counted as return air area.

(c) Joints and seams

Joints and seams of sheet metal and factory-made flexible ducts, including trunks, branches, risers, crossover ducts, and crossover duct plenums, shall be mechanically secured and made substantially airtight. Slip joints in sheet metal ducts shall have a lap of at least 1 inch and shall be mechanically fastened. Tapes or caulking compound shall be permitted to be used to seal mechanically secure joints. Sealants and tapes shall be applied only to surfaces that are dry and dust-, dirt-, oil-, and grease-free. Tapes and mastic closure systems for use with factory-made rigid fiberglass air ducts and air connectors shall be listed in accordance with UL Standard 181A-1994, with 1998 revisions. Tapes and mastic closure systems used with factory-made flexible air ducts and air connectors shall be listed in accordance with UL Standard 181B-1995, with 1998 revisions.

Note: Interpretive Bulletin for Manufactured Home Construction (April 21, 1994): Ducts in conditioned space: "The duct losses for this configuration [duct is located between the floor insulation and the floor(conditioned area)] are not included in the [heat loss] calculation. The space where the duct is located is considered conditioned and the floor deck is not included in the calculation."

Specific Recommendations for Moisture Management

Avoiding Moisture Problems at the Factory

Attend to Critical Flashing Details

(See Ref. [41].) Properly installed flashing is the first line of defense against moisture intrusion. Flashing materials should be shingled and continuous until water is completely drained to outside—this includes adding roofing felt paper over hinged soffit sections and flashing of housewrap systems—don't let water get behind housewrap. Flashing around field installed dormers and second story sections is critical; keep this simple for installers.

Use a secondary weather resistant barrier between vinyl siding and sheathing. If housewrap is used under vinyl siding, it should extend over gabled attic areas as well to avoid water running between the housewrap and sheathing.

Avoid Ceiling Penetrations

Unless tightly sealed, penetrations in the ceiling are pathways for air movement and moisture migration. Moisture can migrate from the home into the attic during winter resulting in condensation in the attic cavity; or moisture can migrate into the home during summer condensing on wall surfaces and increasing moisture loads. Items such as bath fans that are not well sealed to the ceiling, have a leaky housing, or have a back damper that will not close completely are of concern. Warm air entering the attic can also melt snow on the outer surface of the roof and cause ice dams which may result in significant roof leaks.

Maximize Insulation Coverage Over the Entire Building Envelope

Compressed insulation or loss of insulation due to structural needs may result in interior cold spots that encourage condensation in cold climates especially near the wall top plates and outside corners. Avoid positioning insulation that may block designed ventilation [42].

Apply and Store Materials According to Manufacturer's Specifications

Maintain product shelf life of materials in accordance with labels, application rates, and design film thicknesses in accordance with specifications, continuity of vapor retarders during application. Adhere to cure times and application conditions of temperature and humidity and assure materials are compatible with sealants with finishes.

Seal Ducts to Make Airtight, Durable Connections

(See Ref. [43].) Leaky ducts can substantially increase the amount of outside humid air that enters a home, thus adding to the cooling load and increasing opportunities for moisture problems. Joints in the ducts and connections to the furnace should be rigidly mechanically fastened and sealed with mastic or properly applied tape for duct board systems to make durable and leak-proof seals. Redesign fastening of duct parts so that all seams are visible during construction and can be more easily sealed with mastic. Make a repair plan for inevitable misalignments between duct parts.

Carefully Locate and Size Air Supply Registers

Do not locate air supply registers near sources of water, and do not place supply registers where they are likely to be covered by furniture. Do not over supply (and thus overcool) small rooms such as bathrooms. Bathrooms are already relatively wet and overcooling them increases opportunities for condensation.

Provide for Adequate Return Air Pathways

Use current building science guidelines for air-handler induced negative pressures: The pressure differential from the living room to the outside should be close to 0 when the interior doors are open and no more than 3 Pascals when all interior doors are closed. Since contemporary master bathrooms may equal the size of the master bedroom, include the master bathroom area when calculating the need for pressure relief (return air) for the master bedroom. Door closure should not create significant pressure differences in the home.

Maximize return air openings for all major living spaces: Install 70 sq. in. of open return air area for each 100 cfm of supply airflow [44].

Exhaust Ventilation Considerations

Exhaust vents that terminate to soffit areas must be routed over ceiling insulation—displaced insulation from vents running under ceiling batts will allow moisture to condense onto gypsum ceiling board in humid climates. These vents must be sealed and have a good dampering system (or a second damper) to avoid humid air from back drafting into small area such as bathrooms. In humid climates, avoid fan/light combinations, which often have a damper designed not to close completely. Humid air can accumulate and stratify in small rooms and result in moisture damage.

Gaskets and Sealants are Critical

Whether nonporous foam or caulking, gaskets must durably bridge both surfaces to prevent air movement and moisture migration. Key concerns are window seals, marriage lines, top and bottom wall plates, and outdoor electrical fixtures. Be sure the gasket material meets its intended target to avoid air by-passes.

Air Seal Exterior Walls

For nonvented wall designs, air sealing should be applied at the exterior sheathing level; for ventilated wall designs, air sealing should be applied at the interior wall surfaces. Air sealing at both the interior surface and exterior sheathing is a recommended best practice. Wall air sealing is important when interior side wall vapor retarders are specified for homes located in humid climates. Exterior wall sealing coupled with tight duct installations are the key elements required to prevent excess moisture accumulation in wall with interior side vapor retarders.

Use of Wall Vapor Retarders

When moisture moving through a wall system comes in contact with a vapor retarder, the potential for moisture accumulation and, in worst cases, condensation increases. Placement of required vapor retarders is complicated by the following: plant homes are shipped to different climate locations, virtually all homes are now heated and cooled, and some occupants prefer cooler air conditioning temperatures. Wall vapor retarder problems are minimized with effective wall air sealing and tight duct construction.

For humid climates, minimize the use of interior side wall vapor retarders when this is possible. Consider designs that utilize higher permeable interior side surfaces that will aid the inward drying of moisture that migrates into walls.

Ensure that Any Tears in the Bottom Board Material are Durably Sealed and Drained

Make durable patches of the bottom board using both mechanical fastening and a sealant. Punch a 1/4-in. hole at each low spot in the bottom board area to drain errant water that enters the floor cavity.

Add Moisture Control Items to the Final Checkout

No home should leave the plant with a loose or a missing crossover collar, or one that requires the installer to move a structural cross member in order to complete the setup.

Do not allow water to enter the floor cavity during transit or outside storage. Tape the bottom board along the marriage line and take care when adding the plastic transit cover so that it does not drain into the floor cavity.

Specify Plant Installation of Items that Minimize Setup Problems

Plant installed marriage gaskets, phone and cable connections, and other items can easily and more effectively be installed at the factory—where installation is simpler and quality is easier to control.

Store the Home in a Dry Area

Do not store the home over wet or saturated surfaces. Given enough time, water under the home will saturate the materials causing warping and uneven drying (cracking) after installation.

Avoiding Moisture Problems During Installation

Make Sure the Site is Properly Graded to Shed Water

Inspect the site before the home is delivered. Water draining under a home can destabilize the foundation as well as increase the chance of moisture migrating into the house. A small adjustment to the grading immediately surrounding the home to include a small curb or berm can be an effective remedy for rainwater runoff; more drastic measures may require regrading, or the installation of drain tiles. Provide adequate ventilation of the crawl space (minimum vent area = floor area/150).

Check Bottom Plastic at Setup for Water

Check each low spot of the bottom plastic; if it is cold or heavy it may be holding water. Puncture it (or better yet puncture each low spot) and inform the retailer/occupant of any water drainage.

Seal the Marriage Wall Completely with a Nonporous Gasket

A nonporous gasket should be placed along the inside edge of the insulation in a continuous "ring" around the marriage wall perimeter to prevent air and moisture from infiltrating into the home and wall cavities after the home is brought together. A continuous gasket is difficult to make after the home is pulled together regardless of how much spray foam is used; sealing the top of the marriage line may bypass significant air leaks. Make sure there are no air pathways between the crawl space and the attic cavity.

Install a Ground Cover

Installation of a ground cover is one of the most overlooked and underestimated setup tasks. Moisture from the ground is often the largest source of moisture load on a house. Small depressions should be punctured to provide drainage. However, do not install a ground cover if water will settle on top of the plastic.

Ensure that Any Tears in the Bottom Board Material are Durably Sealed

Moisture from the ground will find its way into the floor cavity through tears in the bottom board, adding to the house moisture load and condensing on cold surfaces such as air conditioning ducts. Make durable repairs using both mechanical fastening and a sealant. Do not seal intended holes; for example, do not seal intakes for sealed combustion equipment.

Keep All Installing Materials Dry

Do not enclose wetted materials. Any areas that get wet during setup must be actively dried with fans and dehumidifiers and added heat if necessary. Be sure to check the floor cavity for water if the home is rained on during installation.

Leave No Metal Surfaces or Insulation Exposed When Installing the Crossover Duct

When the air conditioner is operating, exposed metal duct will become cold and condense moisture from the air, which may then wick into the crossover duct insulation layer. Be sure ducts and metal boxes are off the ground, sealed tight, and insulated. Tape over any exposed insulation on the duct system.

Make Sure Exhaust Ducts are Supported and Installed Correctly

Like a drainpipe, the dryer exhaust duct needs to slope downhill and have proper support. Water can easily condense inside this duct, blocking airflow, tearing the duct, and allowing delivery of moist dryer exhaust under the home.

Likewise, kitchen and bath vents in the attic area must exhaust to the outside. Be sure they have not been crushed or dislodged during installation, remove excess vent hose and be sure hose is secure and directed to the outdoors. Exhaust vents that terminate to soffit areas should run over the insulation—if routed below, the displaced insulation will allow moisture to condense onto gypsum ceiling board in humid climates.

Provide Foundation Moisture Control for Basement Installations

Dampproof the exterior of any below grade walls down to the footing level; provide effective perimeter drainage at the footing level, grade site to drain water away from the foundation. For floor slabs, install slabs over a continuous 6-mil poly vapor retarder installed on 4-in. of uniform course aggregate stone. If the interior side of basement walls is to be finished, utilize vapor permeable finishes.

Properly Size Cooling Equipment and Recommend Equipment with Higher Latent Removal Capacity in Humid Climates

Cooling equipment should be sized to closely match the design load to maximize dehumidification capacity. If the equipment is already installed and has a large overcapacity for the load, set the blower as low as 350 cfm per ton of cooling capacity to increase dehumidification. Homes with oversized equipment may achieve lower overall temperatures that create a greater risk of condensation. Some homes may require supplemental dehumidification equipment.

Do Not Disable Fresh Air Ventilation Systems

In humid climates, adding small amounts of fresh outside air into the air handler closet promotes positive pressure and can assist as a moisture prevention strategy; do not disable without providing an engineered alternative. The outside air should be directed towards the air conditioning coils to ensure it is dehumidified.

Make Sure the Condensate Line from the Air Conditioner or Heating with High Efficiency Equipment is Properly Trapped and Terminated Outside of the Skirting

An improperly trapped condensate line will not function properly: air can be drawn in through the condensate line and prevent drainage; condensate water will overflow onto the floor, often resulting in damage under the air handler.

Avoiding Moisture Problems in the Home

Eliminate Moisture Problems at the Source

Some moisture problems begin with excess amounts of water released into the air by common household activities such as cooking and bathing. Vent fans should be turned on during such activities; they should be left on for several minutes after the moisture producing activity ceases. Activities such as drying clothes indoors, storing firewood, and extensive indoor plant cultivation adds significant moisture to the air. If excess moisture sources are present, a dehumidifier may be needed.

Monitor Indoor Relative Humidity

Inexpensive relative humidity meters available at electronics stores installed near the thermostat can help to identify when humidity levels are elevated and potentially damaging. Relative humidity over 70 % may support mold growth. Some climates and lifestyles may require a dehumidifier to control moisture; maintain indoor relative humidity at levels below 65 % and above 40 %.

Avoid Using Unvented Propane, Kerosene, or Other Unvented Combustion Heaters

About a gallon of water is released into the air as vapor for every gallon of fuel consumed. This is a significant source of moisture that can quickly cause damage. No ventilation system is designed to remove this amount of water vapor. Do not operate a vented gas fireplace with the damper closed.

Do Not Cover or Close Off the Floor Registers

Air from the heater or air conditioner is distributed through registers in the floor or ceiling. Closing or covering these registers with furniture or rugs can imbalance the system and create cold spots on room surfaces, increasing the potential for moisture condensation. Closing and covering registers can also imbalance the distribution system resulting in exaggerated duct leakage and negative pressures.

Maintain Cooling Equipment

Clogged filters can interfere with an air conditioner's ability to remove moisture from the air and, in some cases, interfere with condensate drainage. Dirty filters should be either cleaned or replaced. Coiling coils, condensate drain pans and line should be inspected and kept free of debris accumulation and cleared of drain clogs.

Keep the Thermostat Set above 72°F in Hot, Humid Weather and Below 80°F in Cold Weather

In many hot and humid climate areas, the dew point of the outside air is elevated during the summer. Moisture in this air can condense on surfaces lower than the dew point; and may occur hidden within the walls or other building cavities. During winter, indoor air with temperatures over 80°F can hold significant amounts of moisture, which can migrate into cavities.

Do not Leave a Home Unconditioned for Extended Periods

If a home is vacant, the thermostat may be set back 10 to 15 degrees to minimize heating and cooling costs, but only if a dehumidifier is set to operate and keep humidity levels at less than 55 % relative humidity. Be sure all interior doors (including closets) are open to increase air circulation and turn off water supply, add antifreeze to plumbing traps and cover to prevent evaporation, and turn off and drain the water heater. If the refrigerator is to be turned off—do it early so it will defrost then drain the water from the drain pan.

Recognize Signs of Moisture Problems

Big moisture problems started as small ones, and any moisture problem is much more easily cured if discovered early on. The following are warning signs of possible moisture problems: musty smells that linger for several hours or days; discoloration or brown stains on walls or ceilings; swelling of floor, wall, or ceiling finishes; condensation on window glass; or standing water under the home. If spills occur—be sure water has not collected in the floor cavity.

Moisture Problem Remediation

Moisture Remediation

Successful case-by-case remedial actions to abate damage from moisture in existing manufactured housing depend more than anything else upon an accurate 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.

The key to solving moisture problems is to understand the root causes: Why has moisture accumulated at the damage site? What is the source of the moisture? And, how did the moisture travel from its source to the damage site? In many cases, altering just one of these elements is enough to resolve a specific moisture problem. For example, puncturing the low spot in a bottom board to create a drain will let occasional water accumulation drain away and prevent damage. If the source of moisture is small or intermittent, this may be all that is needed. [45]. Some moisture problems, however, are more difficult, especially if multiple sources and transport methods are involved, or if the moisture source is far removed from the site where damage is manifested.

No region of the country is immune from moisture-related damage. Moisture problems occur in all climates; however, different regions are prone to different types of problems. The climate region dictates the level of space heating and cooling needed, and the degree of outdoor humidity. Areas with high outdoor humidity are known for summertime moisture condensation problems arising from the steady use of air conditioning. Cooler areas of the country commonly experience wintertime moisture condensation problems arising from ongoing use of indoor heating and cold exterior temperatures mixing with moisture generated inside the home. Local climates also can subject a home to water damage from driven rain, extreme humidity, and flooding. Warping of ceiling, wall, or floor surfaces, or surface water staining, are known to occur during and immediately after severe weather cycles [46].

Moisture Remediation Involving Mold

Recent elevation of concern over mold resulting from moisture damaged buildings warrants a brief discussion of this topic. Several organizations such as the EPA and IICRC have published excellent documents regarding specific remediation of moisture damaged building materials containing mold [47,48]. Although the degree of health related concerns is not universally accepted, it is prudent to follow guidelines in these documents for mold remediation. EPA describes areas of mold totaling 10 square feet or less as a “small” amount of mold, and a certified mold professional is not indicated to assist in such a remediation. However, if a cleanup is more than 10 square feet, consultation with a Certified Industrial Hygienist or an IAQA Certified Mold Remediation or Indoor Environmental Professional is recommended. It is important to take precautions to limit both occupant and worker exposure to mold and mold spores during remediation efforts. This can be done by wearing appropriate personal protective equipment (PPE) and providing adequate containment. Care should be taken in any moisture damaged home to inspect for hidden mold prior to removing soft, damp, or otherwise moisture damaged wall panels. For example, inspect inside a marriage wall before removing panels to determine if the inside cavity has mold that will necessitate an elevated level of containment.

References

[1] Senior Engineer, National Conference of States on Building Codes and Standards, Herndon, VA 22070.

[2] The U.S. 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] The American Housing Survey for the United States: 2005 (AHS) collects data on the Nation’s housing and is conducted by the Bureau of the Census for the Department of Housing and Urban Development (HUD).

[4] CFR 24 Chapter XX Part 3282 Manufactured Housing Procedural and Enforcement Regulations.

[5] The Consensus Committee, established in August 2004, is mandated under the authority of Section 604(a) of the National Manufactured Housing and Construction Safety Standards Act, with objectives that include providing recommendations to HUD for changes in the MHCSS construction standard.

[6] No access panels are built into the ceilings or floor cavities of manufactured housing. Access holes are cut at the site on rare occasions that require service or limited visual inspection.

[7] The HUD Code does not specify the floor cavity as conditioned, but it is implied; and furthermore the comment in the April 21, 1994 Interpretive Bulletin makes it clear that this is HUD’s intention. Interpretive Bulletins are incorporated in the MHCSS.

[8] Lstiburek, J., and Carmody, J., *Moisture Control Handbook*, Van Nostrand Reinhold, New York, 1993.

[9] Building America Industrialized Housing Partnership administered by the Florida Solar Energy Center made this conclusion based on case studies conducted on HUD Code homes with moisture problems in hot and humid climates. Forum on Moisture Problems in HUD Code Homes in Hot Humid Climates 2002.

[10] The HUD Manufactured Home Construction and Safety Standard (MHCSS), Subpart D, Section 3280.305 (g)(5).

[11] Air Barriers: Increasing Building Performance, Decreasing Energy Costs, The Architectural Record—McGraw Hill Companies—Construction Division http://archrecord.construction.com/resources/conteduc/archives/0601duponttyvek-4.asp

[12] Condensation Control for Exterior Walls of Manufactured Homes Sited in Humid and Fringe Climates; Waiver April 2002.

[13] Conversations with the Manufactured Housing Institute, Vice President of Technical Activities, 2004.

[14] Data collected by HUD-approved State Administrative Agencies (SAA) on the occurrence of consumer reported complaint identifies “Wall Panel Buckled” as representing only 3–4 % of the Structural Subcomponent complaints and even a smaller fraction of total complaints. Ninth Report to Congress on the Manufactured Housing Program, Prepared by the Manufactured Housing and Standards Division, HUD October 1996, Chapter IV Consumer Protection Table IV-3.

[15] Florida Solar Energy Center (FSEC) 2000, Moisture Problems in Manufactured Housing: Probable Causes and Cures presented at the *ASHRAE IAQ2001 Conference*.

[16] 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

in single-section homes are nearly filled with insulation.

[17] See paragraph §3280.504(a) and §3280.504(c)(2) of the HUD MHCSS.

[18] Home manufacturers report significant reductions in complaints attributable to attic condensation in homes that have these ventilation systems installed.

[19] See paragraph §3280.504(a) and §3280.504(c)(2) of the HUD MHCSS.

[20] Tests conducted by this author show that it cannot be assumed that these attics are tightly sealed; tests show that these attics are somewhat ventilated to the outside.

[21] See paragraph §3280.715(b) of the HUD MHCSS.

[22] MHRA: Minimizing moisture problems in manufactured homes located in hot, humid climates. Response of interior air pressures to various operating conditions, 2003.

[23] The HUD MHCSS §3280.715(a)(4).

[24] Alternative Energy Corporation, Air of Importance, A Study of Air Distribution Systems in Manufactured Homes, NC Alternative Energy Corp.

[25] ENERGY STAR Qualified Manufactured Homes: Design, Manufacturing, Installation and Certification Procedures, Fourth Edition, July 2007.

[26] See §3280.103(b) of the HUD MHCSS.

[27] ANSI/ASHRAE Standard 62-2001, Ventilation for Acceptable Indoor Air Quality.

[28] Central Fan Integrated Supply Ventilation, Building Science Corporation Article, 2004.

[29] See paragraph §3280.505 of the HUD MHCSS.

[30] One of the benefits unique to factory assembly is that unimpaired access during critical phases of construction enables thorough application of thermal insulation and vapor retardants as well as complete inspection of the work.

[31] Manufactured Home Procedural and Enforcement Regulations, 3282.351 Primary Inspection Agencies.

[32] The American National Standards Institute (ANSI) is a private non-profit organization (501(c)3) that administers and coordinates the U.S. voluntary standardization and conformity assessment system.

[33] HUD is required to develop a Model Home installation standard by December 2005 via the American Homeownership and Economic Opportunity Act of 2000 Public Law 106-569—Dec. 27, 2000. MHI has developed its own "Manufactured Home Installation Guide," recently adopted by HUD.

[34] These aspects are the same for manufactured housing and for site-built homes built over a crawl space.

[35] Reference ANSI A225.1-1987 §2-6.2.1(d).

[36] Letter from ADONAI Building Science Service, Inc to the General Manager of Construction Products for NOMACO Inc. October 3, 2001, describing results from factory testing of marriage line gaskets.

[37] 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.

[38] United States Department of Housing and Urban Development.

[39] 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.

[40] This wall construction option is almost never used. This observation is based on conversations with several Design Approval Primary Inspection Agencies and thus includes a cross section of wall designs by various manufacturers.

[41] Many of these points were expanded upon from checklists available from MHRA: Moisture Problems in Manufactured Homes Understanding Their Causes and Finding Solutions, written by the chapter author in 2000.

[42] 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.

[43] See MHRA Duct Systems: Guide to best practices.

[44] Minimizing moisture problems in manufactured homes located in hot, humid climates. Response of interior air pressures to various operating conditions, MHRA Sept. 2004.

[45] In site-built homes this happens frequently; moisture spills through the floor into the area below, site-built homes, however, do not have a bottom board that will accumulate the moisture.

[46] 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 dependent on climate and can occur during any season of the year.

[47] Institute of Inspection Cleaning and Restoration Certification, IICRC S520 Standard and Reference Guide of Professional Mold Remediation, December 2003.

[48] U.S. Environmental Protection Agency, "A Brief Guide to Mold, Moisture, and Your Home" [EPA 402-K-02-003], http://www.epa.gov/mold/moldresources.html.

22

Moisture in Historic Buildings and Preservation Guidance

Sharon C. Park[1]

UNCONTROLLED MOISTURE IS THE MOST PRE-valent cause of decay in historic buildings. Over a long period of time, the presence of moisture in all of its forms can erode, rot, corrode, and otherwise deteriorate aging building materials if it is not controlled. Historic buildings are vulnerable to moisture damage for several reasons: building materials are fragile, exterior envelopes are not tight, construction joints have weakened over time, modern aggressive methods used to control moisture often further damage historic materials, and modern insulation and HVAC systems used for energy efficiency often create additional moisture problems. And so we see with historic buildings that moisture management is often more complicated than with newer structures.

This chapter briefly discusses, in laymen's terms, moisture sources and preservation philosophies and identifies in checklist form the typical patterns of decay for historic buildings and outlines generally acceptable remedial treatments to manage unwanted moisture [1]. Historic buildings, by their very nature, are irreplaceable and dedicated owners see themselves as stewards of their architectural resources. With a renewed emphasis on sustainable design, historic buildings, well-maintained or rehabilitated for continued use, play an important role in conserving our cultural and architectural heritage. If buildings are not maintained, or if moisture is improperly diagnosed and treated, buildings may decay beyond the point that makes economic sense to repair them.

ASTM standards are an important component of good repair or replacement specifications. Specific ASTM standards, for example, concerning the use of 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 and complex moisture issues generally require a team of specialists knowledgeable about historic construction. This team may include any or all of the following: historical architects, architectural historians, soil and geo-physical engineers, structural engineers, preservation consultants and contractors with proven experience with historic buildings and sites.

Historic buildings present their own series of challenges just by being designated "historic." In order to preserve cultural heritage, there are ways of designating historic buildings and sites, such as listing them in the National Register of Historic Places. There are standards and guidelines in place to help protect these resources through grants and financial assistance, as well as technical assistance. In the United States, there are the Secretary of the Interior's Standards for the Treatment of Historic Properties [2], which outline approaches to preservation. Most frequently used are the Standards for Rehabilitation which outline ten principles of preservation that stress the importance of protecting historic character through careful repair and retention of historic materials (see Appendix A). The guidelines which accompany the Standards for Rehabilitation identify recommended and not recommended treatments [3]. The principles behind these best practices stress repair over replacement and the use of traditional materials and conservative treatments that can extend the life of the resource without altering its historic character. There are cautions about using nonhistoric coatings and altering the performance characteristics of historic systems and components. This makes identifying the source of moisture and using conventional repair methods key to sound preservation practice.

Sources of Moisture

Moisture is a necessary component of life. It is found in soil, in the air, as well as in absorbent materials that make up our living environments. Moisture is fluid and under pressure can move extensively: from a liquid to a solid, from liquid to a vapor and back again. Moisture, in its vapor form, can migrate from foundation to attic; from exterior outside surface to interior walls; from warm to cold surfaces. Moisture problems occur when the moisture contained in our immediate surroundings becomes out of balance, out of equilibrium, and through various physical stages creates unwanted moisture. Some moisture will saturate a building due to catastrophic storms, plumbing pipe failure, or suppression of fire. Some moisture vapor will migrate in and through materials seasonally and not be a cause of great concern. But most unwanted moisture will manifest itself because of poor maintenance, poorly managed climate control systems, or unsuspecting seepage. When the moisture content of materials is out of equilibrium, the reaction of too much moisture can create problems such as mold, rot, and decay. Con-

[1] *Associate Director, Historic Preservation, Smithsonian Institution, P.O. Box 37012, Washington, DC 20013-7012. The bulk of this chapter was written when Ms. Park was Chief, Technical Preservation Services, National Park Service.*

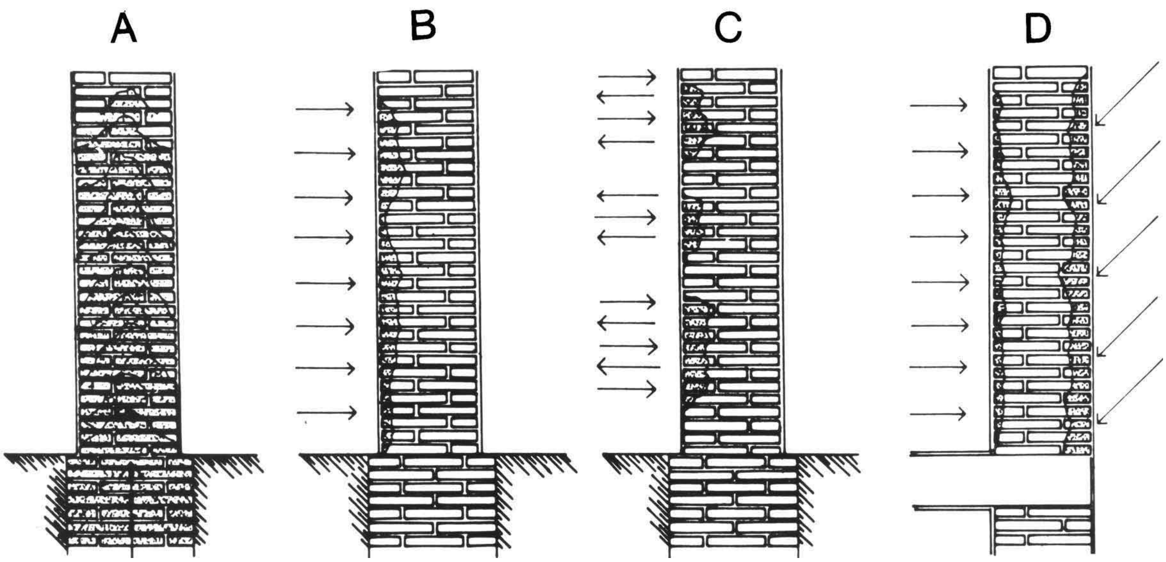


Fig. 1—Moisture from the environment, such as rain, is often the greatest source of moisture that will affect a building. These masonry wall sections illustrate (*A*) ground moisture rising through capillary action into foundations, often known as rising damp; (*B*) driving rain that can saturate poorly maintained exterior wall surfaces; (*C*) the wetting and drying effect of moisture moving in and out of wall exteriors; and finally (*D*) moisture found on both sides of a wall with interior moisture, often from high relative humidity, and exterior moisture from driving rain or other surface contact. It is important that moisture be managed, through controlling relative humidity and proper maintenance so that it can dissipate without harm to the wall structure. Wall section sketches: NPS files.

versely, when there is too little moisture in the air often due to heating and excessively low relative humidity, historic absorbent materials, such as wooden paneling, may crack and be damaged.

The basic sources of moisture are bulk moisture from rain and snow (which create our lakes and rivers), ground moisture from excess bulk moisture, or from underground aqueous storage (acquafers) and moisture in vapor form in the air known as relative humidity (Fig. 1). Moisture in a solid form is known as ice and can do quite a bit of damage, particularly to roofs. Manifestation of moisture in various phases can take it from a solid to a liquid to a vapor. These phases depend on temperature and pressure, such as convection and diffusion, and can result in hidden wall leaks or condensation as vapor turns to liquid. Physical forces such as absorption and adsorption, capillary action and gravity allow moisture to move in and out of most materials. Dew points are an important concept for phase change as saturated vapor converts to moisture on a surface. Interior moisture in a building is often from steam created by cooking, bathing, or drying clothes or as a by-product of combustion with gas appliances. Man-made sources tend to be from modern plumbing and climate control systems. Scientific studies indicate that bulk moisture is the most prevalent source of moisture and that the diffused moisture, or moisture under pressure, is the least damaging and in some cases the least understood (Fig. 2).

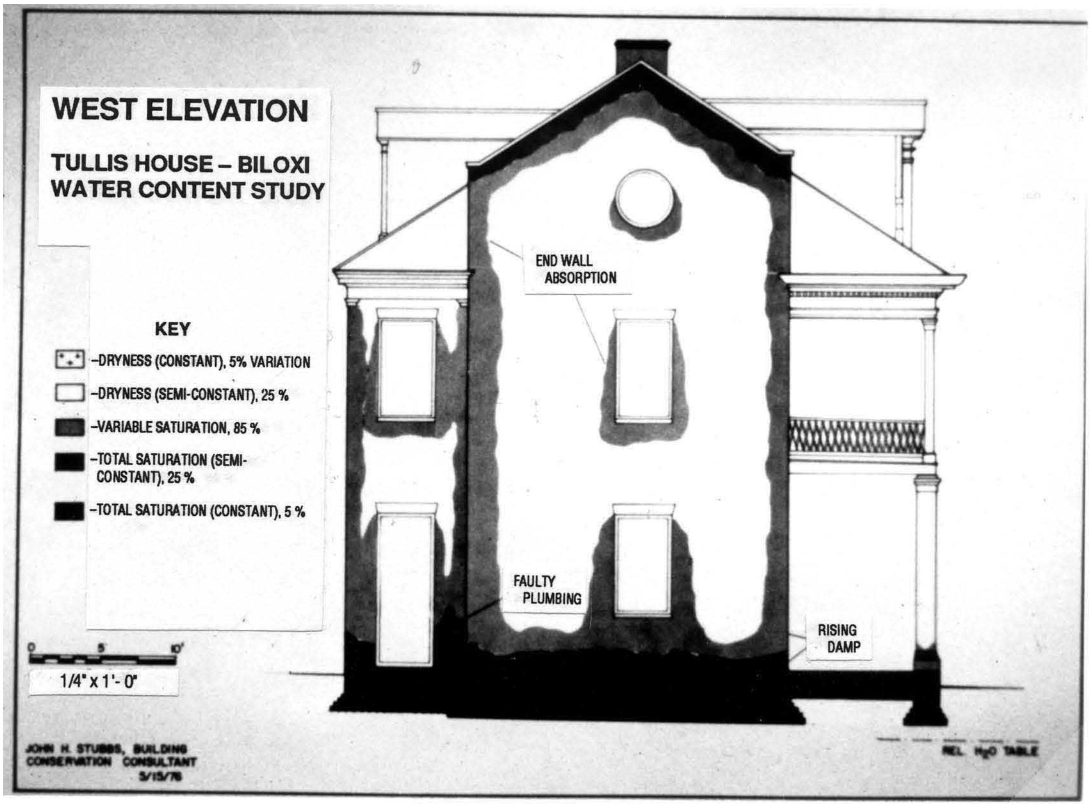
Moisture is notorious for traveling some distance from the source and so it is often misdiagnosed. A damp plaster wall or ceiling may be far from the ice dam that was on the roof, but due to warm air in the attic or rising household heat, the ice, which had worked its way under roofing shingles, eventually melted and dripped into the wall. Historic construction technologies, particularly in unreinforced masonry and frame buildings, are full of irregularly sized materials, undetected cavities, unknown earlier or makeshift repairs, and uneven settlement. Without understanding how moisture enters and moves through a building, it is difficult to identify the true source or multiple sources of moisture. Moisture meters, thermal photography, boroscopes, and small fiber-optic cameras are all useful tools to assist in diagnosing moisture (Fig. 3).

It does little to merely repair or replace the obviously deteriorated materials without eliminating the moisture source or making plans to manage the moisture in a future similar event. In some cases, improper remedial efforts to control moisture, such as sealing exterior frame walls with waterproof coatings, can accelerate the deterioration of fragile historic materials as moisture becomes trapped. It is, therefore, important to have an experienced team to investigate and monitor areas of decay, evaluate options for the control or elimination of the sources of moisture, and undertake remedial treatments within a preservation context.

A methodology for handling moisture problems 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 and establishing acceptable 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.

The first five elements in this methodology are general steps that can be employed for all building types when there



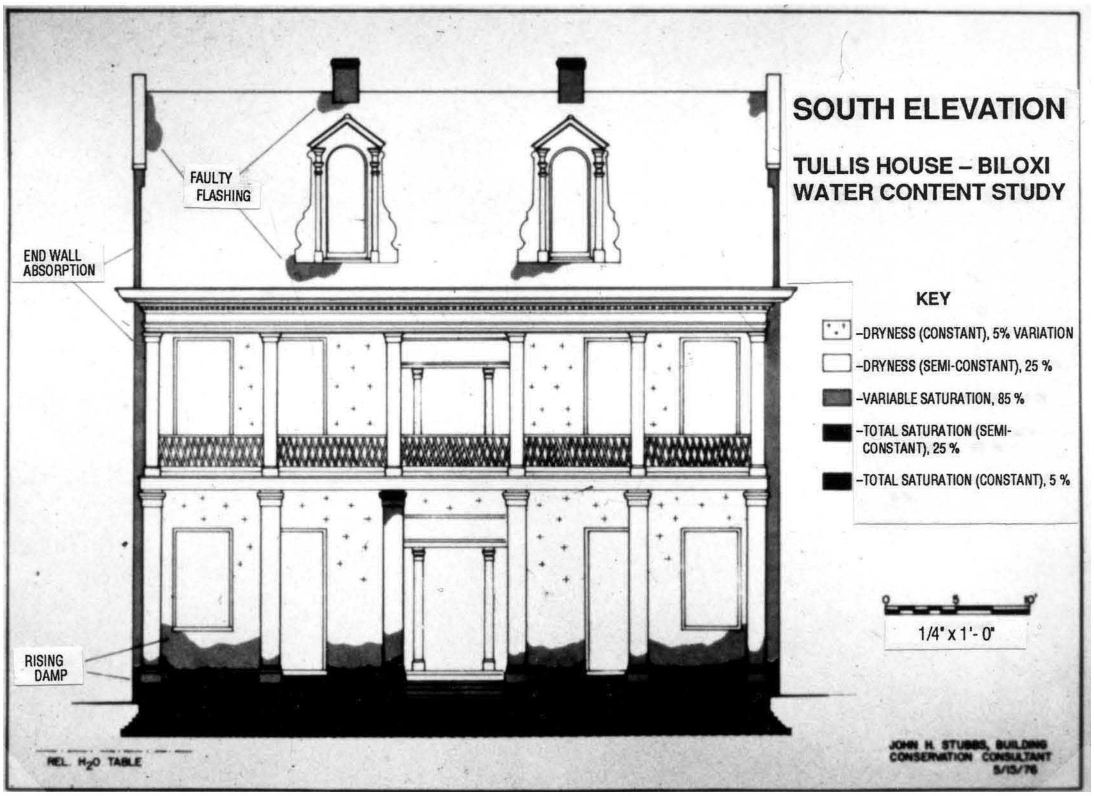


Fig. 2—Historic buildings, often plagued by moisture problems, will benefit from a systematic evaluation to determine the type of moisture, its source, and the level of damage in order to effectively outline the appropriate preservation method to repair the damaged materials. Documenting the building, monitoring the effectiveness of the treatment, and keeping up with good maintenance practices are all part of the long-term care of historic buildings. Drawings courtesy: John H. Stubbs, NPS files.

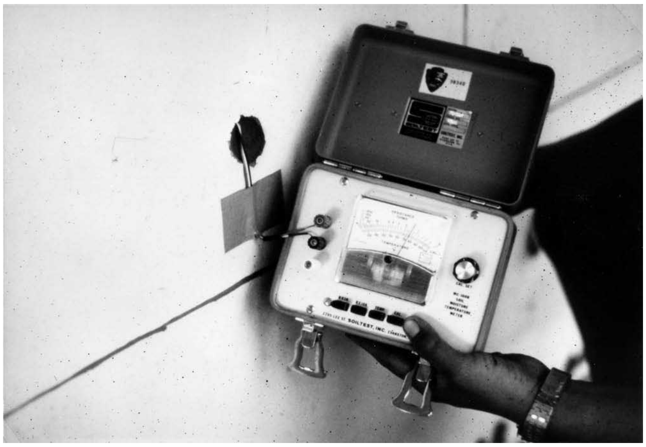


Fig. 3—Moisture meters are a useful tool in monitoring the water content of historic materials. Varying probe lengths can be inserted into small core holes to track the level of moisture. For long-term monitoring, probes are left in the wall, the meter can be attached and information can also be recorded in a data logger as part of a computerized program. Photo: NPS files.

is apparent deterioration. This helps to diagnose and document the problem in order to establish an appropriate repair method. The most difficult aspect of this methodology is the sixth item when corrective action must be taken. The preservation context of a building refers to selecting an appropriate treatment that respects the historic character of a building and works with repairing or selectively replacing existing materials. Maintaining the integrity of these resources is key to their future and so historic materials must be kept to a great extent and the appearance of the building and site should not be radically altered. A comprehensive analysis of the building will require that the first five steps be addressed and the following breakdown of building components will help in assessing an appropriate treatment.

Because there are so many variables when assessing a historic building, it is sometimes best to look as specific areas of a building first and record findings of damage. Then tracking that evidence back to the construction and finding the paths and means of moisture movement can sometimes lead to corrective solutions. While this paper breaks buildings into components, the building and site need to be evaluated holistically to determine the source of moisture.

Historic Exteriors

The historic exterior includes the site and the building's foundation walls, exterior walls, openings, projections, and roofing. Moisture in the form of driving rain, hail, snow, and ice as well as moisture in the ground all contribute to deterioration. Wind, changing temperature, and ultraviolet rays can exacerbate decay and facilitate moisture penetration. One of the challenges of preservation is to keep a building through regular cycles of maintenance weather-tight while still allowing the historic materials to expand and contract naturally. The function of construction details should be understood and not altered. Too often, exterior trim is eliminated for ease of maintenance without understanding that trim pieces were designed specifically to cover joints that were apt to move. As building materials expand and contract, openings for moisture migration will undoubtedly occur. Only routine inspections and regular maintenance can slow down this natural process of deterioration. As most historic exterior materials are still available, in-kind replacement of deteriorated materials should be a first consideration (Fig. 4). Above ground waterproofing of historic building materials with elastomeric coatings, aluminum or vinyl claddings, and sealers should not be used as these treatments can trap moisture in a building and may cause or accelerate decay. 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 that is mostly portland cement and may contain no lime at all. Most 18th, 19th, and early 20th century buildings used lime-rich mortars. Extensive damage has been seen in masonry inappropriately coated or using too hard a mortar. Moisture will travel through the weakest material, which may in fact be bricks softer than the inappropriate replacement mortars.

When assessing moisture damage to exteriors, it is often difficult to disassociate the path of moisture from bulk moisture of rain penetrating the exteriors from excessive site moisture saturating foundations or for poorly discharged site moisture. They all work in tandem and so all aspects of contact between the building and its site must be evaluated.

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. Allowing trees and shrubs to grow up too close around buildings can cause damp earth to contact foundation materials, can crack foundation walls with root penetrations, can erode mortar joints with wall clinging vines, and can reduce beneficial sunlight which helps keep walls dry. Historically significant plantings should be assessed by an arborist or landscape specialist for proper pruning and trimming. Installation of modern underground automatic lawn sprinkler systems too close to foundations or with spray heads improperly angled toward a building can add to unwanted moisture conditions.

Many historic buildings that have been improperly maintained can be successfully rehabilitated with good common sense and cyclical maintenance. Keeping the site clear of vegetative threats, sloping grades away from foundations, repairing the exterior surfaces and opening and ensuring that roof drainage is dispersed away from foundations can go a long way to preventing problems. Properties plagued with ground moisture problems will generally require more thorough evaluation and remedial work. One of the reasons it is advantageous to understand the history and development of a property is that often there were wells and cisterns close to the foundations that have been forgotten and are responsible for many cases of subsurface foundation prob-

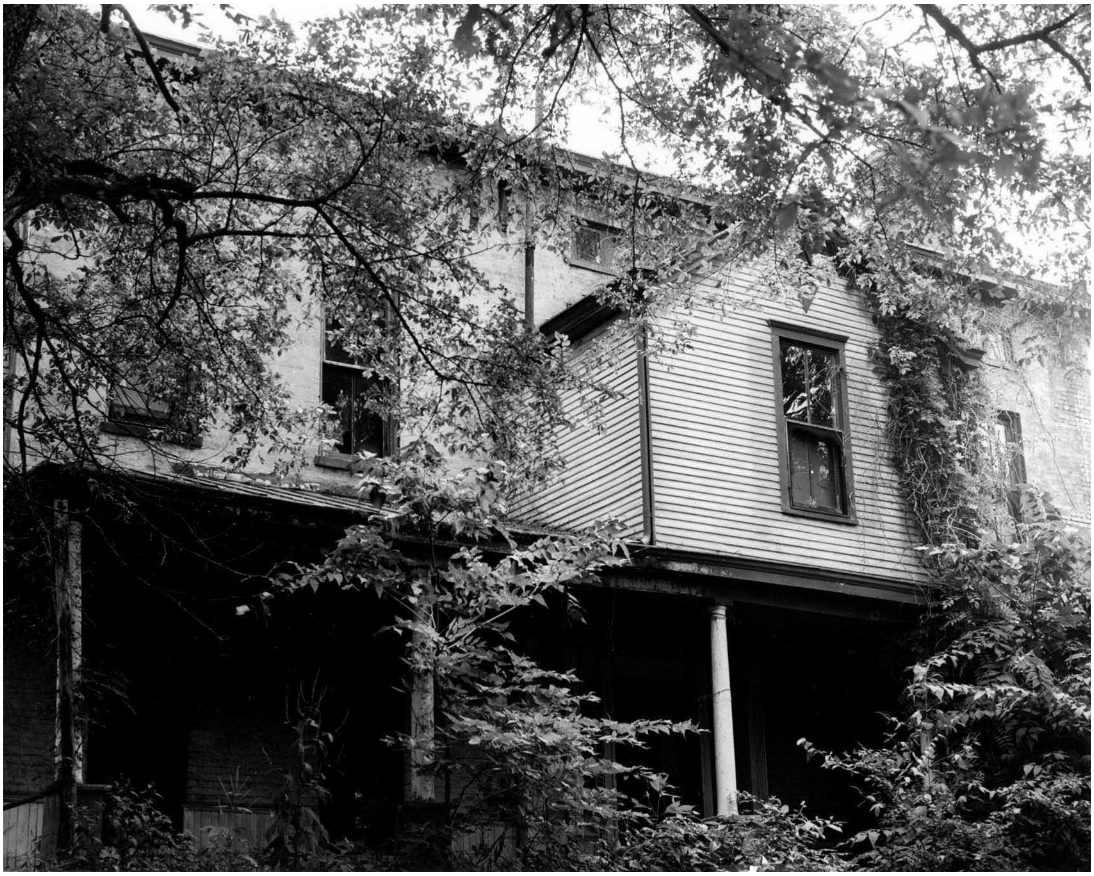


Fig. 4—Deterioration is often most apparent on exterior surfaces exposed to contact with moisture, such as corners, foundations, or areas under and around gutters and downspouts. As part of preservation philosophy, only the damaged portions of the historic materials should be replaced in as close a match with the historic as possible. In this case, new cedar wooden shingles have been installed to replace moisture-damaged shingles and they will shortly be stained to match. It is not appropriate to replace available historic siding materials with nonmatching or synthetic siding as this would change the historic character of the property. Photo: NPS files.

lems. Precautions should be taken to avoid crushing subsurface drains located close to grade if large earthmoving equipment is brought on-site or digging is anticipated on site. Whenever historic sites are to be excavated, if archeological resources or special landscape features are present they should be identified, recorded, or preserved (Fig. 5).

Evidence of Moisture: Site

- Ponding moisture, poor drainage
- Foundation dampness
- Water in basement or crawl space
- Clogged and backed up areaway drains
- Moss or other moisture-holding vegetation

Sources and Pathways of Moisture: Site

- Improper surface grading and run-off from downspouts or underground drains
- High water table
- Underground lawn sprinklers
- Adjacent new construction that has altered water tables or drainage patterns
- Overgrown site vegetation causing root damage to walls or scraping foundations
- Abandoned subsurface features, such as well, icehouses, cisterns, tanks, etc.

Remedial Treatments: Site

- Regrade site to correct problem and remove underground abandoned features, or both
- Remove, trim, or relocate plantings too close to foundations
- Test capacity of exterior site drains with a garden hose and remove blockage if water backs up
- Make sure that roof water is being properly directed away from building foundations

Treatments to Avoid: Site

Do Not:

- Install extensive impervious site paving (alters drainage patterns)
- Plant shrubbery/trees at foundation (roots cause cracks, hold moisture)
- Excavate extensively to create a new feature, such as an English basement, on a highly exposed elevation (alters historic relationships to site)
- Raise of grade too close to absorbent materials of wall construction

Foundations

Eighteenth and nineteenth century foundations were generally constructed of brick, rubble stones, or cut masonry, al-

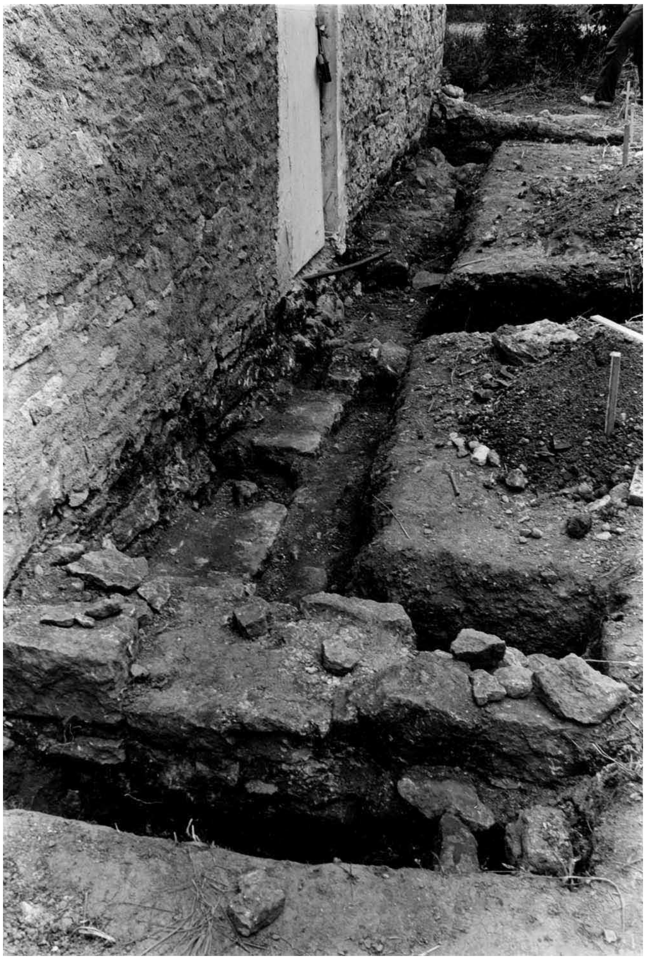


Fig. 5—Archeological evidence may be found when regrading to alleviate poor site drainage, to install underground sewer pipes or to excavate for new footings. Care should be taken to identify and photographically record any evidence, such as lost site features, cisterns, wells, or early foundations, and to contact the State Historic Preservation Office to determine options for preserving this evidence. Photo: NPS files.

though 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 that 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 from the 18th century onward. 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 at the turn of the century. Twentieth century buildings, particularly mid-century highrise structures, 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 necessary to research old building records or archives to determine if any records exist regarding the construction of the building. For late 19th and early 20th 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 and that historic walls are adequately braced.

Because foundations have always been affected primarily by ground moisture, either rising damp or the lateral transmission of surface or groundwater through walls, 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 rain water from the building foundation. In the 19th century, impervious layers of material, such as slate, were often laid in the foundation wall just above grade to act as a dampcourse layer to stop capillary action of damp foundations and 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. Keeping foundation walls dry meant that downspouts had to discharge roof water sufficiently away from walls.

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. Technologies continue to improve in an effort to obtain useful data on moisture.

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 used to probe the surface of the material can record the level and amount of moisture. Fungal growth, or rot, 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 when mortar leaches out of the walls. Historic rendered coatings, such as plaster, were useful in holding mortar in walls. If the surface coatings have eroded, they should be repaired with plasters of the same composition. If hard portland cement mortars are used which restricts vapor transmission, the moisture in the masonry walls may, through capillary action, move up the wall and begin to erode wooden structural elements such as wooden sill plates, joists, flooring, skirting boards, and structural wall framing. This can lead to termite infestation, different kinds of molds or dry rot, and serious structural decay.

Remedial treatments for foundation moisture will vary depending on whether the wetting 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.

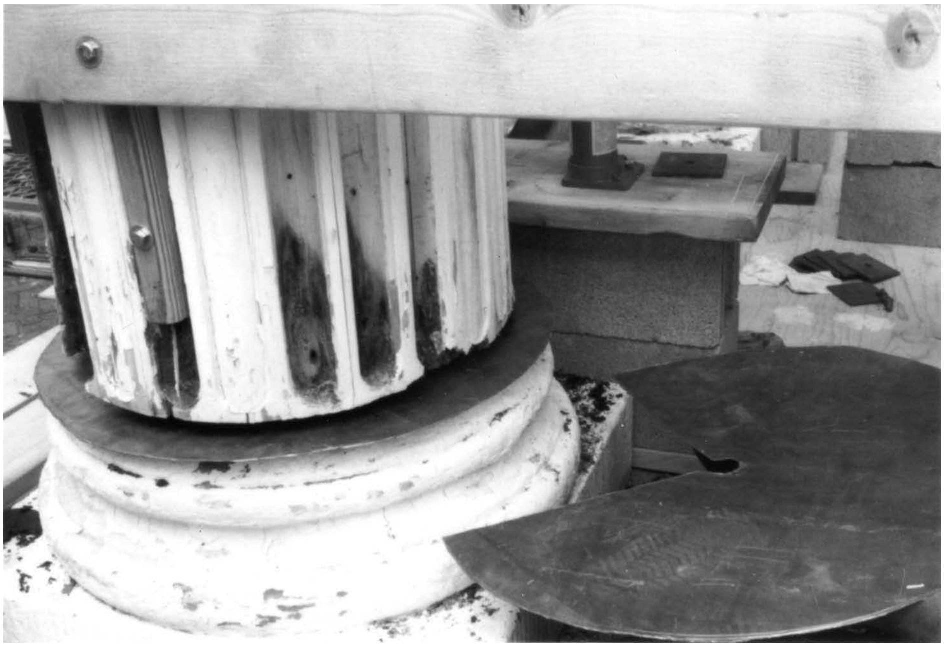


Fig. 6—Ground moisture is often difficult to treat, particularly when it comes into contact with absorbent materials. In some cases, the insertion of a physical barrier may stop capillary action. This wooden replacement column on an entrance portico was showing decay (dark stains) after only 15 years. Moisture from the stone base was traveling up the wooden column. The insertion of a lead shield between the two materials will inhibit the rising damp and extend the life of the column. Photo: Bryan Blundell.

Evidence of Moisture Decay: Foundation

- Damp or decayed materials
- Masonry efflorescence
- Rising damp tide marks about 2 to 3 ft (0.06 to 0.91 m) above grade
- Spalling surfaces below the water table
- Material erosion
- Mold or mildew

Sources of Moisture or Pathways: Foundation

- Excessive ground moisture; high water tables; hydrostatic pressure
- Ineffective gutters and downspouts
- Broken subsurface drainage pipes or gutter discharge boots
- Abandoned cisterns or wells in the basement
- Improper surface grading and runoff
- Rising damp (ineffective dampcourse barriers)
- Moisture-holding lichens, algae, or plant materials
- Penetration through cracked building materials; deteriorated joints

Remedial Treatments: Foundations

- Control bulk moisture from roof run-off with redirected drainage patterns
- Install footing drains, foundation gravel, or sump pumps
- Repair/replace in-kind decayed materials
- Repair a damaged physical dampcoursing layer (slate, lead, etc.) (Fig. 6)
- Improve cross ventilation in basements or crawl space (natural or mechanical)
- Waterproof *exterior* surfaces of foundation wall *below grade* only
- Repoint deteriorated mortar (match historic cement: lime: sand/aggregate mix, color, and appearance)

Treatments to Avoid: Foundations

Do Not:

- Use waterproof coatings above grade (traps moisture)
- Parge with cement coating unfinished damp walls (forces ground moisture further up the wall)
- Install new basement slab over dirt floors without a gravel bed, sump pump, or drainage tiles (alters hydrostatic pressure)
- Use chemical dampcourse injections (consider *only* if all other remedial treatments fail as these have not been proven to have a long-term effect and are visually obtrusive) (Fig. 7)
- Install replacement materials/patches with differing coefficients of expansion and contraction
- Design new features, such as a dry moat or areaway, to accelerate foundation drying on primary elevations (incompatible new design feature)
- Install vapor barriers over excessively damp crawl space (may exacerbate rising damp in foundations)

Exterior Wall Surfaces

Walls may be constructed of almost any material: wood, masonry, adobe, terra cotta, cast iron, concrete, or steel and may be clad with a variety of materials, such as wood, brick veneer, carrara glass, enamelized metal panels, or stucco. The two principal classes or materials in historic buildings being discussed in this chapter are masonry and wood, but all materials will have specific properties of absorption and performance under varying environmental conditions. Some construction is mostly solid and load bearing; some is of structural frame elements and generally will have a hol-

Fig. 7—Not all methods of dealing with rising damp are successful. Chemicals injected through exterior masonry walls are popular in some countries, but should only be considered as a last resort as their long-term effectiveness is questionable and their poor appearance is visually damaging to historic buildings. Often redirecting bulk water with better guttering systems, subsurface waterproofing and footing drains, or the use of sump pumps, can effectively manage unwanted moisture. Photo: NPS files.

low area, or cavity, between the structural elements and the interior and exterior surfaces. 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. The integrity of the wall surface has a great deal to do with how effective the wall is in discouraging moisture problems. It is always critical to identify the moisture source or the pathway of moisture that is allowing deterioration to occur. This avoids band aid solutions which are generally only cosmetic and will soon deteriorate.

Exterior surfaces were carefully detailed to protect from moisture deterioration. Masonry mortars of sand and aggregate generally included lime which gave flexibility to the mortar and allowed expansion and contraction (moisture diffusion) within the masonry joints without causing cracks to open up. If mortar joints in masonry walls, chimneys, or parapets have eroded, often first on the prevailing wind side of a building, it is important to repoint these joints to reduce wind-driven rain from wetting interior surfaces. 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. Too hard a mortar may also shift the natural moisture/vapor diffusion to a less resistant material, such as soft bricks. 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 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 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 generally dissipate without rotting or corroding materials within the wall. This cavity, however, is frequently lost, as modern replacement sidings are installed with wall insulation or wall insulation is pumped into the cavity to improve energy performance. This has been found to impede the natural movement of vapor and create a surface on which condensation can occur. With absorbent wall insulation, a chronic damp condition may occur particularly as the force of gravity allows moisture to settle at the bottom of the cavity. This can create long-term damage. The poor performance of paint retention on wooden siding after insulation of the cavity wall is often a direct result of condensation being held against the back of the painted wooden elements. Insulation added to a frame cavity in a retrofit situation should be held back from the outside wall cladding to retain an air space to help dissipate moisture. There continues to be discussion on whether or not having a vapor retarder will help reduce moisture migration into an insulated wall cavity. For residential properties, if moisture generated by household use can be controlled with exhaust fans, there is not a major problem. Problems can occur when excess humidification is introduced into building interiors through climate control systems and this moisture migrates into the frame walls through poorly overlapped vapor retarders or through electrical outlets.

Maintenance of exterior wall surfaces is critically 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. When repairing or cleaning wall surfaces, the gentlest means possible should be used and the surfaces should not be cleaned with power washers that drive moisture into buildings. Modern flashing and caulking (known as sealants) can improve perimeter protection around exterior openings and, if carefully installed, will not detract from the historic resource. Mortar joints should not be replaced by caulking or sealants, but should be repointed with appropriately formulated mortars. Clear coatings to discourage moisture penetration of rain are discouraged in the preservation field. Coatings may in fact interfere with the normal healthy pattern of movement of moisture in and out of materials and may trap salts and accelerate an efflorescence problem or form a cloudy film just under the applied coating. Rarely are moisture problems from materials that have become overly absorbent over the years. In most cases, repairing the joints or refurbishing aged paint coatings and ensuring that unwanted moisture is not from another source, like a roof leak, will resolve the moisture problem. If, as a last resort, consolidants or coatings are deemed necessary by a preservation specialist, they should be vapor permeable and not alter the historic appearance of the materials.

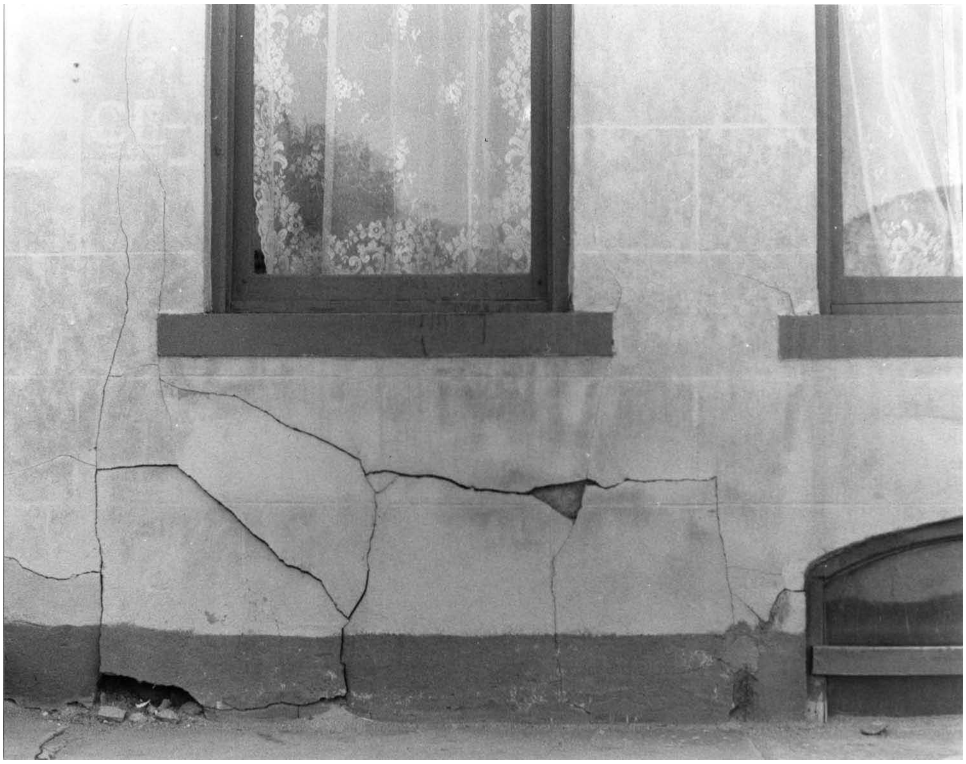


Fig. 8—Any obvious cracks in exterior materials, such as this stucco, should be evaluated and the materials repaired. Moisture has entered these cracks, caused either by impact, foundation settlement, or stucco shrinkage from the modern top-coat of stucco. Moisture has exacerbated the separation of the 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. Historic detailing, such as the scored pattern to represent stone blocks, should be matched as part of the repair. Photo: NPS files.

Evidence of Moisture Decay: Exterior Walls

- Paint: blistered or failed paint to the bare substrate
- Wood: rotted or punky, spongy material
- Bricks: cracked, pushed out of alignment, spalled, eroded, exhibiting efflorescence (salts brought out by moisture
- 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
- Presence of moss, lichens, or other growths fed by excess moisture

Sources or Pathways of Moisture: Exterior Walls

- Wind driven rain through eroded mortar joints, cracks in masonry (Fig. 9)
- Melting snow and ice or rain through open or deteriorated joints between wall surface and door or window openings
- Deteriorated downspouts (external or internal)
- Migration through porous or deteriorated materials
- Trapped moisture behind walls (from condensation in insulated cavities or broken pipes)
- Leaking plumbing pipes, frozen hose bibs, or water pipes in walls
- Most climbing vegetation (vines, ivy) growing on exterior walls and holding moisture against surfaces
- 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; be sure to correct underlying 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
- Ventilate, generally with exhaust fans, the interior of the building to reduce moisture that is transmitted through the exterior walls
- Properly prepare surfaces if they are to be repainted; remove mildew prior to repainting, but make sure that moisture source has been eliminated or mildew will reappear
- Replace deteriorated flashings at joints where features meet the wall
- Remove vegetative threats

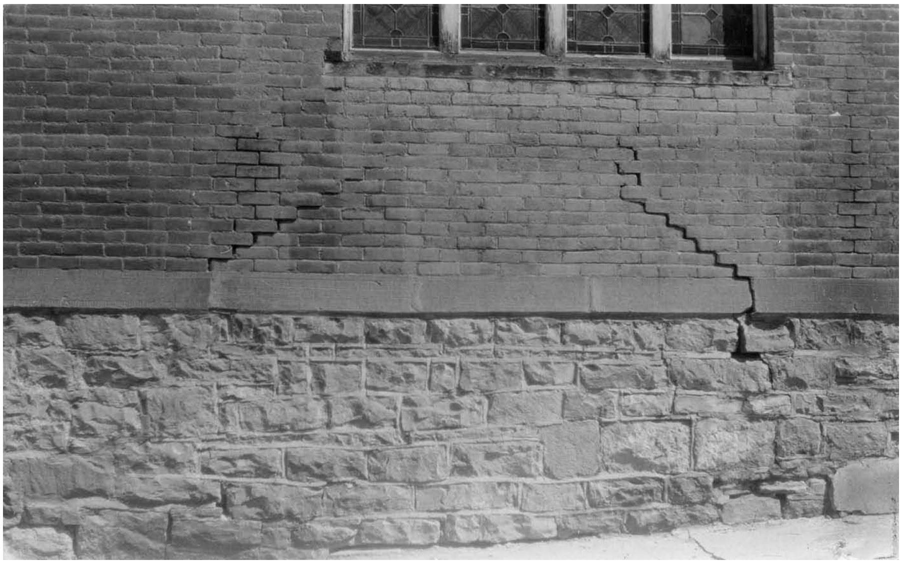


Fig. 9—The preservation team should include a structural engineer familiar with historic construction. The settlement cracks in this masonry wall, seen as staggered along the brick and stone coursing, is indicative of a foundation failure. Instead of merely repointing the masonry, the underlying cause should be determined or settlement will likely return. Mortar analysis of the historic mortar, for both the brick and stone repointing, should be made so that each repointing mortar matches in composition, strength, color, and texture of the historic. Photo: NPS files.

Treatments to Avoid: Exterior Walls

Do Not:

- Use power washing exteriors (force may drive moisture into the building)
- Apply waterproof coatings above grade (these tend to trap moisture within walls)
- Apply water-repellent clear coatings (may discolor materials or trap salts, use only as a last resort if there is a chronic absorption problem)
- Use modern caulking and sealants on vertical masonry wall surfaces (should be properly repointed instead)
- Use high cement content mortars (Fig. 10) or vapor impermeable synthetic patches (may erode weaker historic materials) (Fig. 11).

Windows/Doors

Windows and doors, as operable openings in wall surfaces, are subject to extreme wear which weakens joints, creates irregularities within the supporting frames, and can allow air and moisture infiltration. In addition, poor maintenance or structural settlement can result in deteriorated flashing, out-of-alignment sills and thresholds, perimeter gaps between wall and frame, and deteriorated finishes, such as paint. All of these conditions can provide a pathway for moisture to cause further problems. Historic windows, doors, and storefront assemblies were typically constructed of wood, rolled steel, bronze, Monel or aluminum, and glass (Fig. 12). Doors are hinged, either singly or in pairs, and windows were typically casements or double-hung units and some institutional windows used awning or pivot hinges. For glazing, 18th and early 19th century windows and door sidelights tended to be smaller and have multiple pane configurations. Later 19th and 20th 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, unfortunately, with modern thermal units that do not match the historic detailing of the originals.

Historic windows are usually critically important in imparting the historic character of the building and should be repaired. Owners are often encouraged by manufacturers to replace leaky windows with an energy efficient model. However, historic windows can be made more energy efficient if air infiltration around the perimeter of the sash is addressed. This also reduces wind-driven moisture from entering. Weather stripping sash, caulking or filling gaps around windows, eliminating cracks in glazing, and repair of deteriorated materials can often make the window opening as tight as a new window. Dual glazing with interior or exterior storms or piggyback panels can also help reduce condensation when there is a differential temperature drop between interior and exteriors and there is sufficient moisture in the air to condense on cold surfaces. It is not necessary to replace windows unless they have become so deteriorated that they cannot be saved. If windows are replaced, the design and detailing should carefully match the historic.

Evidence of Moisture Decay: Windows/Doors

- Blistered, peeling paint
- Rust or corrosion of metal
- Rotted, cracked, or punky, spongy wood (Fig. 12)
- Cupped, cracked, deteriorated, spalled window sills
- Water-stained areas around window perimeter
- Missing mortar or sealants around window perimeters

Sources and Pathways of Moisture: Windows/Doors

- Driving rain or dripping water penetrating window surrounds, cracks in units, broken glass
- Snow and ice buildup on sills, ledges, thresholds

Fig. 10—The design of masonry mortar has historically involved formulations, rich in lime, that allow moisture in the wall to evaporate through the joints. When vapor-impermeable paints and portland cement mortars are used as part of a repair in a cold climate, this often results in freeze-thaw damage. The weakest part of this wall is now the bricks and they have suffered irretrievable damage. Photo: NPS files.

Fig. 11—Care must be taken in designing repairs using synthetic patching compounds. When large sections of masonry need repair, it is often best to use new sections of masonry instead of synthetic compounds. Moisture, which moves naturally within a wall, can be trapped by vapor impermeable materials, leading to further decay of the historic substrate, as seen in this epoxy repair of the balcony. Photo: NPS files.

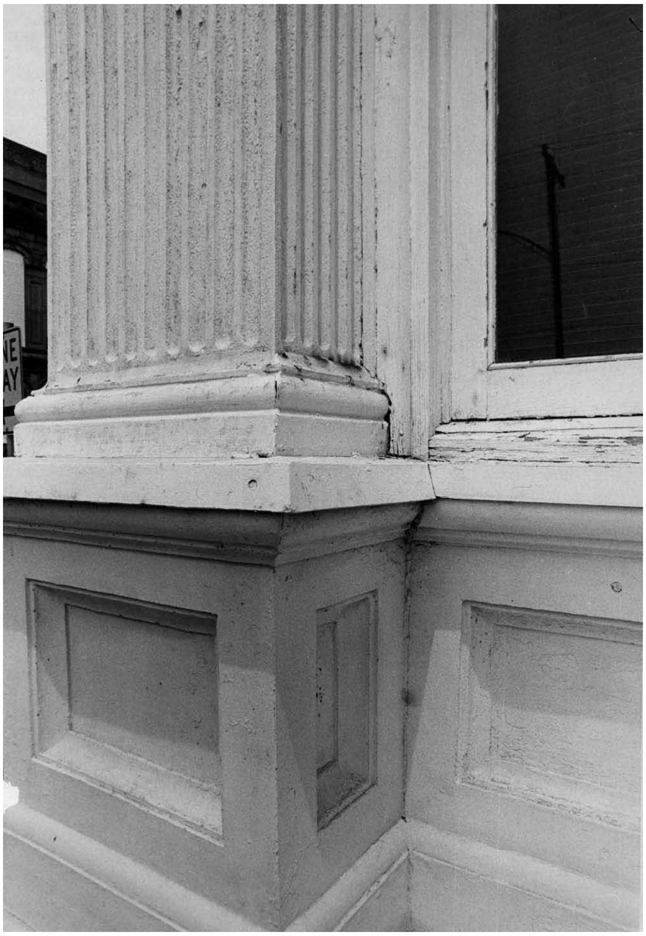


Fig. 12—Window and door openings are vulnerable to moisture decay and must be maintained to protect aging materials. In this leaded window in a historic gymnasium, the wooden frame is rotting and must be reinforced. In this case, either a wooden patch or a synthetic compound with a binder and wood fiber can successfully fill the relatively small hole and be shaped to the correct profile. With prime and top-coats of paint, the patch should be stable for a long time. Photo: NPS files.

- Moisture settlement on deteriorated exterior muntins, stiles, and rails
- Moisture penetration or air infiltration through exterior cracks, missing putty, loose sash
- Moisture condensation on glass
- Poorly fitting sash and doors

Remedial Treatments: Windows/Doors

- Repair windows/doors whenever possible (fillers/putty compounds, splicing/dutchman 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, weatherstripping)
- Upgrade with storm windows (sensitively designed units with venting capacity)
- Consider sash locks or other hardware to tighten window sash and doors

Treatments to Avoid: Windows/Doors

Do Not:

- Use unvented/fixed storm sash (can trap moisture condensation and for stained glass windows can create too much heat resulting in deteriorated lead cames)
- Pan over (covering with aluminum) deteriorated jambs, frames, and sills (will foster continued decay unseen below the new surfaces)

Roofs

Roofs and related guttering systems must be kept in good order and inspected regularly. 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 in the attic can also form 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 and there is positive drainage.

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 when insulation is installed in the rafters. This creates a situation where moisture may condense on roof sheathing, thereby accelerating deterioration of the roof covering. This is often seen in modern wood shingle installations where inadequate under-shingle ventilation is provided and shingles rot out quickly. Laying wooden shingles directly on roofing felts or interweaving roofing felts to reduce the size and overlap of shingles is a false economy and it generally shortens the life of a shingle roof.

Depending on the historic roofing materials, the roof may or may not have been painted. Wooden shingles were sometimes painted both to add color and to extend their useful life; 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 of colored slates. 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.

Flashing is a critical component of roofing and, unfortunately, metal flashing often will fail before the roof slates or coverings need replacement. Metal flashing historically was either copper, lead, or of a ferrous metal that needed repeated painting. If flashing has deteriorated, it is usually necessary to remove the shingles or covering and install new flashing and the new flashing should be of sufficient quality that it can last as long as the roof. When re-roofing, it helps to inspect the sheathing and to consider ice dam membrane flashing in cold climates. Extra protection around eaves and valleys can reduce damage from ice dams and blowing rain as the roof ages.

Evidence of Moisture Decay: Roofs

- Rusted, pitted, or deteriorated metal roofing, flashing, or downspouts (chimneys, valleys, gables, parapets all generally have some ferrous metal components) (Fig. 13)
- Broken or sagging gutters, ponding moisture on flat surfaces
- Missing or slipped roofing units: tiles, slates, shingles, parapet caps
- Cupped, cracked, or broken units, freeze-thaw spalling of tile, slate, or other roofing materials
- White stains (gypsum) or delaminated areas of slate
- Galvanic corrosion from incompatible metal components on the roof

Sources and Pathways of Moisture: Roofs

- Blocked gutters and downspouts as a result of poor maintenance, ice dams, or icicles
- Storm damage with broken, pulled away, or misaligned gutters
- Driving rain
- Ice dams, snow buildup
- Condensation in the attic (poor ventilation and ineffective ceiling/floor insulation, or both)
- Slow leaks from pinholes in flashing, inadequately lapped roofing, broken solder joints or deteriorated materials
- Moss or tree debris holding moisture onto the roof

Remedial Treatments: Roofs

- Monitor attics during a rain to try to locate areas of leaking
- Re-anchor 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

Fig. 13—Historic roofing and guttering systems are vulnerable to moisture penetration and rapid decay. Most roofing has a limited life and must be inspected every few years, but the guttering systems need regular semi-annual inspections and maintenance. Failure to maintain this gutter has caused surrounding damage to the decorative cornice and has saturated the wall closest to the downspout. The expansion of the ice trapped in the downspout has split the copper and will require additional repair. Photo: NPS files.

- During re-roofing consider reinforcements at eaves and intersections (snow membranes, flexible flashing)

Treatments to Avoid: Roofs

Do Not:

- Apply tar or other sealants to metal, tile, or slate roofing (traps moisture, petrochemicals may decay metal, hard to remove, unsightly)
- Insulate rafters without ventilation channels and vapor barriers (condensation)
- Install roofing felts directly under unventilated wooden shingles (shortens life)
- Interweave roofing felts with shakes (traps moisture and accelerates deterioration)
- Seal gable vents to reduce energy costs (leaves humidity and condensation in attic)
- Install vapor impermeable membranes completely under roofing units (traps moisture condensation)
- Install 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. Too often, owners or contractors immediately want to remove moisture-damaged materials, but if well constructed in the first place, some materials can survive if given enough time to dry out.

There has been a great deal of thought by a variety of scientists (some included in this publication) going into how building interiors should be handled to reduce the impact of moisture damage. For example, should frame building walls be insulated? How much ventilation should or should not be introduced in attics? Do humidifiers actually exacerbate a moisture cycle by drawing moisture through walls? This section on historic building interiors is general in nature and reflects the most common of problems. As with determining where moisture is coming from on exteriors, the impact of vapor transmission, condensation, and how moisture moves through historic interiors will vary with each individual building. The local climate, the stack effect of temperature, the amount of natural ventilation found in a somewhat leaky building, and other related microclimate issues may all play a role in determining the pathways of moisture and related damage.

In addition to appropriate treatments for controlling unwanted moisture, historic building owners also need to be aware of the design issues when modifications are made. 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 paneled interiors to relatively functional plastered office spaces. Finished spaces are often less easily monitored for moisture damage. When introducing new elements into a building, they should be compatible with the design of that structure.

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 frame with interior columns, or fireproof brick skewback 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. Thermal imaging can be used to determine different temperatures within walls, from colder damp areas to hot zones where there is termite activity. 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, rot forming fungus (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 and the expansion of ferrous metals due to oxidized corrosion is often seen in the jacking of the steel and the resultant protrusion of facing elements. 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 until the terra cotta cracks. Steel lintels over windows can be seriously damaged by undetected or neglected water leaks and the failure to periodically repaint exposed metal. Rusting streaks from corroding anchors or cracked or spalling elements will hint at an imminent 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. If funds are not available to rehabilitate a building with structural problems, it is often best to vacate a building, reinforce weakened structural elements, and to mothball it until funds are available.

Evidence of Moisture Decay: Structural Systems

- Sagging structural elements from moisture damaged components
- Settlement cracks in load-bearing walls from moisture saturated soil or ice heaving
- Separation of building elements (chimneys, porches) from deteriorated flashing and moisture penetration
- Spalling and erosion of materials
- Corrosion of metal structural elements and surface staining of rust
- Insect or fungal damage in wooden elements

Sources and Pathways 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 or snow pack on roof

Remedial Treatments: Structural Systems

- Investigate to determine source of moisture and correct the problem
- Repair deteriorated elements; eliminate source of moisture

Fig. 14—Fungal decay is a by-product of moisture damage in damp areas that can weaken structural elements. The removal of the flooring boards on this interior illustrates the loss of bearing capacity of the floor joist and that the dry rot, a type of fungus, has permeated the underside of the cupboard as well. The repair will fail unless the new joists are isolated from the damp foundation, preferably by deepening the crawl space and placing a slate or impervious element between the masonry wall and the joist. It is not advisable to install a poured concrete slab in the crawl space unless under-slab drains are installed to handle subsurface moisture as the build-up of ground moisture might cause a rising-damp condition in the wall. Photo: NPS files.

- Remove insect-damaged or fungal contaminated elements; treat areas to avoid recurrence
- Reinforce weakened elements (sistering, or doubling, of joists, epoxy repairs)
- Mothball or undertake emergency bracing or stabilization of weakened systems

Treatments to Avoid: Structural Systems

Do Not:

- Remove historic materials that can be reinforced and retained in place
- Use ferrous metal anchors or synthetic materials inappropriately (rusting, stress cracks)
- Cosmetically cover deterioration without removing moisture source
- Install 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 cause moisture problems within the building. 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 % relative humidity. Condensation at the dew point within a wall or on windows can cause moisture damage and even structural deterioration depending on its location and the rate of dissipation of moisture (Fig. 15). The presence of condensation on window interiors is a good indication that moisture vapor may be migrating into wall cavities. Conversely, condensation may occur on the outside of an air conditioned building in a hot, moist climate and may generate mold. The greater the differential between interior and exterior temperature and humidity levels, the greater the potential for condensation to form within building walls deteriorating wooden and metal elements. In cold climates, freeze-thaw damage to masonry exteriors and wooden walls 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. 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 and mold growth in historic buildings.

When considering the installation of new mechanical systems or upgrading existing systems, both the visual and performance characteristics need to be evaluated. There are two primary systems: forced air, usually ducted, and hydronic, usually in the form of two and four pipe fan coil systems. Each has its benefits and problems. Piped systems are often easier to install in finished spaces as the pipe runs are small and fan coils often fit comfortably where radiators have been removed. However, fan coils are notorious for leaking over time and any water source is subject to valve and pipe joint deterioration. Fan coil units of the type requiring direct fresh air intake grilles are damaging physically and visually to historic exterior walls and these type are not recommended. Ducted systems can distribute air more evenly, can be quieter, and can provide humidity as well, so they tend to be more conventional. However, they can cause more visual damage as boxed out soffits are intrusive and installation can cause physical damage as historic materials are removed to accommodate large ductwork. Smaller and flexible ducting systems have been developed for retrofit situations that are gaining popularity in the residential market.

In the rehabilitation of historic industrial buildings for a new use, for example housing, it is possible to use exposed mechanical ducts for heating and cooling in a manner that is visually compatible with the industrial character of the building. Because the ambient temperature around the exposed sheet metal ducts acclimatizes rapidly, there generally is not a problem of condensation occurring on the ductwork and dripping onto finished surfaces. If condensation does occur, it is usually corrected in balancing the system. However, any water pipes or ductwork in uninsulated or uncontrolled areas are subject to condensation, freezing and bursting, or both, so should be properly designed and insulated if necessary. For finished spaces where forced air ductwork is

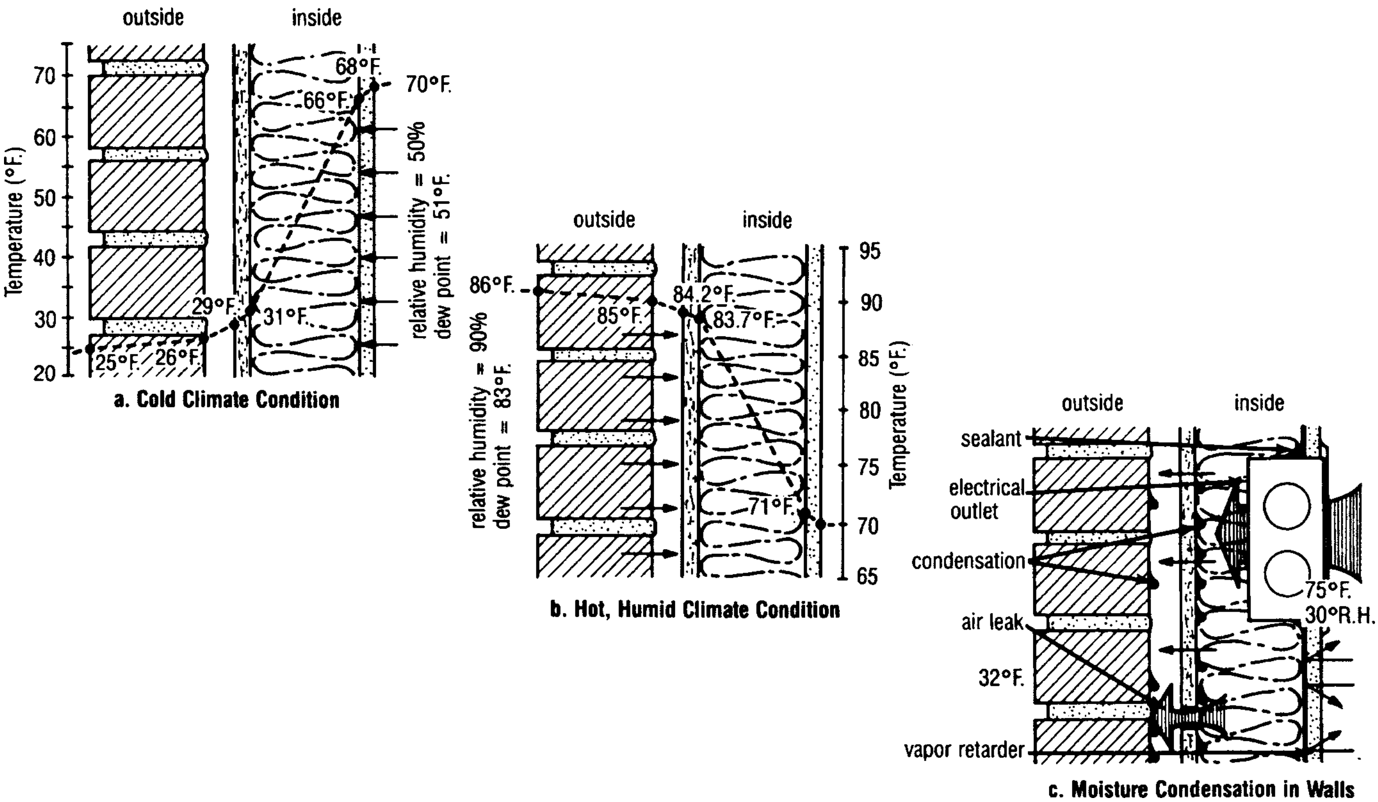


Fig. 15—Mechanical heating and cooling systems are designed to change the interior climate of a building, and, in so doing, the way buildings handle moisture is affected. The greater the differential between the interior climate and the outside environment, the greater will be the stress on the external envelope of the building. As moisture in the air dissipates from the warmer area to the colder area, there is often the evidence of condensation on the cold surfaces. There is also the chance for dewpoint condensation to occur within walls as moist air moves into insulated cavities, as seen in the diagram. Managing the temperature and relative humidity within buildings to avoid condensation is an important part of managing moisture problems. Image taken from the NPS publication *Preservation Briefs 24: Heating, Ventilating and Cooling Historic Buildings; Problems and Recommended Approaches*.

intended to be hidden, it is important to run soffits so that they do not run across window heads. Likewise, the placement of registers and grille work should not interfere with the design of symmetrical paneling or be cut into decorative trim work.

Installing climate control systems that infuse humidity into the air must be evaluated by a mechanical engineer familiar with the performance of these systems relative to the construction technology of the historic building. This is particularly important for museums. Studies using psychrometric charts can quantify when and where dew points will occur based on the temperature and relative humidity projected for specific situations. The notion that a building should remain at 70 °F with 50 % relative humidity has been challenged by the preservation community as perhaps good for a furniture or art collection but damaging for historic buildings. This is particularly true for frame buildings that cannot hold the controlled climate on the interior and tend to seek equilibrium with the outside temperature and relative humidity. If building doors are opened frequently for the passage of visitors, the HVAC system is strained to maintain a constant output. Many museums are utilizing climate controlled display cases for specialty collections and allowing the ambient air to fluctuate within larger parameters seasonally. When condensation is seen on window glass, it is usually an indication that moisture under vapor pressure may be migrating into cavity walls. In a number of unfortunate cases, historic frame buildings used for house museums have been insulated, sealed tight around exterior openings, and have had sophisticated climate controlled systems installed only to have extensive moisture damage. When there is too much interior moisture, it is driven into the cavity walls, wetting insulation and dripping moisture out of the sill plates. A tragedy in every case and often the result of humidity control valves failing over a weekend when no one was around to see the damage occur. Likewise, there have been instances where humidification systems have stopped and dry heat has resulted in cracking historic wooden paneling. While not a direct moisture problem, it is just as troublesome for a house museum.

As with any intervention into a historic building, there should be studies, backup systems to detect problems, and qualified maintenance personnel to monitor the systems.

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 and Pathways of Moisture: Mechanical Systems

- Condensation from poorly designed or malfunctioning climate control system
- Improperly maintained drainage and condensate lines
- Condensate forming on uninsulated sheet metal a/c duct-work
- 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 bathrooms, kitchens, laundry areas
- Maintain equipment and monitors
- Remove dampened insulation or other materials holding moisture
- Repair or remove rot damage before repairs are made

Treatments to Avoid: Mechanical Systems

Do Not:

- Install insulation in unvented walls (insulate attic and crawl space instead)
- Install through-wall or window air conditioners if condensate will wet wall
- Reduce ventilation as part of an energy retrofit (closing grills)
- Install 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 or plumbing leaks (Fig. 16), but catastrophic damage can result from hurricanes, storms, or firefighting. 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 (Fig. 17). 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. Mold is becoming a serious problem in buildings that have suffered extensive water damage and may have cultivated mold spores inside walls that have not been fully treated or abated with a biocide agent.

The question of using dehumidifiers in interior spaces continues to be controversial. In some cases, small residential dehumidifiers can be used seasonally to reduce ambient moisture and control mold. However, using a dehumidifier constantly as a means of reducing moisture in the air can acerbate a moisture problem by setting up a cycle where moisture is drawn through a wall from outside. Care should be taken not to set up this unwanted system. Sump pumps are often a helpful device where there is a periodic, seasonal, or in some cases, persistent, ground moisture problem.

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
- Cracked and detached plaster when connection between plaster and lath is lost or weakened (commonly called keys)
- Peeling paint; delaminating surfaces

Sources and Pathways of Moisture: Interior Finishes

- Leaking plumbing, fan coil, 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, or moisture resulting from construction, such as new plaster
- 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 if beneficial in basement areas

Treatments to Avoid: Interior Finishes

Do Not:

- Undertake wholesale removal of damaged interiors if repair is possible
- Apply vinyl, varnish, or other waterproof coatings over chronic dampness
- Rapidly drying out water-damaged interiors with heaters (will warp, crack, deteriorate finishes)

Conclusion

There are no shortcuts to curing or managing moisture problems in historic buildings. It is important that a systematic approach be taken to ensure that the source or pathways of the moisture have been properly identified so that an effective treatment can be implemented. In the case of historic buildings, however, modern waterproofing treatments and

Fig. 16—Many historic buildings have elaborate finishes that can easily be damaged by moisture. Damage, as seen in the circa 1880s wallpapered ceiling, may be the direct result of a leaking roof, poor flashing around a chimney, or may come from a slow plumbing leak. Once damaged, these decorative finishes are hard to repair and generally must be replaced. Any evidence of peeling paint or damp staining should immediately be investigated to determine and repair the source of the leak. Photo: NPS files.

other techniques for stemming the flow of moisture through the building may be damaging or simply a band aid solution that may allow more damage to occur in the long run. As a result, careful monitoring of conditions, 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.

Maintenance may be one of the most effective means of controlling moisture damage in historic buildings. By keeping exterior surfaces in prime condition, by cleaning gutters and downspouts regularly, by checking the effectiveness of bulk water run off away from foundations and basements, it may be possible to eliminate all unwanted moisture penetration. Likewise, on the interior of a building, providing adequate ventilation in areas where excessive moisture is generated, such as kitchens and bathrooms, or controlling interior temperature and relative humidity levels to avoid condensation can go a long way to avoiding internal moisture damage. Regular inspections of plumbing pipes and control valves on mechanical equipment should be part of any regular maintenance plan. If there is water damage from an unforeseen disaster that has saturated finishes, it is important to dry out a building slowly while avoiding creating a mold problem.

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 list of publications is available on the web at the Technical Preservation Services pages found at www.cr.nps.gov/hps/tps.

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 of 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

Fig. 17—Moisture damage does not mean that all is lost. This decorative plaster ceiling in a circa 1900 Beaux Arts mansion was damaged when plumbing pipes under the roof froze and burst, but the ceiling was saved. After inspection both from below and using a fiberoptic boroscope inserted into the ceiling cavity, it was determined that most of the plaster keys holding the ceiling in place were sound and just needed to dry out. It takes about a month for every inch of damp plaster to fully dry and so the ceiling was left to dry for about a month. Next, with rubber mallet soundings, selective loose areas were reattached with epoxy adhesive injected through the plaster into the wood lath strips to create new keys. When dry, the ceiling was repainted and all the decorative elements were saved. Photo: NPS files.

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, Technical Preservation Services 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:

Technical Preservation Services
National Park Service (org.2255)
Washington, DC 20240
Tel. (202) 354-2034
⟨http:www.cr.nps.gov/hps/bookstore.htm⟩

Superintendent of Documents
Government Printing Office
PO Box 371964
Pittsburgh, PA 15250-7954
Tel. (202) 512-2250 (in Washington, DC)
⟨http://bookstore.gpo.gov/sb/sb-140.html⟩

U.S. Department of Commerce
National Technical Information Service (NTIS)
For orders: 1-800-553-6847
⟨http://www.ntis.gov/support/ordering.htm#online⟩

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. Reprinted in 1997. Free from NPS, Heritage Preservation Services.

Metals in America's Historic Buildings: Uses and Preservation Treatments. Margot Gayle and David W. Look, AIA. 1980. Updated in 1992 by John G. Waite, FAIA. Government Printing Office stock number: 024-005-01108-1. $15.00 per copy.

Moisture Problems in Historic Masonry Walls. Baird M. Smith. 1984. Government Printing Office. This book is now out of print, but may be found in some libraries, call number TH9031.s65.1984.

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, listed below, deal with documentation and moisture-related damage. Individual briefs cost approximately $2.00 and are available from the Government Printing Office (phone: (202) 512-1800). The Briefs are available in bundled sets from GPO, but are listed separately to identify the topics relevant to moisture. See the NPS website (www.cr.nps.gov/hps) for the "bookstore" which lists a variety of publications and how the sets of Preservation Briefs are packaged. Prices are subject to change.

- *Preservation Briefs* 1: *The Cleaning and Waterproof Coating of Masonry Buildings*, Robert C. Mack, AIA, and Anne Grimmer, 2000, GPO No. 024-005-01207-9.
- *Preservation Briefs* 2: *Repointing Mortar Joints in Historic Brick Buildings*, Robert C. Mack, AIA, and John P. Speweik, 1998, GPO No. 024-005-01192-7.
- *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,-f 988, 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.
- *Preservation Briefs* 35: *Understanding Old Buildings: The Process of Architectural Investigation*, Travis C. McDonald, Jr., 1994, GPO No. 024-005-01143-9.
- *Preservation Briefs* 39: *Holding the Line: Controlling Unwanted Moisture in Historic Buildings*, Sharon C. Park, AIA, 1996, GPO No. 024-005-01168-4.
- *Preservation Briefs* 43: *The Preparation and Use of Historic Structure Reports*, Deborah Slaton, 2004, GPO No. 024-005-01191-9.

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, $4.00 per copy.

The Secretary of the Interior's Standards and Illustrated Guidelines for Rehabilitating Historic Buildings, 1992, GPO No. 024-005-01091-2, $13.00 per copy.

ADDITIONAL PUBLICATIONS

- Conrad, Ernest A., P.E., "The Dews and Don'ts of Insulating," *Old-House Journal*, May/June, 1996.
- Labine, Clem, "Managing Moisture in Historic Buildings," Special Report and Moisture Monitoring Source List, *Traditional Building*, Vol. 9, No. 2, May–June 1996.
- Leeke, John, "Detecting Moisture; Methods and Tools for Evaluating Water in Old Houses," *Old-House Journal*, May/June 1996.
- Oxley, T. A. and Gobert, A. E., *Dampness in Buildings: Diagnosis, Treatment, Instruments*, Butterworth-Heinemann, London, Boston, 1994.
- Rose, William, "Effects of Climate Control on the Museum Building Envelope," *Journal of the American Institute for Conservation*, Vol. 33, No. 2, 1994.
- Rose, William B, *Water in Buildings: An Architects' Guide to Moisture and Mold*, John Wiley & Sons, Toronto, Hoboken, NJ, 2005.

REFERENCES

[1] A most authoritative book on technical issues of moisture is *Water in Buildings; An Architect's Guide to Moisture and Mold* by William B. Rose, one of the contributing authors to this ASTM publication on moisture.

[2] Secretary of the Interior's Standards for the Treatment of Historic Properties were first published in 1977 and can be found on the Web at www.cr.nps.gov/hps/tps.

[3] The Rehabilitation Guidelines are set up by materials and features and stress the importance of conservative, traditional approaches to maintenance and using the gentlest means possible to care for materials so that the new work is physically compatible with the building materials.

MNL18-EB/Oct. 2009

23

Contract Documents and Moisture Control

Horace Calvin Crofford[1] and 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.

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.

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 was named MasterFormat by CSI and consisted of 16 divisions in the 1978 edition, which provided 16 separate classified work results or construction practices. These 16 divisions served the industry well for many years; however, as the construction industry progressed, new products and systems were produced that were not originally envisioned by the format developers. These new products and systems lacked proper classification and also overloaded the organizational structure of several divisions. CSI responded to the industry's need by updating MasterFormat. The updated MasterFormat 2004 provided an expanded organizational structure that allowed room for future growth, an expanded numbering system, and identification of current technology. To accomplish this change MasterFormat 2004 was expanded to 49 divisions, and installed a new numbering system. Because the industry is presently in the transition of employing the new MasterFormat 2004, both the old and the new systems will be described; however, references within the below text will default to new MasterFormat 2004 divisions, numbering, and title conventions when not identified as a MasterFormat convention. The following table compares the division layout of MasterFormat and MasterFormat 2004.

MasterFormat (1995)

Division	Title
00	Procurement and Contracting Requirements
01	General Requirements
02	Site Work
03	Concrete
04	Masonry
05	Metals
06	Wood and Plastics

MasterFormat 2004

Division	Title
00	Procurement and Contracting Requirements
01	General Requirements
02	Existing Conditions
03	Concrete
04	Masonry
05	Metals
06	Wood, Plastics, and Composites

[1]Original document was authored by Mr. Mundle (deceased) and updated by Mr. Crofford. Both authors are current or past employees of Naval Facilities Engineering Command. The opinions expressed in this paper are the author's and are not intended to represent the opinions of any government agency.

MasterFormat (1995)

Division	Title
07	Thermal and Moisture Protection
08	Doors and Windows
09	Finishes
10	Specialties
11	Equipment
12	Furnishings
13	Special Construction
14	Conveying Equipment
15	Mechanical
16	Electrical

MasterFormat 2004

Division	Title
07	Thermal and Moisture Protection
08	Openings
09	Finishes
10	Specialties
11	Equipment
12	Furnishings
13	Special Construction
14	Conveying Equipment
15	*Reserved for Future Expansion*
16	*Reserved for Future Expansion*
17	*Reserved for Future Expansion*
18	*Reserved for Future Expansion*
19	*Reserved for Future Expansion*
20	*Reserved for Future Expansion*
21	Fire Suppression
22	Plumbing
23	Heating, Ventilation, and Air-Conditioning (HVAC)
24	*Reserved for Future Expansion*
25	Integration Automation
26	Electrical
27	Communications
28	Electronic Safety and Security
29	*Reserved for Future Expansion*
30	*Reserved for Future Expansion*
31	Earthwork
32	Exterior Improvements
33	Utilities
34	Waterway and Marine Construction
35	*Reserved for Future Expansion*
36	*Reserved for Future Expansion*
37	*Reserved for Future Expansion*
38	*Reserved for Future Expansion*
39	*Reserved for Future Expansion*
40	Process Integration
41	Material Processing and Handling Equipment
42	Process Heating, Cooling, and Drying Equipment
43	Process Gas and Liquid Handling, Purification, and Storage Equipment
44	Pollution Control Equipment
45	Industry-Specific Manufacturing Equipment
46	*Reserved for Future Expansion*
47	*Reserved for Future Expansion*
48	Electrical Power Generation
49	*Reserved for Future Expansion*

Organization of Specifications

Divisions

Each division covers a major trade or building component or a group of related components or products. For example, all plumbing work is specified in Division 22, while all masonry is specified in Division 04. A useful tool to find where a particular material may be specified is CSI's Masterformat 2004 Keyword Index. Each keyword listed is referenced to a preferred specification location. Most professionals writing construction specifications and most systems of guide specifications follow CSI's format recommendations [1]. The following are Masterformat 2004 division titles and descriptions of items listed in the division.

Division 00—Procurement and Contracting Requirements. This division includes the contractual documents that advise the contractor how to pursue the business aspects of the contract. The solicitation, bidding, conditions of the contract, and award are specified in this division.

Division 01—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 02—Existing Conditions. This includes assessment, investigation, demolition, and remediation of the site.

Division 03—Concrete. This includes cast-in-place concrete and precast concrete. The provision of an underslab vapor retarder is generally specified in this division but is listed in Division 07. Also included is lightweight insulating concrete.

Division 04—Masonry. Includes concrete, brick, and stone masonry, mortar, and grout. Cementitious dampproofing (parging) for moisture control is located in Division 07.

Division 05—Metals. Structural steel, joists, steel deck, cold-formed metal framing, miscellaneous metals, and expansion joints. Shop applied corrosion protection is specified in this division and field applied protection against moisture-induced corrosion is specified in Division 09.

Division 06—Wood and Plastics, and Composites. Includes rough and finish carpentry, framing and decking, cabinetry, and plastic fabrications. 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 07—Thermal and Moisture Protection. This is the division in which most moisture and water protection items and materials are specified, including dampproofing and waterproofing, roofing, siding, flashing, and vapor retarders. The individual sections of this division will be discussed in greater detail below.

Division 08—Openings. The division includes all types of windows (aluminum, steel, wood, and plastics), metal curtain walls, doors, louvers, and skylights. 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 will be drastically different from that for a one-story residence, 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 09—Finishes. Includes lathing, plaster, stucco, drywall, floor finishes, such as 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 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 from vault doors, library equipment, and 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 ventilation to the indoor face of exterior walls in cold climates can cause cold spots that can result in moisture condensation and mold growth. But such problems are the result of improper design and cannot 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, steam rooms, and cold storage rooms. Solar collectors are located in Division 23 and energy monitoring and control systems are located in Division 25.

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 walks, and turntables. None of these systems should be of concern with regard to moisture control.

Division 21—Fire Suppression. This division includes systems that are used for fire extinguishing and suppression.

Division 22—Plumbing. This includes the materials, fixtures, and equipment used in plumbing of domestic, sanitary, storm, gas, air, and chemical systems within the building.

Division 23—Heating, Ventilating, and Air-Conditioning (HVAC). This division includes heating, ventilating, air conditioning, and intergal piping systems. 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.

Division 25—Integrated Automation. The contents of this division range from network to facility controls systems.

Division 26—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.

Division 27—Communications. As the title implies, this division is devoted to communications systems. These include cabling, data, voice, and video systems.

Division 28—Electronic Safety and Security. This includes access control, surveillance, detection and alarm, and monitoring systems.

Division 31—Earthwork. This division includes clearing, earth moving, shoring, special foundations, and tunneling, With regard to moisture control, grading for proper surface run-off and subsurface drainage are of importance and are specified in this division.

Division 32—Exterior Improvements. The contents of this division include paving, fencing, irrigation, and planting.

Division 33—Utilities. As the title implies, this division lists the site utilities. This includes storm, fuel distribution, steam, electrical, and communications systems.

Division 34—Transportation. This includes rail, traction, signaling and control equipment, and bridges.

Division 35—Waterway and Marine Construction. This division includes waterfront and dam signaling, control, and construction equipment.

Division 40 through Division 48—Process Equipment Subgroup. Each individual division is listed above. This Subgroup contains materials, equipment, temperature control, drying, pollution control, and power generation for process system.

Sections

The divisions are subdivided into individual sections, each covering a specific building component, system, or work result. 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 49 divisions and gives it a six-digit number. The section describes the basic unit of work. A section must answer three fundamental questions:

1. What inter-relationship 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. Broadscope sections have three significant digits followed by three zeros. The broadscope titles for Division 07, Thermal and Moisture Protection listed in the CSI Masterformat 2004, are

071000 Dampproofing and Waterproofing: This broadscope section covers dampproofing and waterproofing membranes and coatings. Dampproofing and waterproofing are used for different purposes and are further defined in the medium scope and narrow scope sections.

072000 Thermal Protection: 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.

074000 Roofing and Siding Panels: Metal and plastic fabrications which often include insulation and vapor retardant components.

075000 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.

076000 Flashing and Sheet Metal: A very important section for moisture investigators. This section needs to be very carefully coordinated with the drawings to ensure proper details for flashing.

077000 Roof and Wall Specialties and Accessories: Included here are roof ventilators and other roof attachments. The primary interest for moisture investigators is that of flashing.

079000 Joint Protection: Sealants and Caulkings used to seal joints to prevent the intrusion of water. Care should be taken to ensure that these sealants and caulkings form an integral part of the water management system of the building envelope and 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. Mediumscope sections have four significant digits followed by two zeros. For example, the broadscope categories 071000, Dampproofing and Waterproofing; 072000, Thermal Protection; 073000, Steep Slope Roofing; and 078000, Fire and Smoke Detection; can be subdivided into these mediumscope section titles:

071100 Dampproofing: This covers coatings which are not expected to withstand water under pressure.

071300 Sheet Waterproofing: This contains one of the waterproofing systems using a single ply sheet material. Waterproofing is expected to withstand hydrostatic pressure.

071800 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.

071900 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.

072100 Thermal 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.

072200 Roof and Deck Insulation: Covers both flat and tapered insulation for low slope roofs.

072400 Exterior Insulation and Finish Systems: Complete wall assemblies which include inside and outside finishes, structure, and insulation and vapor retardant properties.

072600 Vapor Retarders: Usually single-purpose membranes to prevent the passage of water vapor by means of low permeance.

072700 Air Barriers: Products, such as House-Wrap or TYVEK®, used to restrict air flow through building enclosures.

073100 Shingles and Shakes: Composition shingles, metal and wood shingles, and ceramic products used to cover (usually residential or light commercial buildings) sloped roofs. Sometimes products which function as a vapor barrier are included in these sections.

078100 Applied 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.

078400 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.

Narrowscope: A narrowscope section becomes very specific, limited to subsets of the mediumscope section, covering a particular product. Narrowscope sections have six significant digits. For example, using mediumscope Section 072100 Thermal Insulation, some narrowscope sections are

072113 Board Insulation: Plastic foam and mineral fiber boards.

072116 Blanket Insulation: Fiberglass and mineral fiber.

072119 Foamed-in-Place Insulation: Urethanes.

072123 Loose Fill Insulation: Vermiculite, perlite, mineral wool, and cellulose.

072126 Blown Insulation: Cellulose, mineral fiber.

072129 Sprayed Insulation: Spray-on 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 has provided a standardized format for the sections themselves, known as the three-part format. This three-part format is called CSI SectionFormat [1]. 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 Project Resource Manual-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 (Prescriptive)

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.

Performance specifications are the preferred specification method for design-build contracts. Specifying the material or system results follows the design-build concept of allowing the contractor latitude to meet the needs of the facility user. However, pure performance specifications are difficult to create. The performance characteristics or means of assuring performance compliance are not always available. This lack of performance standards often leads the specifier of a design-build contract to utilize combinations of performance, reference standard, and descriptive specifications to establish a level of materials and systems quality for the facility.

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, 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 are 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 07, some are specified elsewhere. For example, vapor retarders are sometimes found in Division 03 Concrete when used under a concrete slab and in Division 09 when the vapor retarder is also a finish such as vinyl fabric wall covering or water vapor resistant paint. (Vinyl wall coverings are fairly good vapor retarders. 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:

033000 Cast-In Place 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.

042000 Unit Masonry: In this section will be specified the allowable absorption of masonry units and parging to provide moisture protection to masonry walls.

085100 Metal Windows, 085200 Wood, 085300 Plastic Windows, and 085600 Special Windows: In these sections, window performance factors, such as condensation resistance factor, are specified. Also included are discussions of flashing methods.

087100 Door Hardware: Weatherstripping is the only subject in this section with relevance to moisture.

088000 Glazing: Use of sealed insulating glazing is covered in this section.

089000 Louvers and Vents: This section covers metal louvers used in walls and doors. Mechanisms to prevent the entry of moisture should be included.

092900 Gypsum 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.

097216 Vinyl-Coated Fabric Wall Coverings: This section covers wall-decorating materials which can act as a vapor retarder.

099000 Painting and Coating: In this section, consideration should be given to the permeability of coatings specified.

220000 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.

230000 Heating, Ventilating, and Air Conditioning (HVAC): 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.

230700 HVAC Insulation: This section covers insulation used on piping and ductwork and will have an impact on possible condensation problems.

238413 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.

238416 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. Part 3 of all sections related to moisture protection needs to be carefully reviewed and coordinated with other related sections.

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. This provides the specification writer an opportunity to act as a quality control person: 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? These types of questions must be answered before a specification is considered done and completed.

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 automated software program was originally developed for NASA's construction program. SpecsIntact utilizes the currently Department of Defense—Unified Facilities Guide Specification (UFGS) database to create project specific specifications. The Naval Facilities Engineering Command, the Army Corps of Engineers, and the Air Force have further developed and adopted SpecsIntact, which has become the official specification processing system for the four 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) or accessible on the Internet [5,6].

Water Vapor, Air, and Weather Barriers/Retarders

Probably no other issue related to moisture control in buildings has generated as much discussion, controversies, and misunderstandings as the need for, usefulness of, and undesirability of installing or omitting vapor retarders, air barriers, and weather barriers. The specification writer must be fully cognizant of the purposes of each of the three components and the differences between them.

The functions of building envelope include control of the flow of water vapor, air, and liquid water into and out of the building interior and envelope cavities. A membrane whose purpose it is to control water vapor movement is called a vapor retarder (formerly called a vapor barrier), a membrane or structure whose purpose it is to control the flow of air is called an air barrier, and a membrane or structure whose purpose is to exclude liquid water is commonly called a weather barrier or water resistive barrier. It must be kept in mind that the same membrane or structure may perform several functions; for example, a vapor retarder can also function as an air barrier if it has the structural capacity to withstand air pressure and if it is installed in such a way as also to prevent air flow.

Specifying any of those barriers is difficult for a number of reasons:

(1) Moisture may be carried by air or water vapor diffusion through materials.
(2) Air flow is more effective in carrying moisture than vapor diffusion.
(3) Moisture diffusion takes place when there is a difference in vapor pressure or a difference in temperature.
(4) Vapor always moves to the lower vapor pressure or to lower temperature.
(5) Depending on the degree of air tightness the requirements for vapor control may vary.
(6) Depending on the climate different degrees of vapor retardance may be required.

Effectively, the specification writer must consider air and vapor controls together and be fully cognizant of the purposes of either of the two components and the differences between the two. Note that for both vapor retarders and air barriers, the installation details are critical. The specification writer has to give careful thought to Part 3 of the two sections. Both vapor retarders and air barriers also require to be installed in the proper location. This depends mainly on climate factors. And both vapor retarders and air barriers must be carefully coordinated with other envelope constructions and materials. For more detailed discussions on vapor retarders and air barriers, see Chapters 12 through 16 of this manual. As a general rule, a hydrothermal analysis is the only reliable method to determine whether a vapor retarder or air barrier is needed and where it is to be located.

Vapor Retarders

The beginning of this category of membranes dates to 1920s when the pioneering work by University of Minnesota led to acceptance of building paper weather barriers, as distinct from roofing materials. The building paper was placed on the external side of the wall, impeding the movement of air and rain while permitting some moisture to permeate to the outdoors. The building paper reduced heat losses by limiting air leakage, improved indoor comfort by reducing drafts, and reduced moisture damage to the walls by preventing entry of wind. The multitude of functions performed by building paper applied to the exterior of frame walls led to variations in the name ascribed to this material layer: it has been called a weather, moisture, or water barrier; weather resistive barrier or water resistive barrier both having the same acronym, and therefore the term WRB is typically used.

To improve thermal comfort in 1920s wall cavities were filled with insulation—first using wood chips stabilized with lime, then with shredded newsprint, and eventually mineral fiber batts. Yet, scientists observed that the presence of thermal insulation in the wood frame cavity lowered the temperature on the outer side of the cavity, leading to a higher potential for vapor condensation that, in turn, may be detrimental to the durability of the wall.

The risk for condensation inside wood-frame walls gave rise to a new area of research. As a result of these studies, the term vapor barrier was coined and defined as a membrane having a water vapor flow rate of 1 perm (57 $ng/m^2 \cdot s \cdot Pa$). In the 1960s the term was revised to vapor retarders as, technically speaking, commonly used materials of 1 perm do not constitute a complete barrier but do allow some minor vapor flow. This is the term used by ASHRAE and ASTM and should be used in specifications exclusively.

More recently, some technical people attempted to distinguish between more effective control associated with the name of barriers and less effective control of retarders. However, there is no consensus as to what the performance levels associated with the two terms should be. Accordingly, the specification community has not accepted the concept of dual levels of water vapor retardation and current guide specification systems include only vapor retarders of 1 perm (57 ng/m^2·s·Pa).

As a general rule, it is highly desirable to conduct a moisture analysis to determine whether, and in what location, a vapor retarder should be installed in any particular case. See Chapter 9 for guidance on moisture analysis.

Air Barriers

The purpose of air barriers is to restrict the flow of air through and into envelope components. Most concerns relating to vapor retarders also apply to air barriers, except that air tightness of the installation is more critical for air barriers than for vapor retarders. Also, air barriers must be designed and installed such as to withstand significant air pressures. Since water and water vapor can move in conjunction with air flow, restricting air flow also can be beneficial by reducing moisture flow through and into envelope components, but restricting such flow can also inhibit timely drying out of envelope constructions. Air barriers can be applied membranes or can be in the form of panels, such as gypsum board or plywood, as long as their edges are adequately sealed.

Weather Barriers

The term weather barrier has been used to identify membrane-type barriers to prevent liquid moisture to gain access into the envelope construction. The term is prominently used in envelope construction in the rain screen principle.

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 supersede 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.

BIBLIOGRAPHY

Ayers, C., *Specifications for Architecture, Engineering and Construction*, 2nd ed., McGraw-Hill, New York, 1984.

Jellinger, T. C., *Construction Contract Documents and Specifications*, Addison-Wesley Publishing Co., Reading, MA, 1981.

Rosen, H. J., *Construction Specifications Writing, Principles and Procedures*, John Wiley and Sons, New York, 1974.

Rosenfeld, W., *The Practical Specifier*, AIA, McGraw-Hill, New York, 1985.

Simmons, H. L., *The Specification Writer's Handbook*, John Wiley and Sons, New York, 1985.

Simmons, H. L., *The Specification Writer's Book of Checklists and Forms*, John Wiley and Sons, New York, 1986.

References

[1] CSI Masterformat 2004/CSI SectionFormat, The Construction Specifications Institute, Alexandria, VA.

[2] *The Project Resource Manual-CSI Manual of Practice*, The Construction Specifications Institute, Alexandria, VA.

[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, Washington, DC.

24

Guidelines, Standards, and Codes

Theresa A. Weston[1] and Wayne P. Ellis[2]

Preface

SIGNIFICANT DEVELOPMENTS HAVE OCCURRED over the 13 years since this chapter was originally published. That being said, the industry is continuing a significant amount of development activity in codes and standards. The update of the chapter maintains the same format as the original chapter. The 1994 chapter was reviewed and revised as well as updated. Much of the chapter's original content remains pertinent and was retained. New information is added. Of special interest are a number of new standards related to the analysis of building systems for moisture performance and standards for system installation or performance testing. There has also been increased focus on climate-based guidelines and recommendations.

Standard Terminology in Moisture Control

In 1994, this chapter stated that "there was no standard terminology of moisture control in building design, operation, and maintenance." And continued stating "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." Since then, although some standard terminology has begun to be used, much of the confusion and ambiguity remains.

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*[3] is "a written statement or outline of policy, practice, or conduct."

There are many definitions for the term *standard*

1. "a physical reference used as a basis for comparison or calibration;[4]
2. "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;"
3. "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."[5]
4. "Common and repeated use of rules, conditions, guidelines or characteristics for products or related processes and production methods, and related management systems practices."[6]
5. "The definition of terms; classification of components; delineation of procedures; specification of dimensions, materials, performance, designs, or operations; measurement of quality and quantity in describing materials, processes, products, systems, services, or practices; test methods and sampling procedures; or descriptions of fit and measurements of size or strength."[4]

Standards 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). In addition to general consensus and industry standards, there are labeling/certification programs which recognize specific qualities of buildings, such as their energy efficiency, or sustainability and often have developed certification standards specifically for their purposes. Examples of certification programs in the construction industry are *ENERGY STAR*[7] for Residential Housing (U.S. Environmental Protection Agency), the *LEED*[8] family of rating systems, and *Health House:*

- ENERGYSTAR for Residential Housing is a part of the energy efficiency program developed and implemented by the U.S. Environmental Protection Agency. ENERGYSTAR is often most associated with rating of appliance energy performance. The residential housing ENERGYSTAR recognizes new home construction with energy efficiency performance 20–30 % above the IECC 2004. The certification relies on the Home Energy Rating System (HERS) and has been updated since its inception to reflect changes to both the HERS rating sys-

[1] *DuPont Building Innovations, P.O. Box 27001, Richmond, VA 23261.*
[2] *Standards consultant* (*deceased*).
[3] ASTM E631-06, Standard Terminology of Building Constructions.
[4] ASTM E1316-09a, Standard Terminology for Nondestructive Examination.
[5] ISO/IEC Guide 2:2004, "Standardization and Related Activities—General Vocabulary," International Organization for Standards, Geneva, 2004.
[6] U.S. Environmental Protection Agency, www.energystar.gov
[7] Circular A-119, U.S. Government Office of Management and Budget, Washington, DC, Oct. 1982.
[8] U.S. Green Building Council, www.usgbc.org.

tem and the energy code. In 2006 a "thermal bypass checklist" was added to the criteria and provides a list of common problematic air sealing details.

- *Leadership in Energy and Environmental Design* (*LEED*) is a family of rating systems developed by the U.S. Green Building Council to rate the environmental impact of buildings. The first rating system was *LEED NC* which was introduced in 2000 to cover new nonresidential construction. It was followed by *LEED EB* (existing buildings) and *LEED CI* (commercial interiors) in 2004 and *LEED CS* (core and shell) in 2005. *LEED H* (homes) and *LEED ND* (neighborhood development) are due to be introduced in 2007.
- *Health House* introduced by the American Lung Association[9] is focused on indoor environmental quality and provides a set of guidelines promoting moisture management and reducing pollutants.

ASTM International has a specific definition of the term standard, "a document that has been developed and established within the consensus principles of the Society and that meets the approval requirements of ASTM procedures and regulations." It is further noted that "the term "standard" serves in ASTM International as a nominative adjective in the title of documents, such as test methods or specifications, to connote specified consensus and approval."[10] ASTM also categorizes its standards as *classifications, guides, practices, specifications, terminology*, and *test methods*. Other consensus organizations have similarly defined their standards documents.

A *code* (in the law) "is a collection of laws (regulations, ordinances, or statutory requirements) adopted by governmental (legislative) authority."[3] Codes are further classified as building codes, energy codes, fire codes, plumbing codes, mechanical codes, and electrical codes. In North America, codes are normally written as model codes. They do not take on the force of law until they are adopted by a jurisdiction, usually a state or local municipality In addition to the adoption of model codes, some jurisdictions will enact special legislation. In relation to the topic of moisture, special legislation most commonly covers legal and insurance issues related to remediation of uncontrolled moisture or mold damage.

Information Sources

This chapter used as its basis Chapter 24 in the 1994 edition of *ASTM Manual 18: Moisture Control in Buildings* by Wayne P. Ellis. References were updated and, as in the 1994 edition are detailed in the bibliography and footnotes to this chapter (the bibliography is arranged in chronological order). Updates to this chapter were primarily a result of search for moisture-control information standards available through on-line databases as shown in Table 1. On-line databases were chosen as the basis for the searching because the results would be most readily available to the user of this manual.

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 25 years, much field study and research has been conducted on the overall subject of control of moisture problems in buildings. Valuable guidance has been developed in this period, but much of it is recorded in technical papers, symposia, and articles in the technical press. Many standards have only been recently published, others are in the draft or prepublication form. This chapter references published sources from 1955 to through 2007, but is not intended to be an all inclusive citation of resources for this time period.

[9] American Lung Association, www.healthhouse.org

[10] ASTM International, Form and Style for ASTM Standards, 2002.

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.[3] This chapter will categorize the standards identified according to these building elements, i.e., the roof, walls, floors, and foundations (earth-coupled spaces). Standards related to the specification and installation of common building components and systems, or both, used in building envelope are also included. Although building mechanical systems can affect the moisture loads and transport within or through the building envelope standards specifically related to buildings' mechanical (HVAC) systems are not covered in this chapter.

The basic mechanisms of moisture movement through the envelope are leakage or permeation of liquid water, entrainment of moisture within *air leakage*, and diffusion of water vapor. Control of direct leakage of liquid water has received significant recent attention due to several highly publicized moisture and mold related building failures including the failure of EIFS cladded buildings in North Carolina, and the "leaky condo" problems in Vancouver, British Columbia Moisture intrusion studies have found that a key issue is to reduce the water intrusion at building envelope interfaces, such as those around windows.[11,12] These failures have led to an increase in development activity of standards on the design and construction of building elements to resist intrusion from precipitation, i.e., rain.

Control or reduction of *air leakage* has received much attention in energy conservation research and practice because of potentially significant heating and cooling 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.[13] Control of air infiltration or leakage for energy conservation also benefits moisture control, but it often considered a secondary consideration. In a 1984 review,[14] it was found that twelve countries had adopted standards of build-

[11] Best, Al et al., "Water Intrusion and Remediation for Wood Frame Homes with Exterior Insulation and Finish Systems (EIFS)," The EIFS Review Committee, Jan., 1999.

[12] Morrison Hershfield Limited, "Survey of Building Envelope Failures on the Coastal Climate of British Columbia," prepared for CMHC, November 22, 1996.

[13] 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.

[14] Jackman, P. A., "Review of Building Airtightness and Ventilation Standards," *Implementation and Effectiveness of Air Infiltration Standards in Buildings, Proceedings, 5th AIC Conference*, Reno, Nevada, Air Infiltration Centre, Bracknell, UK, 1984.

TABLE 1—Information sources.

Organization	Website	Topic
AAMA, American Architectural Manufacturers Association	www.aamanet.org	Aluminum and vinyl windows and curtain walls
ABAA	www.airbarrier.org	Air barriers
APA, The Engineered Wood Association	www.apawood.org	Wood based sheathing and cladding
ASHRAE, American Society of Heating, Refrigeration and Air-conditioning Engineers	www.ashrae.org	Moisture control standards for building envelope and HVAC
ASTM International	www.astm.org	General
BIA, Brick Industry Association	www.bia.org	Brick and masonry cladding
BSI British Standards On-line	www.bsonline.bsi-global.com	General
Canada Mortgage and Housing Corporation,	www.cmhc-schl.gc.ca	Residential Construction
CSA, Canadian Standards Association	www.csa.ca	General/Building Performance
EEBA, Energy and Environmental Building Association	www.eeba.org	Building Envelope/ Water Management
European Committee for Standardizations	www.cenorm.be	General
GA, Gypsum Association	www.gypsum.org	Gypsum-based sheathings, exterior and interior
International Code Council Evaluation Services	www.icc-es.org	Model code acceptable materials and products
ISO, International Standards Organization	www.iso.org	General/Building Performance
NAHB Research Center	www.nahbrc.org	Residential Construction
National Research Council Canada	www.nrc-cnrc.gc.ca	Building Performance
NIBS	www.nibs.org	Building Envelope Research
NIST, Building & Fire Research	www.nist.govlab	Building Durability Research
NRCA	www.nrca.net	Roofing and water-proofing
SWRI	www.swrionline.org	Sealants and water-proofing
U.S. DOE Building America	www.eere.energy.gov/ buildings/building_america	Energy efficient residential construction

ing airtightness and ventilation requirements. Achenbach et al.[15] described and discussed envelope condensation control including that relating to leakage of moisture laden air. Since 1984, air infiltration control has been included in the 1995 Canadian National Building Code.[16] Di Lenardo et al. describes the technical requirements for an air barrier system to meet the intent of the Canadian National Building Code.[17] Building airtightness provisions have also been added at the state level in the United States, most notably in the provisions of the 2001 Massachusetts Commercial Energy Code[18] and in the residential construction provisions in the 2000 Minnesota Energy Code[19] and energy design credits in the California Energy Code.[20]

In the *Whole Building Design Guide*[21] the building envelope is viewed as a combination of the individual building systems (e.g., roofs, walls, etc.). Moisture control considerations are considered as it relates to each of the individual building systems.

Guidelines and Installation Practices

Although there has been significant activity in the development of guidelines for the control of moisture control problems, there are still only relatively few universally accepted, reliable guidelines. One widely referenced work is the *ASHRAE Handbook of Fundamentals*,[22] in which chapters prepared by ASHRAE Technical Committees 4.4 on Building Materials and Building Envelope Performance and 4.3 on Ventilation Requirements and Infiltration provide moisture control guidance. ASHRAE Standards 90.1[23] and 90.2[24] pro-

[15] 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.

[16] 1995 National Building Code of Canada.

[17] Di Lenardo, B. Brown, W. C., Dalgleish, W. A., Kumaran, K., and Poirier, G. F., "Technical Guide for Air Barrier Systems for Exterior Walls of Low-Rise Buildings," National Research Council Canada, Ottawa, Ontario, Canada, 1995.

[18] Massachusetts Board of Building Regulations and Standards, www.mass.gov/bbrs/

[19] Minnesota Department of Labor and Industry, www.doli.state.mn.us/bc_energy.html

[20] California Energy Commission, *Low Rise Residential Alternative Calculation Method Approval Manual for Compliance with California's1998 Energy Efficiency Standards*, Section 3.9, Publication Number: P400-98-003, Dated Published: November 1998, Effective Date: July 1, 1999.

[21] *www.wbdg.org*, © National Institute of Building Science, 2006.

[22] 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.

[23] ASHRAE Standard 90A-1980: Energy Conservation in New Building Design.

[24] ASHRAE Standard 90.1-1989: Energy Efficient Design of New Buildings Except Low-Rise Residential Buildings.

vide guidelines for energy conservation including control of air infiltration, but moisture control is not specifically addressed. ASHRAE Standards 62.1 and 62.2 address ventilation and indoor air quality.

The past ten years have seen an increase in the use of hygrothermal modeling for diagnosis and design of building envelopes. *ASTM Manual 40: Moisture Analysis and Condensation Control in Building Envelopes*[25] provides a comprehensive review of the use of hygrothermal models. Accurate material properties are required for model operation and this has led to research on test methods to determine material hygrothermal properties and ultimately to several new standards. In order to standardize the loads, boundary conditions and criteria used in hygrothermal analysis, ASHRAE is currently developing Standard 160P Design for Moisture Control in Buildings. The purpose and scope of this proposed standard are shown below.[26]

1. "PURPOSE

1.1 The purpose of this Standard is to specify performance-based design criteria for predicting, mitigating or reducing moisture damage to the building envelope, materials, components, systems and furnishings, depending on climate, construction type, and system operation. These criteria include:

- *criteria for selecting analytic procedures*
- *criteria for inputs*
- *criteria for evaluation and use of outputs*

2. SCOPE

2.1 This standard applies to the design of new buildings and retrofit and renovation of existing buildings.

2.2 This standard applies to all types of buildings, building components and materials.

2.3 This standard applies to all interior and exterior zones and building envelope cavities.

2.4 This standard does not directly apply to thermal comfort, or acceptable air quality.

2.5 This standard does not address the design of building components or envelopes to resist liquid water leakage from sources such as rain water, ground water, flooding, or ice dams."

Other guidelines exist in technical publications,[27] but many are based on the ASHRAE guidelines and upon published results of 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 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.

Guidelines and standard practices for the use and installation of specific materials or systems are published by some building trade organizations, materials manufacturer organizations, and standards organizations. These documents are beneficial in understanding and implementing good trade practices.

[25] "Moisture Analysis and Condensation Control in Building Envelopes," "*Moisture Primer*," Heinz R. Trechsel, *ASTM Manual 40*, 2001.

[26] "Titles, Purposes, and Scopes of ASHRAE Standards and Guidelines" (July 5, 2005), www.ashrae.org

[27] See bibliography.

ASTM Standard Guidelines and Practices

In the field of moisture control, several ASTM standard practices and guidelines are directed to quality in construction. Examples include:

C755-03 Standard Practice for Selection of Water Vapor Retarders for Thermal Insulation: Outlines factors to be considered, describes design principles and procedures for water vapor retarder selection, and defines water vapor transmission values appropriate for established criteria. It is intended for the guidance of design engineers in preparing vapor retarder application specifications for control of water vapor flow through thermal insulation. It covers commercial and residential building construction and industrial applications in the service temperature range of −40 to +150°F (−40 to +66°C). Emphasis is placed on the control of moisture penetration by choice of the most suitable components of the system.

C1158-05 Standard Practice for Installation and Use of Radiant Barrier Systems (RBS) in Building Construction: Describes recommendations relative to the use and installation of RBS including surfaces normally having a far-infrared emittance of 0.1 or less. Among other applications this standard addresses: (1) low emittance surfaces in vented or unvented building envelope cavities intended to retard radiant transfer across the airspace; (2) low emittance surfaces at interior building surfaces intended to retard radiant transfer to or from building inhabitants; and (3) low emittance surfaces at interior building surfaces intended to reduce radiant transfer to or from radiant heating or cooling systems. The installation process from preinstallation inspection through post-installation procedure is covered.

C1193-09 Standard Guide for Use of Joint Sealants: Describes the use of a cold liquid-applied sealant for joint sealing applications. Including joints on buildings and related adjacent areas, such as plazas, decks, and pavements for vehicular or pedestrian use, and types of construction other than highways and airfield pavements and bridges. Information in this guide is primarily applicable to a single and multi-component, cold liquid-applied joint sealant and secondarily to a precured sealant when used with a properly prepared joint opening and substrate surfaces. This standard replaced an earlier standard C962 "*Guide for Use of Elastomeric Joint Sealants*."

C1320-05 Standard Practice for Installation of Mineral Fiber Batt and Blanket Thermal Insulation for Light Frame Construction: Describes procedures for the installation of mineral fiber batt and blanket thermal insulation in ceilings, attics, floors, and walls of new or existing housing and other light frame construction. This practice covers the installation process from preinstallation inspection through post-installation inspection, including information relating to installation of vapor retarder facings.

C1321-04 Standard Practice for Installation and Use of Interior Radiation Control Coating Systems (IRCCS) in Building Construction: Describes recommendations related to the use and installation of IRCCS, including a surface(s) having a far-infrared emittance of 0.25 or less that is sprayed or painted. Some examples that this practice is intended to address include: (1) low emittance surfaces in vented building envelope cavities intended to retard radiant transfer across the vented airspace; (2) low emittance surfaces at interior building surfaces intended to retard radiant transfer to or from building inhabitants; and (3) low emittance surfaces at interior building surfaces intended to reduce radiant transfer to or from heating or cooling systems. This practice covers the installation process from pre-installation inspection through post-installation.

C1401-09a Standard Guide for Structural Sealant Glazing: Describes information useful to design professionals, manufacturers, contractors, and others for the design and installation of a SSG system. This information is applicable only to this glazing method when used for a building wall that is not more than 15° from vertical; however, limited information is included concerning a sloped SSG application. Structural sealant glazing (SSG) is an application where a sealant not only can function as a barrier against the passage of air and water through a building envelope, but also primarily provides structural support and attachment of glazing or other components to a window, curtain wall, or other framing system.

D6135-05 Standard Practice for Application of Self-Adhering Modified Bituminous Waterproofing: Describes minimum installation recommendations for self-adhering sheets used in waterproofing.

D6622-01(2009) Standard Guide for Application of Fully Adhered Hot-Applied Reinforced Waterproofing Systems: Describes the minimum installation recommendations for fully adhered, hot-applied reinforced waterproofing systems on vertical and low-slope (plaza deck) surfaces.

D6769-02 Standard Guide for Application of Fully Adhered, Cold-Applied, Prefabricated Reinforced Modified Bituminous Membrane Waterproofing Systems: Describes application and installation requirements for fully adhered, cold-applied, prefabricated modified bituminous membrane waterproofing systems for below-grade or below-wearing-surface (such as plaza decks) vertical or horizontal applications.

E241-08 Standard Guide for Limiting Water-Induced Damage to Buildings: Describes the need for systematic evaluation of factors that can result in moisture-induced damage to a building or its components. This standard presents design construction, commissioning, operation, and maintenance. practices intended to limit deterioration problems involving combinations of building materials. The emphasis of this guide is on low-rise buildings. Portions of this guide, however, may also be applicable to high-rise buildings. This guide was retitled from its original title, "Practices for Increasing Durability of Building Constructions Against Water-Induced Damage" when it went through a major revision published in 2000.

E2112-07 Standard Practice for Installation of Exterior Windows, Doors and Skylights: Describes the installation of fenestration products in new and existing construction. Originally adopted in 2000 this standard has been revised several times to reflect on-going progress in installation methods.

E2267-04 Standard Guide for Specifying and Evaluating Performance of Single Family Attached and Detached Dwellings-Indoor Air Quality: Contains suggested performance statements for single family residential buildings that address indoor air quality performance including indoor air pollution and thermal comfort. These performance statements are not presented as proposed requirements, but are written in permissive language as suggestions that can be used in developing specifications to satisfy user needs.

E2351-04a Standard Guide for Specifying and Evaluating Performance of Single Family Attached and Detached Dwellings-Functionality: Describes examples of performance statements for functional and operable, spaces, products, components, and subsystems for single family attached and detached dwellings.

Canadian Standards

CAN/CGSB 149.10-M86 Determination of the Airtightness of Building Envelopes by the Fan Depressurization Method

CAN/CGSB 149.15-96 Determination of the Overall Envelope Airtightness of Buildings by the Fan Pressurization Method Using the Building's Air Handling Systems

CSA A440.4-07 Window, Door, and Skylight Installation

CSA S478(2001) Guideline on Durability in Buildings: Considers the agents and mechanisms related to durability and provides advice for incorporating requirements for durability into the design, operation, and maintenance provisions for buildings and their components. It includes (a) definitions of performance, failure, service life, and other concepts related to building durability; and (b) guidance for designers, builders, owners, and operators on achieving durability by planning the design, construction, maintenance, repair, and renovation of buildings.

European and British Standards

EN ISO 10211:2007 Thermal bridges in building construction—Calculation of heat flows and surface temperatures: Describes specifications for a three-dimensional and a two-dimensional geometrical model of a thermal bridge for the numerical calculation of heat flows, in order to assess the overall heat loss from a building or part of it and minimum surface temperatures, in order to assess the risk of surface condensation.

EN 12114:2000 Thermal performance of buildings—Air permeability of building components and building elements—Laboratory test methods.

EN ISO 13788:2001 Hygrothermal performance of building components and building elements—Internal surface temperature to avoid critical surface humidity and interstitial condensation—Calculation methods.

EN ISO 15927:2003 Hygrothermal performance of buildings—Calculation and presentation of climatic data—

- *Part 1 (2003): Monthly means of single meteorological elements:* Specifies procedures for calculating and presenting the monthly means of those parameters of climatic data needed to assess some aspects of the thermal and moisture performance of buildings. This specification covers the following single climate variables: air temperature; atmospheric humidity; wind speed; precipitation; solar radiation; longwave radiation.
- *Part 4 (2005):* Specifies a method for constructing a reference year of hourly values of appropriate meteorological data suitable for assessing the average annual energy for heating and cooling.
- *Part 5: Data for design heat load for space heating:* Specifies the definition, method of calculation and method of presentation of the climatic data to be used in determin-

ing the design heat load for space heating in buildings. These include the winter external design air temperatures and the relevant wind speed and direction, where appropriate.

- *Part 6:* Specifies the definition, method of computation and method of presentation of data on accumulated temperature differences, used for assessing the energy used for space heating in buildings. These are normally expressed in degree-hours or degree-days, and such data are often referred to simply as "heating degree-hours" or "heating degree-days."

North American Industry Guidelines

APA[28] *Build a Better Home Series:* A series of documents relating wood frame construction which highlight design and simple construction details of building components. There are separate documents on roofs, walls and foundations:

- Build A Better Home—Foundations—Revised 2003;
- Build A Better Home—Mold and Mildew—Revised 2003;
- Build A Better Home—Walls—Revised 2002;
- Build A Better Home—Roofs—Revised 2003.

CMHC[29] *Best Practice Guides:* Provide recommendations for architects, contractors, engineers, developers and other building professionals. Guides on the following subjects are published:

- Glass and Metal Curtain Walls
- Exterior Insulation and Finish Systems
- Fire and Sound Control in Wood Frame, Multi-family Buildings
- Architectural Precast Concrete: Walls and Structure—Revised
- Brick Veneer Steel Stud
- Brick Veneer Concrete Masonry Unit Backing
- Flashings
- Wood Frame Envelopes
- Wood-Frame Envelopes in the Coastal Climate of British Columbia

EEBA[30] *Builders Guides:* Provide a compendia of illustrations and resources on building design and systems (e.g., house layout and design, foundations, framing, HVAC, insulation, drywall, plumbing, electrical systems, painting, sheathings, and windows) and their relationship to moisture control, energy efficiency, and ventilation. There are four guides, each written with a focus on specific climate:

- Cold (*heating*) (2006)
- Hot Humid (2005)
- Hot Dry-Mixed Dry (*cooling*) (2004)
- Mixed Humid (*heating and cooling*) (2005)

EEBA Water Management Guide:[31] Describes a variety of recommendations for minimizing water intrusion into homes. The recommendations that are not intended to apply to every conceivable situation but are intended to illustrate principles as they apply to water in the liquid form—rain water and ground water. This guide has been referenced in industry specifications, for example by the Environments for Living Program[32]

GA[33] *216-04: Application and Finishing of Gypsum Panel Products:* Provides recommendations for the proper installation and finishing of gypsum board products, including related accessories, over a variety of substrates and framing.

GA 238-03: Guidelines for Prevention of Mold Growth on Gypsum Board: Provides guidelines on protecting gypsum board products from moisture exposure during on transportation, storage, and application. Guidelines are designed to minimize the potential for mold growth on gypsum board products.

GA 600-03: Fire-Retardant Design Manual: Includes design and application of water-vapor retarders in conjunction with gypsum board products.

NAHB Green Building Guidelines (*2007*)*:* Provide a practical baseline for determining minimum thresholds for resource-efficient, cost-effective home building.

SWRI Clear Water Repellent Manual (*2007*)*:* Discusses the surface preparation, the proper equipment and the proper applications necessary to ensure long term performance of clear water repellants. Includes a "Clear Water Repellent Checklist."

SWRI Sealants: The Professional's Guide (*1995*)*:* Provides an overview of building sealants.

U.S. DOE Building America[34] *Best Practices Series:* Provides design recommendations and process improvements developed under the Building America program to aid builders interested in re-engineering their home designs to achieve high performance. Five volumes are published, each focusing on a specific climate:

- Volume 1 (2004) Builders and Buyers Handbook for Improving New Home Efficiency, Comfort, and Durability in the Hot and Humid Climate
- Volume 2 (2005) Builders and Buyers Handbook for Improving New Home Efficiency, Comfort, and Durability in the Hot-Dry and Mixed-Dry Climates
- Volume 3 (2005) Builders and Buyers Handbook for Improving New Home Efficiency, Comfort, and Durability in the Cold and Very Cold Climates
- Volume 4 (2005) Builders and Buyers Handbook for Improving New Home Efficiency, Comfort, and Durability in the Mixed-Humid Climate
- Volume 5 (2006) Builders and Buyers Handbook for Improving New Home Efficiency, Comfort, and Durability in the Marine Climate

U.S. HUD-PATH Durability by Design: A Guide for Residential Builders and Designers (*2002*)*:* Provides information on housing durability issues, and addresses ground and surface water, rain and water vapor, sunlight, insects, decay and corrosion, natural hazards, and miscellaneous issues.

Material Property Test Method Standards

This section does not intend to include a list of all possible test methods but focuses on test methods that are used to

[28] APA-The Engineered Wood Association, www.apawood.crg

[29] Canada Mortgage and Housing Corporation, www.cmhc-schl.gc.ca

[30] Lstiburek, J. W. Ph.D., P.Eng., *EEBA Water Management Guide*, 3rd ed., 2006,© EEBA, Inc.

[31] Energy and Environmental Energy Association, www.eeba.org

[32] Environments for Living®, www.eflbuilder.com

[33] Gypsum Association, 810 First St. NE, Suite 510, Washington, DC 20002 (www.gypsum.org)

[34] U.S. DOE Building America, www.eere.energy.gov/buildings/building_america

characterize materials for inclusion in hygrothermal analysis or which are used in water or moisture resistance material specification.

ASTM Standards

C1104/C1104M-00(2006) Standard Test Method for Determining the Water Vapor Sorption of Unfaced Mineral Fiber Insulation: Describes the determination of the amount of water vapor sorbed by mineral fiber insulation exposed to a high-humidity atmosphere. This test method is applicable only to fibrous base material and binder. The results obtained by this test method cannot be used in describing faced products, since the facing is not tested by using this test method.

C1134-90(2007) Standard Test Method for Water Retention of Rigid Thermal Insulations Following Partial Immersion: Describes the determination of the amount of water retained (including surface water) by rigid block and board thermal insulations used in building construction applications after these materials have been partially immersed in liquid water for prescribed time intervals under isothermal conditions. This test method does not apply to the 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.

C1498-04a Standard Test Method for Hygroscopic Sorption Isotherms of Building Materials: Specifies a laboratory procedure for the determination of hygroscopic sorption isotherms of any construction materials. The purpose of this procedure is to obtain, for a specified temperature, by means of a specified laboratory procedure, the values of the equilibrium moisture content at various levels of RH. These values are used either as means to characterize the material or as material characteristics needed as input to appropriate computer models that can simulate wetting or drying potential of individual building materials or material assemblies under specified environmental conditions.

C1512-07 Standard Test Method for Characterizing the Effect of Exposure to Environmental Cycling on Thermal Performance of Insulation Products: Evaluates the ability of a product to maintain thermal performance and critical physical attributes after being subjected to standardized exposure conditions. A comparison is made between material properties for reference specimens stored in the laboratory for the test period and specimens subjected to a two-stage test method. This test method is applicable to preformed or field manufactured thermal insulation products, such as board stock foams, rigid fibrous and composite materials manufactured with or without protective facings.

D779-03 Standard Test Method for Water Resistance of Paper, Paperboard, and Other Sheet Materials by the Dry Indicator Method: Describes the determination of the time required for water to pass through a specimen of paper. This test method measures the combined effect of vapor and liquid transmission. For test times up to approximately 30 s, liquid transudation rate is dominant and this test method can be considered to measure this property. As test times exceed 30 s, the influence of vapor-transmission rate increases and this test method cannot be regarded as a valid measure of liquid resistance. This test method is of value in cases where paper or a paper container comes into contact with water on one face. This method is referenced in ICC-ES AC38 Acceptance Criteria for Water-Resistive Barriers.

D1499-05: Standard Practice for Filtered Open-Flame Carbon-Arc Exposures 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.

D1653(2008): Standard Test Methods 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 E96.

E96/E96M-05: Standard 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. A major revision in 2005 included the addition of method corrections for:

- Buoyancy
- Resistance Due to Still Air and Specimen Surface
- Edge Masking

E398-03(2009)e1: Standard Test Method for Water Vapor Transmission Rate of Sheet Materials Using Dynamic Relative Humidity Measurement: Describes the dynamic evaluation of the rate of transfer of water vapor through a flexible barrier material and allows conversion to the generally recognized units of water vapor transmission (WVT) as obtained by various other test methods. 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.

E2178-03 Standard Test Method for Air Permeance of Building Materials: Determines the air permeance of building materials at various pressure differentials with the intent of determining an assigned air permeance rate of the material at the reference pressure difference (P) of 75 Pa. The method is intended to assess flexible sheet or rigid panel-type materials using a 1 m by 1 m specimen size.

F372-99(2003): Standard Test Method for Water Vapor Transmission Rate of Flexible Barrier Materials Using an Infrared Detection Technique: A procedure for measuring water vapor transmission 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.

F1249-06: Standard Test Method for Water Vapor Transmission Rate Through Plastic Film and Sheeting Using a Modulated Infrared Sensor: A method for evaluating water vapor transmission, in which, 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.

G154-06 Standard Practice for Operating Fluorescent Light Apparatus for UV Exposure of Nonmetallic Materials: Covers the basic principles and operating procedures for using fluorescent UV light, and water apparatus intended to reproduce the weathering effects that occur when materials are exposed to sunlight (either direct or through window glass) and moisture as rain or dew in actual usage. Replaced G53-96 Practice for Operating Light-and Water Exposure Apparatus (Fluorescent UV-Condensation Type) for Exposure of Nonmetallic Materials.

European and British Standards

CEN/TR 14613:2003 Thermal performance of building materials and components—Principles for the determination of thermal properties of moist material and components

EN 12524:2000 Building materials and products—Hygrothermal properties—Tabulated design values

EN ISO 12570:2000 Hygrothermal performance of building materials and products—Determination of moisture content by drying at elevated temperature

EN ISO 12571:2000 Hygrothermal performance of building materials and products—Determination of hygroscopic sorption properties

EN 12664:2001 Thermal performance of building materials and products—Determination of thermal resistance by means of guarded hot plate and heat flow meter methods—Dry and moist products of medium and low thermal resistance

EN 1266:2001 Thermal performance of building materials and products—Determination of thermal resistance by means of guarded hot plate and heat flow meter methods—Products of high and medium thermal resistance

EN 13009:2000 Hygrothermal performance of building materials and products—Determination of hygric expansion coefficient

EN ISO 15148:2002 Hygrothermal performance of building materials and products—Determination of water absorption coefficient by partial immersion

North American Industry Standards

AATCC[35] *Method 35-2006: Water Resistance: Rain Test:* Measures the resistance of fabrics to the penetration of water by impact, and thus can be used to predict the probable rain penetration resistance of fabrics. Tests may be made at different intensities of water impact to give a complete picture of the penetration resistance of a single fabric or combination of fabrics. This method has been suggested for use in evaluating water-resistive barriers.[36]

AATCC "Method 127-2003: Water Resistance: Hydrostatic Pressure Test:" Measures the resistance of a fabric to the penetration of water under hydrostatic pressure. It is applicable to all types of fabrics, including those treated with a water resistant or water repellent finish. This method is referenced in ICC-ES Acceptance Criteria AC-38 for Water-Resistive Barriers.

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 system testing or design guidelines. Exceptions are the standards described below. Also included are standards relating to decks over enclosed spaces.

C898-01: Standard 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.

C981-05: Standard Guide for Design of Built-Up Bituminous Membrane Waterproofing Systems for Building Decks: Describes the design of fully adhered built-up bituminous membrane waterproofing systems for plaza deck and promenade construction over occupied spaces of buildings where covered by a separate wearing course.

D5843-95(2006) Standard Guide for Application of Fully Adhered Vulcanized Rubber Sheets Used in Waterproofing: Provides information to assist the specifier in developing a specification for the application and protection of fully adhered EPDM (elastomeric terpolymer synthesized from ethylene, propylene, and diene monomer), butyl, and neoprene vulcanized rubber sheets to be installed on concrete substrates.

D5957-98(2005) Standard Guide for Flood Testing Horizontal Waterproofing Installations: Provides a method for testing the watertightness of waterproofing installations applied to horizontal surfaces having a slope not greater than 20 mm/m (2 % slope) (1/4 in. per ft). The method is intended for waterproofing installation on parking garages and plaza deck type applications over habitable spaces or on elevated structures, but is not intended for use on building roofing systems.

E936-98(2004) Standard Practice for Roof System Assemblies Employing Steel Deck, Preformed Roof Insulation, and Bituminous Built-up Roofing: Describes 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.

Canadian Standards

CAN3-A123.52-M85 (R2001) Asphalt Shingle Application on Roof Slopes 1:6 to Less Than 1:3

[35] American Association of Textile Chemists and Colorists (AATCC), www.aatcc.org

[36] Weston, T. A., et al., "Water Resistance and Durability of Weather-Resistive Barriers," *Journal of ASTM International*, Vol. 3, No. 3, March 2006, Paper ID JAI12842. Presented at the *Symposium on the Performance of the Window-Wall Interface*, sponsored by ASTM Committee E06 on Performance of Buildings, April 18, 2004.

European and British Standards

CR 833:1992 General Requirements for a Discontinuously Laid Roofing Covering

BS EN 1304:1998 Clay Roofing Tiles for Discontinuous Laying. Products Definitions and Specifications

EN 1847:2001 Flexible Sheets for Waterproofing—Plastic and Rubber Sheets for Roof Waterproofing—Methods for Exposure to Liquid Chemicals, Including Water

EN 12056-3:2000 Gravity Drainage Systems Inside Buildings—Part 3: Roof Drainage, Layout and Calculation

North American Industry Standards

The NRCA Roofing and Waterproofing Manual [37] is a comprehensive description of roofing system design and application. NRCA published its first manual, *A Manual of Roofing Practice*, in 1970. This was NRCA's first reference guide developed by roofing contractors that dealt with good roofing practice. This manual subsequently was revised in 1971, 1973, and 1976. In its original and revised editions, *A Manual of Roofing Practice* primarily addressed roofing practices relating to built-up membrane roof systems. It includes construction details for several types of roofing systems. Currently, the NRCA Manual covers roofing deck and below-grade waterproofing.

The NRCA Guide to Roof Coatings: Includes application of various types, where best used and preparation for successful performance.

Walls, Fenestration, Materials, and Systems

ASTM Standards

There are many ASTM standards concerned with materials used in walls and fenestrations promulgated by the ASTM committees:

- C01 Cement
- C09 Concrete and Concrete Aggregates
- C11 Gypsum and Related Building Materials and Systems
- C12 Mortars and Grouts for Unit Masonry
- C14 Glass and Glass Products
- C15 Manufactured Masonry Units
- C16 Thermal Insulation
- C17 Fiber-Reinforced Cement Products
- C18 Dimension Stone
- C24 Building Seals and Sealants
- C27 Precast Concrete Products
- D01 Paint and Related Coatings, Materials, and Applications
- D06 Paper and Paper Products
- D07 Wood

Most of the standards produced by these committees are concerned with materials and their testing, not with system testing or design guidelines. Exceptions are the standards described below.

C209-07ae1: Standard Test Methods for Cellulosic Fiber Insulating Board: Included are test methods for water absorption (immersion), water vapor transmission (ASTM E96), and water vapor content (gravimetric).

C240-08e1: Standard Test Methods of Testing Cellular Glass Insulation Block: Included is a test method for water absorption by immersion under isothermal conditions.

C553-08: Standard Specification for Mineral Fiber Blanket 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.

C739-08: Standard Specification for Cellulosic Fiber 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.

C846-94(2003) Standard Practice for Application of Cellulosic Fiber Insulating Board for Wall Sheathing: Describes the requirements for storing, handling, and application of cellulosic fiber insulating board products.

C1136-08: Standard 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).

C1601-09: Standard Test Method for Field Determination of Water Penetration of Masonry Wall Surfaces: Describes the field determination of water penetration of a masonry wall surface under specific water flow rate and air pressure conditions. Surface penetration is defined as the amount of water passing through the wall surface exposed to testing per unit time per unit area. This property is not directly comparable to water penetration and leakage, which are typically defined as the amount of water travelling completely through a masonry system.

D822-01(2006): Standard Practice for Filtered Open-Flame Carbon-Arc Exposures of Paint and Related Coatings: Evaluates the behavior of films exposed in apparatus that produces ultraviolet radiation, high temperatures, and water condensation on the films. Used to make an "early-material" comparison of the exterior exposure quality of paints.

D870-02: Standard Practice for Testing Water Resistance of Coatings Using Water Immersion: Evaluates 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.

D2247-02: Standard Practice for Testing Water Resistance of Coatings in 100% Relative Humidity: Evaluates 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.

D4585-07: Standard Practice for Testing Water Resistance of Coatings Using Controlled Condensation: Evaluates the degradation of coatings by water exposure, conducted on metal or wood specimens, with the coating facing inside a 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.

E283-04: Standard Test Method for Determining Rate of

[37] Roofing and Waterproofing Manual, 5th ed., National Roofing Contractors Association, Carol Stream, IL 2003 (www.nrca.net)

Air Leakage Through Exterior Windows, Curtain Walls, and Doors Under Specified Pressure Differences Across the Specimen: Determines the resistance to air infiltration resulting from air pressure differences, with constant temperature and humidity across the specimen.

E331-00(2009): Standard Test Method for Water Penetration of Exterior Windows, Skylights, Doors, and Curtain Walls by Uniform Static Air Pressure Difference: Determines the 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.

E514-08: Standard Test Method for Water Penetration and Leakage Through 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.

E546-08: Standard Test Method for Frost/Dew 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.

E547-00(2009): Standard Test Method for Water Penetration of Exterior Windows, Skylights, Doors, and Curtain Walls by Cyclic Static Air Pressure Difference: Evaluates 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.

E576-08: Standard Test Method for Frost/Dew 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.

E741-00(2006): Standard Test Method for Determining Air Change in a Single Zone by Means of a Tracer Gas 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.

E773-01: Standard Test Method for Accelerated Weathering of Sealed Insulating Glass Units: Describes procedures for testing the performance of preassembled permanently sealed insulating glass units against accelerated weathering.

E779-03: Standard Test 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.

E783-02: Standard Test 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.

E1105-00(2008): Standard Test Method for Field Determination of Water Penetration of Installed Exterior Windows, Skylights, Doors, and Curtain Walls by Uniform or 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.

E1677-05: Standard Specification for an Air Retarder (AR) Material or System for Low-Rise Framed Building Walls: Establishes minimum performances and specification criteria for an air barrier (AB) material or system for framed walls of low-rise buildings. This specification are intended to allow the user to design the wall performance criteria and increase AB specifications to accommodate a particular climate location, function, or design of the intended building.

E1825-06: Standard Guide for Evaluation of Exterior Building Wall Materials, Products, and Systems: Provides guidance to design professionals in the evaluation of materials, products, or systems with which they are not familiar and to help determine that the selected materials, products, or systems are suitable for use on or as a part of an exterior building wall.

E2099-00(2007): Standard Practice for the Specification and Evaluation of Pre-Construction Laboratory Mockups of Exterior Wall Systems: Describes procedures and documentation to assist in the specification and evaluation of preconstruction laboratory mockups of exterior wall systems. Specifically, the design and construction of the mockup; observation during mockup construction and testing; evaluation of the mockup test results; and documentation of the mockup and testing process.

E2128-01a: Standard Guide for Evaluating Water Leakage of Building Walls: Describes methods for determining and evaluating causes of water leakage of exterior walls. For this purpose, water penetration is considered leakage, and therefore problematic, if it exceeds the planned resistance or temporary retention and drainage capacity of the wall, is causing or is likely to cause premature deterioration of a building or its contents, or is adversely affecting the performance of other components. A wall is considered a system including its exterior and interior finishes, fenestration, structural components and components for maintaining the building interior environment.

E2266-04: Standard Guide for Design and Construction of Low-Rise Frame Building Wall Systems to Resist Water Intrusion: Describes design, specification, selection, installation, and inspection of new building wall systems, exterior deck and stair components, doors, windows, penetrations and sealant joints of wood and metal frame buildings, typically four stories or less, to minimize water intrusion.

E2357-05: Standard Test Method for Determining Air Leakage of Air Barrier Assemblies: Describes the determination of the air leakage rate of air barrier assemblies that are used in building enclosures. This procedure measures the air leakage of a representative air barrier assembly before and after exposure to specific conditioning cycles and then assigns a rating dependent upon the results.

Canadian Standards

CAN/CGSB 51.32-M77 Sheathing, Membrane, Breather Type: Provides minimum specification for vapor permeable building papers and water-resistive barriers.

CAN/CGSB 51.33-M89 Vapour Barrier Sheet, Excluding Polyethylene, for Use in Building Construction

CAN/CGSB 51.34-M86 Vapour Barrier, Polyethylene Sheet for Use in Building Construction

CSA A371-04 Masonry Construction for Buildings

European and British Standards

BS [38] *4315 (1970): 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 (1976): Methods of Testing Windows. Part 1: Air Permeability Test. Assesses the ability of a closed window to let air pass when it is subjected to a differential pressure. *Part 2: Watertightness Test Under Static Pressure*. Assesses the watertightness of a window. *Part 3: Wind Resistance Tests*. Assesses the resistance under positive and negative pressures for all windows, including door height windows.

BS 6375 (2004): Performance of Windows. Part 1 Classification for Weathertightness: Establishes terms of exposure categories related to test pressure levels for air permeability, watertightness, and wind resistance.

EN 1934:1998: Thermal performance of buildings—Determination of thermal resistance by hot box method using heat flow meter—Masonry

EN 1026:2000 Windows and doors—Air permeability—Test method

EN 1027:2000 Windows and doors—Watertightness—Test method

EN 1121:2000 Doors—Behaviour between two different climates—Test method

BS EN 1279-2 2002 Glass in building. Insulating glass units. Long term test method and requirements for moisture penetration

EN 1294:2000 Door leaves—Determination of the behaviour under humidity variations in successive uniform climates

EN ISO 10077-1: 2000 Thermal performance of windows, doors and shutters—Calculation of thermal transmittance—Part 1: Simplified method (ISO 10077-1:2000), Part 2: Numerical method for frames: Specifies methods for the calculation of the thermal transmittance of windows and pedestrian doors consisting of glazed and opaque panels or both fitted in a frame, with and without shutters. This standard allows for the following:

- different types of glazing (glass or plastic; single or multiple glazing; with or without low emissivity coatings, and with spaces filled with air or other gases);
- opaque panels within the window or door;
- various types of frames (wood, plastic, metallic with and without thermal barrier, metallic with pinpoint metallic connections or any combination of materials);
- where appropriate, the additional thermal resistance introduced by different types of closed shutter, depending on their air permeability.

  Default values for glazing, frames and shutters are given in ISO 10077-1:2006.

Thermal bridge effects at the rebate or joint between the window or door frame and the rest of the building envelope are excluded from the calculation. The calculation also does not include effects of solar radiation, heat transfer caused by air leakage, calculation of condensation, ventilation of air spaces in double and coupled windows and surrounding parts of an oriel window.

EN 12152:2002 Curtain walling—Air permeability—Performance requirements and classification

EN 12153:2000 Curtain walling—Air permeability—Test method

EN 12154:1999 Curtain walling—Watertightness—Performance requirements and classification

EN 12155:2000 Curtain walling—Watertightness—Laboratory test under static pressure

EN 12207:1999 Windows and doors—Air permeability—Classification

EN 12208:1999 Windows and doors—Watertightness—Classification

EN 12219:1999 Doors—Climatic influences—Requirements and classification

EN 12365-1:2003 Building hardware—Gasket and weatherstripping for doors, windows, shutters and curtain walling—Part 1: Performance requirements and classification

EN 12425:2000 Industrial, commercial and garage doors and gates—Resistance to water penetration—Classification

EN 12426:2000 Industrial, commercial and garage doors and gates—Air permeability—Classification

EN 12427:2000 Industrial, commercial and garage doors and gates—Air permeability—Test method

EN 12428:2000 Industrial, commercial and garage doors and gates—Thermal transmittance—Requirements for the calculation

EN 12489:2000 Industrial, commercial and garage doors and gates—Resistance to water penetration—Test method

EN ISO 12567 Thermal performance of windows and doors—Determination of thermal transmittance by hot box method:

Part 1(2000): Complete windows and doors

Part 2 (2005): Specifies a method to measure the thermal transmittance of roof windows and projecting windows. It does not include: edge effects occurring outside the perimeter of the specimen, energy transfer due to solar radiation on the specimen and effects of air leakage through the specimen.

EN 12635:2002 Industrial, commercial and garage doors and gates—Installation and use

EN 12835:2000 Airtight shutters—Air permeability test

EN 12865:2001 Hygrothermal performance of building components and building elements—Determination of the resistance of external wall systems to driving rain under pulsating air pressure

ENV 13050:2000 Curtain walling—Watertightness—Laboratory test under dynamic condition of air pressure and water spray

EN 13051:2001 Curtain Walling—Watertightness—Site test

EN 13125:2001 Shutters and blinds—Additional thermal resistance—Allocation of a class of air permeability to a product

ENV 13420 Windows—Behaviour between different climates—Test method

North American Industry Standards

AAMA/FMA 100-07, Standard Practice for the Installation of Windows with Flanges or Mounting Fins in Wood Frame Con-

[38] British Standards Institution, Linford Wood, Milton Keynes, MK14 6LE, England. (www.bsonline.bsi-global.com)

struction: Covers the installation of windows in new construction utilizing a membrane/drainage system of no more than three stories in height and the installation process for windows from pre- to post-installation. Also provides minimum requirements for window installation based on current best practices. This practice applies to windows which employ a mounting flange or fin that is attached and sealed to the window perimeter frame and is designed as an installation fastening appendage.

AAMA/NWWDA 101/I.S. 2-97[39] *Voluntary Specifications for Aluminum, Vinyl (PVC) and Wood Windows and Glass Doors:* Defines requirements for five classes of windows and glass doors: Residential, Light Commercial, Commercial, Heavy Commercial, and Architectural.

AAMA [40] */WDMA/CSA 101/I.S.2/A440-05 Standard/ Specification for Windows, Doors, and Unit Skylights:* The first edition of a jointly published fenestration standard by U.S. and Canadian Associations (AAMA/WDMA and CSA). Replaces previous versions of AAMA/NWWDA 101/I.S.2-97, AAMA/WDMA 101/I.S.2/NAFS-02 and CSA A440. Identifies the requirements for windows, glass doors, skylights and side-hinged exterior doors. Included (when applicable) are performance requirements for structural integrity, water resistance, air leakage, and forced entry.

AAMA 501.1-05 Standard Test Method for Water Penetration of Windows, Curtain Walls and Doors Using Dynamic Pressure: Establishes the equipment, procedures and requirements for field testing of exterior windows, curtain wall and door systems for water penetration using dynamic pressure. Formerly included in AAMA 501-94 but now a stand alone document.

AAMA 501.2-03 Quality Assurance and Diagnostic Water Leakage Field Check of Installed Storefronts, Curtain Walls, and Sloped Glazing Systems: Provides a quality assurance and diagnostic field water check method for installed storefronts, curtain walls, and sloped glazing systems.

AAMA 501.5-07 Voluntary Test Method for Thermal Cycling of Exterior Walls Test Method for Thermal Cycling of Exterior Walls: Procedures recommended for evaluating the effects of thermal movement on large wall sections. Includes standardized approach for thermal cycle testing of joints, anchors, and other components of exterior walls.

AAMA 503-03 Voluntary Specification for Field Testing of Storefronts, Curtain Walls and Sloped Glazing Systems: Establishes the requirements for test specimens, apparatus, sampling, test procedures, and test reports to be used in evaluating the performance of installed storefronts, curtain walls, and sloped glazing systems. This specification provides a guide which can be used to evaluate the installed performance of storefronts, curtain walls, and sloped glazing systems for resistance to water penetration under controllable and reproducible wind driven rain conditions.

AAMA 507-07, Standard Practice for Determining the Thermal Performance Characteristics of Fenestration Systems Installed in Commercial Buildings: Provides a uniform standard method for determining the thermal performance of building specific fenestration systems that are installed in commercial buildings. The following thermal performance characteristics are included in this document: Thermal Transmittance (Ufactor), Solar Heat Gain Coefficient (SHGC), Visible Transmittance (VT), Air Leakage, Condensation Resistance Factor (CRF).

AAMA 508-07 Voluntary Test Method and Specification for Pressure-Equalized Rain-Screen Wall Cladding Systems: Establishes the requirements for test specimens, apparatus, test procedures, test reports, and minimum performance criteria to be used in the evaluation of pressure equalized rain screen wall cladding (panel) systems.

AAMA 711-07 Voluntary Specification for Self-Adhering Flashing Used for Installation of Exterior Wall Fenestration Products: Establishes the test methods and minimum performance requirements for self adhering flashing products that are used around the perimeter of exterior fenestration products. It also provides a method to determine the minimum width of the flashing products and to evaluate the influence of the environmental factors on the installation of self adhering flashing products applied under typical field conditions.

AAMA 800-07 Voluntary Specifications and Test Methods for Sealants: A compilation of standards and test methods for determining the performance of both compounds and tapes used in the manufacture and installation of windows, sliding glass doors, and curtain walls. Sealant specifications in this publication include: Back Bedding Compounds, Back Bedding Mastic Tapes, Glazing Tapes, Narrow Joint Seam Sealers, Exterior Perimeter Sealing Compounds, Non-Drying Sealants, and Expanded Cellular Glazing Tapes.

AAMA 812-04 Voluntary Practice for Assessment of Single Component Aerosol Expanding Polyurethane Foams for Sealing Rough Openings of Fenestration Installations: Provides two test methods for determining the expansion properties of polyurethane foams used for sealing perimeter openings in fenestration installations. One method allows the user to determine intrinsic foam properties and the second method allows the user to relate the expansion properties to their probable effect on fenestration framing.

AAMA 850-91 Fenestration Sealants Guide Manual: Provides information relating to the selection, use, and application of sealants for factory or field glazing as well as weatherseal applications. Sealant types, considerations for selection, and application are discussed.

AAMA 1402-86 Standard Specifications for Aluminum Siding, Soffit and Fascia: Includes performance test methods and installation specifications.

AAMA CW-DG-1-96 (2005) Aluminum Curtain Wall Design Guide Manual: Provides information on specific aspects of aluminum curtain wall construction.

AAMA CW-RS-1-04 The Rain Screen Principle and Pressure Equalized Wall Design: Details a design approach to make curtain walls water resistant by eliminating the pressure differential between interior and exterior surfaces.

AAMA CWG-1-89 (2004) Installation of Aluminum Curtain Walls: Describes curtain wall installation procedures including architects' concerns and responsibilities. Contractors' responsibilities are also addressed. Manual reviews details and steps to take for proper installation to assure good curtain wall performance.

AAMA 2400-02 Standard Practice for Installation of Windows with a Mounting Flange in Stud Frame Construction: Provides guidance for the proper installation of windows with mounting flanges or nail fins into buildings with stud

[39] American Architectural Manufactures's Association (www. aamanet.org)
[40] American Architectural Manufacturers Association www.aamanet.org

frame construction. It includes details of anchorage, flashing, and sealing window installations to guide the user. It also includes information on preparing the building opening for window installation.

AAMA 2410-03 Standard Practice for Installation of Windows with an Exterior Flush Fin Over an Existing Window Frame: Covers installation of retrofit windows in residential buildings of no more than four stories in height, from preinstallation procedures through post-installation.

AAMA 450-06 Voluntary Performance Rating Method for Mulled Fenestration Assemblies: Describes procedures and requirements for determining the air infiltration, water resistance, and structural performance of mulled fenestration assemblies.

AAMA 502-02 Voluntary Specification for Field Testing of Windows and Sliding Glass Doors: Establishes requirements for testing to evaluate performance of installed windows and sliding glass doors. Provides test methods for use in the field to evaluate performance under controllable and reproducible conditions.

AAMA 504-05 Voluntary Laboratory Test Method to Qualify Fenestration Installation Procedures: Evaluates and qualifies specific fenestration installation procedures based on laboratory measurements of air leakage and water penetration resistance. The test specimen and procedures are based on wood frame construction generally used in new construction residential applications.

AAMA 1503-98 (2004) Voluntary Test Method for Thermal Transmittance and Condensation Resistance of Windows, Doors and Glazed Wall Section: Describes test method parameters and equipment for determining thermal transmittance (U-value) and Condensation Resistance Factor (CRF) for windows, doors, and glazed wall sections.

BIA[41] *Technotes:* The Brick Industry Association publishes a series of guidelines on brick and masonry construction. The Technotes which have moisture management as primary subject are:

#7A (2005) Water Resistance of Brick Masonry—Materials, Part 2 of 3

#7B (2005) Water Resistance of Brick Masonry—Construction and Workmanship, Part III

#7C (2005) Moisture Control in Brick and Tile Walls—Condensation

#7D (2005) Moisture Resistance of Brick Masonry Walls Condensation Analysis

#7F (2005) Moisture Resistance of Brick Masonry—Maintenance

#11 (2005) Guide Specifications for Brick Masonry

GA[23]*239-04 Water-Resistant Gypsum Backing Board for Ceramic Tile in Wet Areas:* Includes design and construction considerations to reduce condensation damage. This document discusses the properties and proper installation considerations for water-resistant gypsum backing board.

GA[23] *253-99 Application of Gypsum Sheathing:* Describes the industry's latest recommendations for handling, storing, and installing gypsum sheathing under a variety of conditions.

SWRI Practical Guide to Waterproofing Exterior Walls: Provides an overview of above-grade waterproofing techniques and products for exterior walls. It covers best practices in the field of waterproofing repairs, including brick, concrete, curtainwall, EIFS, stone, stucco, and terra cotta.

[41] Brick Industry Association (www.bia.org)

Floors, Foundations, Earth-Coupled Spaces

ASTM Standards

C836-06: Standard 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 water.

C957-06: Standard 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 water.

D529-04: Standard Practice for Enclosed Carbon-Arc Exposures 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.

E154-08a: Standard Test Methods for Water Vapor Retarders Used in Contact with Earth Under Concrete Slabs, on Walls, or as Ground Cover: 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 E96.

E1907-04 Standard Guide to Methods of Evaluating Moisture Conditions of Concrete Floors to Receive Resilient Floor Coverings: Includes both quantitative and qualitative procedures used to determine the amount of water or water vapor present in or emitting from concrete slabs and criteria for evaluating the moisture-related acceptability of concrete slabs to receive resilient floor coverings and related adhesives.

E1643-09: Standard Practice for Selection, Design, Installation, and Inspection of Water Vapor Retarders Used in Contact with Earth or Granular Fill Under Concrete Slabs: Describes procedures for installing flexible, prefabricated sheet membranes in contact with earth or granular fill used as vapor retarders under concrete slabs.

F710-08: Standard Practice for Preparing Concrete Floors to Receive Resilient Flooring: Describes the determination of the acceptability of a concrete floor for the installation of resilient flooring. Includes suggestions for the construction of a concrete floor to ensure its acceptability for installation of resilient flooring.

Canadian Standards

CAN/CSA-S406-92 (R2003) Construction of Preserved Wood Foundations: Provides information for the selection of materials for, and the fabrication and installation of, preserved wood foundations. Specific details are provided for buildings up to two storeys in building height above the foundation and having a building area not exceeding 600 m^2.

European and British Standards

EN ISO 13793:2001 Thermal performance of buildings—Thermal design of foundations to avoid frost heave

BS 6576: 1985 Code of practice for installation of chemical damp-proof courses

BS 8215:1991 Code of practice for design and installation of damp-proof courses in masonry construction

CP 102:1973 Code of practice for protection of buildings against water from the ground

BS 8004:1986 Code of practice for foundations

North American Industry Standards

ASCE Standard 32-01: Design and Construction of Frost-Protected Shallow Foundations: Describes the design and construction of frost-protected shallow foundations in areas subject to seasonal ground freezing.

SWRI Below Grade Waterproofing Manual (2000): Provides an overview dealing with below grade waterproofing. It covers the importance of proper design, material selection, surface preparation, and problem solving.

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. Model building codes become law once they are adopted by a state, province, or other local jurisdiction. The International Code Councils' (ICC) family of codes is the most prevalent set of model codes in the United States. The ICC was formed even when the three regional model code organizations—BOCA (the Building Officials and Code Administrators International), ICBO (the International Conference of Building Officials), and SBCCI (the Southern Building Code Congress International)—combined and published the first International Building Code in 2000.

North American Model Building Codes

The ICC publishes both the International Building Code (IBC) and the International Residential Code (IRC). These two codes address design and construction for the building envelope, including roofs, walls, and foundations. The IRC is a more prescriptive code than the IBC and is targeted specifically at one and two family, low rise residential buildings. Requirements for moisture management are included within the general requirements for different building assemblies, i.e., moisture provisions for walls are included in the chapter on walls. The applicable chapters of the International Building Code (IBC) and International Residential Code (IRC) for the different parts of the building envelope are shown in Table 2.

The ICC publishes a new version of its codes every three years. Revisions are made throughout two consecutive 18-month public hearing cycles. An example of the moisture related code requirements in the 2006 Edition of the International Building Code for walls includes:

> *"1403.2 Weather protection. Exterior walls shall provide the building with a weather-resistant exterior wall envelope. The exterior wall envelope shall include flashing, as described in Section 1405.3. The exterior wall envelope shall be designed and constructed in such a manner as to prevent the accumulation of water within the wall assembly by providing a water-resistive barrier behind the exterior veneer, as described in Section 1404.2 and a means for draining water that enters the assembly to the exterior. Protection against condensation in the exterior wall assembly shall be provided in accordance with the International Energy Conservation Code."*

TABLE 2—I-Code chapters applicable to building envelope systems (2000, 2003, and 2006 editions).

Building Envelope System	IBC	IRC
Roofing	Chapter 15	Chapters 8 and 9
Walls	Chapter 14	Chapter 7
Foundations	Chapter 18	Chapter 4

The Canadian National Building Code (NBC) is the model code that is adopted by the provinces of Canada. The single code includes provisions for both residential and non-residential buildings. The 2005 NBC included a major revision in the inclusion of wall requirements being tied to a climatic moisture index (MI). The moisture index which is provided in the NBC-2005 for locations throughout Canada expresses in a single index the rain load and the drying capability (based on relative humidity).

In addition to prescriptive specifications in the building code, alternative methods and materials are allowed if they can be shown to be equivalent to the code requirements. For example, Section 104.11 of the IBC-06 states.

> **104.11 Alternative materials, design and methods of construction and equipment**. *The provisions of this code are not intended to prevent the installation of any material or to prohibit any design or method of construction not specifically prescribed by this code, provided that any such alternative has been approved. An alternative material, design or method of construction shall be approved where the building official finds that the proposed design is satisfactory and complies with the intent of the provisions of this code, and that the material, method or work offered is, for the purpose intended, at least the equivalent of that prescribed in this code in quality, strength, effectiveness, fire resistance, durability and safety*.
>
> **104.11.1 Research reports**. *Supporting data, where necessary to assist in the approval of materials or assemblies not specifically provided for in this code, shall consist of valid research reports from approved sources*.
>
> **104.11.2 Tests**. *Whenever there is insufficient evidence of compliance with the provisions of this code, or evidence that a material or method does not conform to the requirements of this code, or in order to substantiate claims for alternative materials or methods, the building official shall have the authority to require tests as evidence of compliance to be made at no expense to the jurisdiction. Test methods shall be as specified in this code or by other recognized test standards. In the absence of recognized and accepted test methods, the building official shall ap-*

prove the testing procedures. Tests shall be performed by an approved agency. Reports of such tests shall be retained by the building official for the period required for retention of public records."

To aid in the consideration of alternate materials and methods, ICC Evaluation Services has established a series of acceptance criteria and evaluation guidelines. Each one of these criteria provide specific criteria showing equivalency to a specific code requirement. Relevant acceptance critieria for ICC-ES (those in *Division 7, Thermal and Moisture Control* are listed below.

ICC-ES Acceptance Criteria—Roofs

- *AC07*(*2007*) *Special Roofing Systems*
- *AC02*(*2006*) *Reflective Foil Insulation*
- *AC17*(*2007*) *Glass Glazed Unit Skylights and Sloped Glass Glazing*
- *AC48*(*2005*) *Roof Underlayment for Use in Severe Climate Areas*
- *AC75*(*2007*) *Membrane Roof-Covering Systems*
- *AC132*(*2005*) *Attic Vents*
- *AC160*(*2006*) *Nonasphaltic Fiberglass-Based Roof Underlayment*
- *AC165*(*2004*)) *Asphalt-Coated Glass-Fiber Mat Roof Underlayment*
- *AC166*(*2007*) *Metal Roof Coverings*
- *AC180*(*2007*) *Clay and Concrete Roof Tiles*
- *AC188*(*2007*) *Roof Underlayments*
- *AC200*(*2007*) *Plastic Battens Used in Clay or Concrete Tile Roof Systems*
- *AC207*(*2005*) *Polypropylene Roof Underlayments*
- *EG220*(*2003*) *Sheet Radiant Barriers*
- *AC266*(*2007*) *Wood Structural Panel Roof Sheathing Factory-laminated with an Alternative Roof Underlayment*
- *EG270*(*2004*) *Asphalt Shingles made with an Attached Interply*
- *AC330*(*2006*) *Corrugated Asphalt Roofing Sheets and Tiles*
- *AC384*(*2007*) *Hot-applied Rubberized-Asphalt Roof Membranes Used with Protected Membrane Ballasted Roof Systems*

ICC-ES Acceptance Criteria—Walls

- *AC11*(*2007*) *Cementitious Exterior Wall Coatings*
- *AC12*(*2007*) *Foam Plastic Insulation*
- *AC15*(*2007*) *Concrete Floor, Roof and Wall Systems and Concrete Masonry Wall Systems*
- *AC24*(*2007*) *Exterior Insulation and Finish Systems*
- *AC37*(*2007*) *Vinyl Siding*
- *AC38*(*2004*) *Water-Resistive Barriers*
- *AC51*(*2005*) *Precast Stone Veneer*
- *AC59*(*2002*) *Direct-Applied Exterior Finish Systems*
- *AC71*(*2005*) *Foam Plastic Sheathing Panels Used as Weather-Resistive Barriers*
- *AC90*(*2007*) *Fiber Cement Siding Used as Exterior Wall Siding*
- *AC92*(*2007*) *Polymer-Based and Polymer-Modified Exterior and Interior Wall Cladding*
- *AC148*(*2006*) *Flashing Materials*
- *AC176*(*2001*) *Composite Wall and Roof Panel Systems with an Expanded Polystyrene Core and Spray- or Trowel-Applied Cementitious Facings*
- *AC181*(*2007*) *Rigid Cellular Polyurethane Panels Used as Exterior and Interior Wall Cladding*
- *AC187*(*2006*) *Polyester Loose-fill and Blanket Insulations*
- *AC191*(*2007*) *Metal Plaster Bases* (*Lath*)
- *AC209*(*2006*) *Trowel-, Spray- or Roller-Applied Water-resistive Coatings Used as Weather-resistive Barriers Over Exterior Cementitious Wall Coverings*
- *AC212*(*2005*) *Water-resistive Coatings Used as Water-resistive Barriers over Exterior Sheathing*
- *AC219*(*2007*) *Exterior Insulation and Finish Systems*
- *AC235*(*2004*) *EIFS Clad Drainage Wall Assemblies*
- *AC245*(*2004*) *Doors and Windows Subject to Wind-Borne Debris*
- *AC275*(*2007*) *Glass Fiber Lath Used in Exterior Cementitious Wall Coatings or Exterior Cement Plaster*(*Stucco*)
- *AC310*(*2005*) *Water-Resistive Membranes Factory-bonded to Wood-Structural Sheathing, Used as Water-Resistive Barriers*
- *EG3159*(*2006*) *Masonry Veneer with Polystyrene Foam Plastic Backing*
- *AC321*(*2005*) *Treated-engineered-Wood Siding*
- *AC333*(*2007*) *Injection Molded Composite Material* (*IMCM*) *Wall Panels* [*Replaced by* (*AC25*) *Metal Composite Material*]
- *EG356*(*2006*) *A Moisture Drainage System Used with Exterior Wall Veneers*
- *AC366*(*2007*) *Polypropylene Siding*
- *AC367*(*2007*) *Fiber-Reinforced Cement Sheet Structural Floor Sheathing*
- *AC376*(*2007*) *Reinforced Cementitious Sheets Used as Wall Sheathing and Floor Underlayment*
- *AC378*(*2007*) *Fiber-Cement Interior Substrate Sheets Used in Wet and Dry Areas*
- *AC382*(*2007*) *Laminated Fibrous Board Sheathing Material Used as a Water-Resistive Barrier*

ICC-ES Acceptance Criteria—Foundation

- *AC29*(*2004*) *Cold, Liquid-applied, Below-grade Exterior Dampproofing and Waterproofing Materials*
- *EG114*(*2005*) *Rigid Polyethylene, Below-grade, Dampproofing and Wall Waterproofing Material*
- *AC115*(*2005*) *Waterproof Membranes for Flooring and Shower Lining*
- *AC243*(*2005*) *Composite Foundation Drainage Systems*

HUD-FHA[42] *Minimum Property Standards* (*MPS*) *for Housing*[43] establishes minimum standards for buildings constructed under HUD housing programs, such as housing for which mortgage financing has federal government guarantees. Jurisdiction includes new single family homes, multi-family housing and health care type facilities. Additionally in areas of the United States that have not adopted building codes, the appropriate HUD Field Office has authority to specify a building code. Prior to issuance of the 1984 MPS, HUD maintained separate Minimum Property Standards for different types of structures. The 1984 MPS required that all buildings be constructed in compliance with the 1983 CABO Model Energy Code (with certain excep-

[42] Federal Housing Administration, within HUD, U.S. Dept. of Housing and Urban Development, Washington, DC.

[43] 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.

tions). Since that time, HUD has continued to reference model building codes rather than developing separate and prescriptive HUD standards.

Energy Codes for Buildings

The Energy Policy Act of 1992 mandated that states should have energy codes that are at least equivalent to the CABO (Council of American Building Officials)[44] Model Energy Code (MEC-92) for residential construction or ASHRAE Standard 90.1 for nonresidential construction. Since 1992 there has been mixed level of adoption by the states to meet this ruling. Also since 2000 the International Energy Conservation Code (IECC), which is produced by the ICC, has superseded the MEC. Athough 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 2006 IECC had significant revisions including a simplification of the climate regions in the United States. Climate regions are primarily used to specify the levels of insulation R-value and required U-factors for windows. The 2006 IECC includes eight climate zones each which have marine, dry and moist subregions. The eight climate zones are defined in Table 3.

Marine subregions are defined as locations meeting the following four criteria:

- mean temperature of coldest month between −3°C (27°F) and 18°C (65°F),
- warmest month mean <22°C (72°F),
- at least four months with mean temperatures over 10°C (50°F), and
- the month with the heaviest precipitation in the cold season has at least three times as much precipitation as the month with the least precipitation in the rest of the year. The cold season is October through March in the Northern Hemisphere and April through September in the Southern Hemisphere.

Dry subregions are defined as locations which are not Marine and $Pin < 0.44 \times (TF - 19.5)$ where:

Pin = Annual precipitation in inches (cm)
T = Annual mean temperature in °F (°C).

All other locations are moist subregions. Figure 1 is the climate map for the continental United States with notes on climate regions for Alaska and Hawaii from the IECC.[45] In addition to the climate zone simplification a significant change in the vapor retarder requirements was made to the 2006 IECC. Prior to the 2006 edition vapor retarders were required on the warm-in-winter side of the wall with only hot-humid climates exempted. The 2006 IECC exempts climates zones 1 to 3 and zone 4 dry and moist from the requirement.

TABLE 3—IECC climate zone descriptions.

Zone Number	Thermal Criteria: IP Units	Thermal Criteria: SI Units
1	9000 < CDD50°F	5000 < CDD10°C
2	6300 < CDD50°F ≤ 9000	3500 < CDD10°C ≤ 5000
3A and 3B	4500 < CDD50°F ≤ 6300	2500 < CDD10°C ≤ 3500
	AND HDD65°F ≤ 5400	AND HDD18°C ≤ 3000
4A and 4B	CDD50°F ≤ 4500 AND	CDD10°C ≤ 2500 AND
	HDD65°F ≤ 5400	HDD18°C ≤ 3000
3C	HDD65°F ≤ 3600	HDD18°C ≤ 2000
4C	3600 < HDD65°F ≤ 5400	2000 < HDD18°C ≤ 3000
5	5400 < HDD65°F ≤ 7200	3000 < HDD18°C ≤ 4000
6	7200 < HDD65°F ≤ 9000	4000 < HDD18°C ≤ 5000
7	9000 < HDD65°F ≤ 12600	5000 < HDD18°C ≤ 7000
8	12600 < HDD65°F	7000 < HDD18°C

Conclusions

Many sources of guidelines, standards, and building and energy codes have been cited in this chapter. There is no single information source, index, database, or compendium in which the building designer or construction industry practitioner may find all standards, codes, and guidelines dealing with moisture control in buildings. Obviously such a resource would be valuable providing that it could be available in electronic form, and periodically updated.

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 existing buildings managed, and their service to the owner and user maximized.

Since the first publication of this manual the development of standards and industry guidelines has accelerated. It is expected that this process will continue. Review of industry trends and of current standard development activity, indicates that the following predictions for future code and standard development:

- Test methods and specification standards will increasingly cover assembly and system provisions rather than material provisions.
- Code provisions and standards will be increasingly climate zone specific.
- Proliferation of code provisions and standards concerning air leakage and methods and means of controlling air leakage.
- Proliferation of standards and guidelines concerning sustainability.
- Activity to standardize the use of hygrothermal simulation.

[44] 5203 Leesburg Pike, Suite 708, Falls Church, VA 22041.
[45] International Energy Conservation Code 2006, International Code Council, www.iccsafe.org

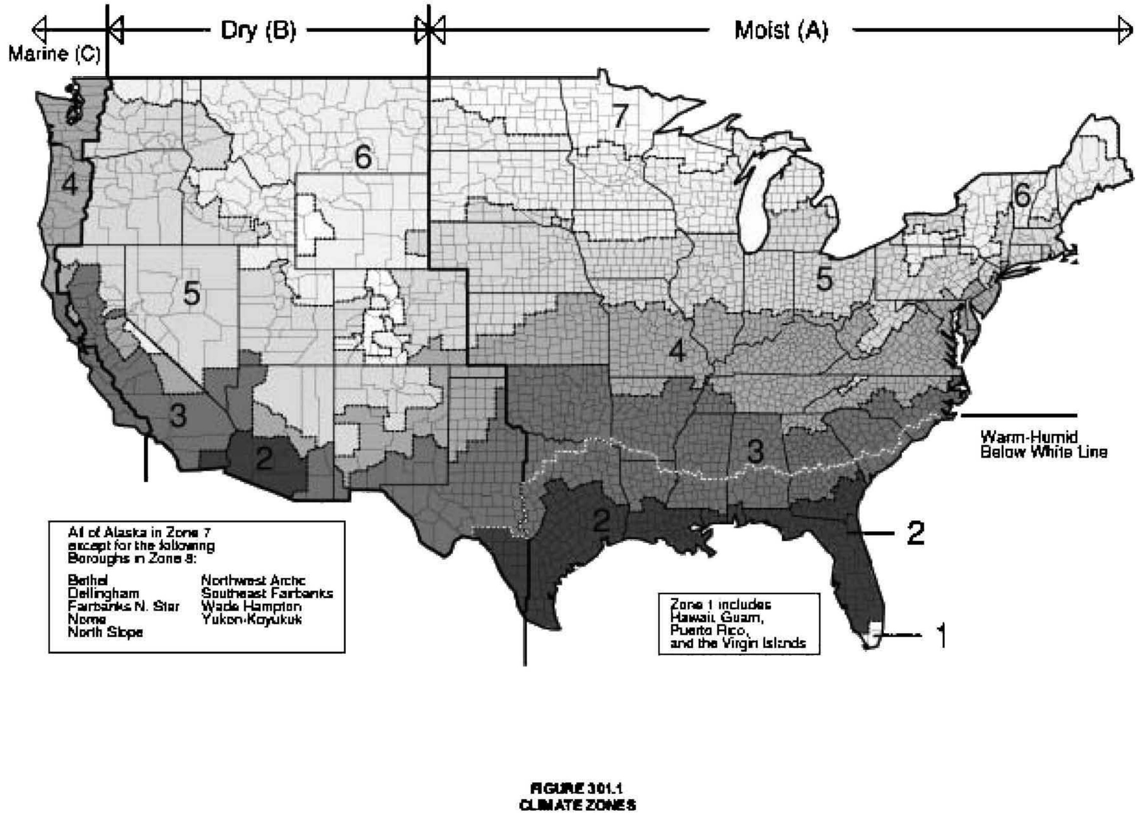


Fig. 1—IECC Climate Zone Map.

References

[1] Whippo, H. M. and Arnberg, B. T., *Survey and Analysis of the Vapor Transmission Properties of Building Materials*, University of Colorado, Boulder, CO, Jan. 1955.

[2] Meggers, E. R., *Selected Bibliography on Building Construction and Maintenance. Building Materials and Structures Report* 140, 2nd ed., U.S. Department of Commerce, National Bureau of Standards, Washington, DC, 1956.

[3] "Condensation Problems and How They Can Be Eliminated," Chapter 5, *Thermal Design of Buildings* by T. S. Rogers, John Wiley & Sons, New York, 1964.

[4] Wilson, A. G. and Garden, G. K., *Moisture Accumulation in Walls Due to Air Leakage*, NRC 9131, National Research Council of Canada, Division of Building Research, Ottawa, 1965.

[5] "Moisture in Buildings and Its Control," Chapter 11 in *Thermal Performance of Buildings* by J. F. van Straaten, Elsevier Publishing Co., Amsterdam, 1967.

[6] Griffin, C. W. ,Jr., *Manual of Built-up Roof Systems*, McGraw-Hill Book Co., New York, 1970.

[7] Saarimaa, J., "A Morphological Performance Evaluation Technique for Moisture Problems in Buildings," *Performance Concept in Buildings; Proceedings of the Joint RILEM-ASTM-CIB Symposium*, NBS Special Publication 361, National Bureau of Standards, Washington, DC, 1972.

[8] Wilson, A. G. and Sasaki, J. R., "Evaluation of Window Performance," *Performance Concept in Buildings; Proceedings of the Joint RILEM-ASTM-CIB Symposium*, NBS Special Publication 361, National Bureau of Standards, Washington, DC, 1972.

[9] Seiffert, K., *Wasserdampfdiffusion im Bauwesen* (Water Vapor Diffusion in Building Materials), Bauverlag GMBH, Wiesbaden and Berlin, 1974.

[10] Lee, K. and Rehr, S. L., "Energy Conservation and Building Codes: The Legislative and Planning Processes," Environmental Design and Research Center, Boston, 1977.

[11] Ross, H. and Grimsrud, D., *Air Infiltration in Buildings: Literature Survey and Proposed Research Agency*, Report LBL-W7822, U.S. Department of Energy, May 1978.

[12] McElroy, D. L. and Tye, R. P., Eds., *Thermal Insulation Performance, ASTM STP 718*, ASTM International, West Conshohocken, PA, 1980.

[13] Thompson, G. P., *Building to Save Energy: Legal and Regulatory Approaches*, Ballinger Publishing Co., Cambridge, MA, 1980.

[14] *Thermal Performance of the Exterior Envelopes of Buildings, Proceedings of the ASHRAE/DOE-ORNL Conference*, ASHRAE SP 28, ASHRAE, Atlanta, 1981.

[15] 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., ASTM International, West Conshohocken, PA, 1982.

[16] Govan, F. A., Greason, D. M., and McAllister, J. D., Eds., *Thermal Insulation, Materials, and Systems for Energy Conservation in the '80s, ASTM STP 789*, ASTM International, West Conshohocken, PA, 1983.

[17] National Center for Appropriate Technology, "Moisture and Home Energy Conservation: How to Detect, Solve, and Avoid Related Problems," DOE/CE/15095–4, U.S. Department of Energy, Washington, DC, Sept. 1983.

[18] Olin, H. B., Schmidt, J. L., and Lewis, W. H., "Construction Principles, Materials, and Methods," Chapter 104, *Moisture, Control*, U.S. League of Savings Institutions, Institute of Financial Education and Interstate Printers, Danville, IL, 5th ed., 1983.

[19] *Thermal Performance of the Exterior Envelopes of Buildings, Proceedings of the ASHRAE/DOE-Conference*, ASHRAE SP 38, Atlanta, 1983.

[20] "Building Regulations on Durability in the Nordic Countries," by B. Roman in *Proceedings, 3rd International Conference on the Durability of Building Materials and Components*, Vol. 1, Technical Research Centre of Finland, Espoo, 1984, p. 65ff.

[21] "Field Investigations of Moisture in Buildings," by N. Tolstoy in *Proceedings, 3rd International Conference on the Durability of Building Materials and Components*, Vol. 2, Technical Research Centre of Finland, Espoo, 1984, p. 422ff.

[22] Trechsel, H. R. and Lagus, P. L., Eds., *Measured Air Leakage of Buildings, ASTM STP 904*, ASTM International, West Conshohocken, PA, 1986.

[23] *Thermal Performance of the Exterior Envelopes of Buildings, Proceedings of the ASHRAE/DOE/BTECC Conference*, ASHRAE SP 49, Atlanta, 1986.

[24] *Controlling Moisture in Homes*, National Association of Home Builders, Washington, DC, 1987.

[25] Powell, F. J. and Matthews, S. L., Eds., *Thermal Insulation: Materials and Systems, ASTM STP 922*, ASTM International, West Conshohocken, PA, 1987.

[26] *Symposium on Air Infiltration, Ventilation, and Moisture and Transfer*, D. Eakin, Ed., Building Thermal Envelope Coordinating Council, Washington, 1987.

[27] *Manual of British Standards in Building Construction and Specification*, 2nd ed., M. Smith, Ed., British Standards Institution, London, 1987.

[28] *Wood Handbook: Wood as an Engineering Material*, Agriculture Handbook 72, U.S. Department of Agriculture, Forest Service, Washington, DC, 1987.

[29] Oliver, A. C., *Dampness in Buildings*, Nichols Publishing, New York, 1988.

[30] Liebing, R. W., *Construction Regulations Handbook*, John Wiley & Sons, New York, 1987.

[31] *Water Vapor Transmission Through Building Materials and Systems: Mechanisms and Measurement, ASTM STP 1039*, Trechsel, H. R. and Bomberg, M., Eds., ASTM International, West Conshohocken, PA, 1989.

[32] *Thermal Performance of the Exterior Envelopes of Buildings, Proceedings of the ASHRAE/DOE/BTECC/CIBSE Conference*, ASHRAE, Atlanta, 1989.

[33] *Vapor Retarders*, SpecGUIDE© 07190, The Construction Specifications Institute, Alexandria, VA, May 1990.

[34] McElroy, D. L. and Kimpflen, J. F., Eds., *Insulation Materials, Testing and Applications, ASTM STP 1030*, ASTM International, West Conshohocken, PA, 1990.

[35] O'Connor T. F., Ed., *Buildings Sealants: Materials, Properties, and Performance: ASTM STP* 1069, ASTM International, West Conshohocken, PA, 1990.

[36] *SpecGUIDE 07190, Vapor Retarders*, The Construction Specifications Institute, Alexandria, VA, May 1990.

[37] Tsongas, G. A., "*The Northwest Wall Moisture Study: A Field Study of Excess Moisture in Wall and Moisture Problems and Damage in New Northwest Homes*," U.S. DOE/Bonneville Power Administration, Report No. DOE/BP-91489-1, 1990.

[38] Rose, W. and Bales, E. Eds., *Bugs, Mold & Rot*, Proceedings are from a sponsored by BETEC and Oak Ridge National Laboratory, 1991.

[39] Schwartz, T. A., Ed., *Water in Exterior Building Walls: Problems and Solutions, ASTM STP 1107*, ASTM International, West Conshohocken, PA, 1991.

[40] Lotz, W. A., "Moisture Doomed Iowa Hospital Before It Opened," *Engineered Systems*, Jan./Feb. 1991, pp. 46–49.

[41] Olivieri, J. B., "Humidity Control: Not Too Much, Not Too Little," *Engineered Systems*, May 1991, pp. 37–40.

[42] Patenaude, A., "Migration of Water by Capillarity." CMHC-SCHL Research Report, 1993.

[43] Burnett, E. F. P., Straube, J. F., and Sloof, P., "The Relative Merits of Zero-Cavity Brick Veneer Walls," *Proceedings of the 10th International Brick and Block Masonry Conference*, Calgary, Alta., Canada, 5–7 July, 1994, pp. 369–381.

[44] Straube, J. F. and Burnett, E. F. P., "Performance Measurement of Pressure-Moderated Screened Walls," *Proceedings of International Conference on Building Envelope Systems and Technology*, Singapore, Dec. 7–8, 1994, pp. 479–484.

[45] Flynn, K. A., Quarles, S. L., and Dost, W. A., "Comparison of Ambient Conditions and Wood Moisture Contents in Crawl Spaces in a California Condominium Complex," *ASHRAE Trans.*, Vol. 100, Part 1, Paper number NO-94-19-2, 1994, pp. 1302–1313.

[46] Rose, W. B., "A Review of the Regulatory and Technical Literature Related to Crawl Space Moisture Control," *ASHRAE Trans.*, Vol. 100, Part 1, Paper number NO-94-19-1, 1994, pp. 1289–1301.

[47] Rose, W. and Ten Wolde, A., *Bugs, Mold & Rot II, Proceedings are from a Workshop Sponsored by BETEC*, 1994.

[48] Samuelson, I., "Moisture Control in Crawl Spaces," *ASHRAE Trans.*, Vol. 100, Part 1, Paper number NO-94-22-2, 1994, pp. 1420–1426.

[49] Stiles, L. and Custer, M., "Reduction of Moisture in Wood Joists in Crawl Spaces—A Study of Seventeen Houses in Southern New Jersey," *ASHRAE Trans.*, Vol. 100, Part 1, Paper number NO-94-19-3, 1994, pp. 1314–1324.

[50] Tsongas, G. A., "Crawl Space Moisture Conditions in New and Existing Northwest Homes," *ASHRAE Trans.*, Vol. 100, Part 1, Paper number NO-94-19-4, 1994, pp. 1325–1332.

[51] Trethowen, H. A., "Three Surveys of Subfloor Moisture in New Zealand," *ASHRAE Trans.*, Vol. 100, Part 1, Paper number NO-94-22-3, 1994, pp. 1427–1438.

[52] Burch, D. M. and Desjarlais, A. O., "Water-Vapor Measurements of Low-Slope Roofing Materials." NISTIR 5681; July 1995, p. 32.

[53] Burch, D. M. and Saunders, C. A., *Computer Analysis of Wall Constructions in the Moisture Control Handbook*, NISTIR 5627, May 1995, p. 70.

[54] Burch, D. M., Saunders, C. A., and TenWolde, A., "Manufactured Housing Walls that Provide Satisfactory Moisture Performance in All Climates," NISTIR 5558, Jan. 1995, p. 33.

[55] Hagentoft, C.-E. and Harderup, E., "Moisture Conditions in a North-Facing Wall with Cellulose Loose-Fill Insulation. Construction With and Without a Vapour Retarder and Air Leakage," *ASHRAE Trans.*, Vol. 101, Part 1, Paper number CH-95-3-4, 1995, pp. 639–646.

[56] Hens, H. and Fatin, A. M., "Heat-Air-Moisture Design of Masonry Cavity Walls. Theoretical and Experimental Results and Practice," *ASHRAE Trans.*, Vol. 101, Part 1, Paper number CH-95-3-2, 1995, pp. 607–626.

[57] Modera, M. P. and Persily, A. K., Eds., *Airflow Performance of Building Envelopes, Components, and Systems, ASTM STP 1255*, ASTM International, West Conshohocken, PA, 1995, pp. 156–177.

[58] Verschoor, J., *ASHRAE RP-496—Investigation of Water Vapor Migration and Moisture Storage in an Insulated Wall Structure*, Conducted: December 1987—January 1995, online@www.ashrae.org.

[59] Zarr, R. R., Burch, D. M., and Fanney, A. H., "Heat and Moisture Transfer in Wood-Based Wall Construction: Measured Versus Predicted," NIST BSS 173, Feb. 1995, p. 83.

[60] *Thermal Performance of Building Envelopes VI, Proceedings of the ASHRAE/DOE/BETEC Conference*, ASHRAE, Atlanta, 1995.

[61] Burnett, E. F. P. and Straube, J. F., "The Brick Veneer

Screened Wall," *Proceedings of the 7th Canadian Masonry Symposium*, Hamilton, Ont., Canada, June 5–7, 1995, pp. 651–662.

[62] Melander, J. M. and Isberner, A. W., *Portland Cement Plaster (Stucco) Manual*, 1996.

[63] Morrison Hershfield Limited, *Survey of Building Envelope Failures on the Coastal Climate of British Columbia*, prepared for CMHC, November 22, 1996.

[64] Nelson, P. E./Kroll, R. E., Eds., *Exterior Insulation Finish Systems (EIFS): Materials, Properties, and Performance ASTM STP 1269*, ASTM International, West Conshohocken, PA, 1996.

[65] Tsongas, G. A., Thornton, B. A., Burch, D. M., and Walton, G. N., "Computer Analysis of the Moisture Performance of Roof Constructions in the U.S.," *DOE Moisture Control Handbook*, NISTIR 5919, Dec. 1996, p. 56.

[66] Thomas, W., ASHRAE RP-810—Moisture Transfer In Porous Materials Exposed To Combined Humidity and Temperature Gradients, Conducted: April 1994—January 1997, on-line at www.ashrae.org.

[67] Kudder, R. J. and Erdly, J. L., Eds., *Water Leakage Through Building Facades, ASTM STP 1314*, ASTM International, West Conshohocken, PA, 1997.

[68] Brown, W., Ullett, J., Karagiozis, A., and Tonyon, T., "Barrier EIFS Clad Walls: Results for a Moisture Engineering Study," *J. Thermal Insulation and Building Envelopes*, Vol. 20, Jan. 1997.

[69] Straube, J. F. and Burnett, E. F. P., "Driving Rain and Building Facades," *Proceedings of Clima 2000*, Brussels, August 30–September 2, 1997.

[70] Straube, J. F. and Burnett, E. F. P., "Field Testing of Filled-Cavity Wall Systems," *Proceedings of International Conference Building Envelope Science and Tech. '97*, Bath, UK, April 15–17, 1997, pp. 429–434.

[71] Straube, J. F. and Burnett, E. F. P., "Rain Control and Screened Wall Systems," *Proceedings of the 7th Building Science and Technology Conference*, Toronto, March 20–21, 1997, pp. 17–37.

[72] Webber, R., "The Stucco Solution—Creating Exterior Stucco Designed to Last a Lifetime," *Walls and Ceilings*, Feb. 1997, pp. 30–37.

[73] *Thermal Performance of Building Envelopes VII, Proceedings of the ASHRAE/DOE Conference*, ASHRAE, Atlanta, 1998.

[74] Clarkin, M. E. and Brennan, T. M., "Stack-Driven Moisture Problems in a Multi-Family Residential Building," *ASHRAE Trans.*, Paper number TO-98-25-3, 1998, pp. 1373–1378.

[75] Lotz, W. A., "Insulation Failure and Moisture Problems Resulting from Inadequate Installation of Insulation and/or Vapor Retarders," *ASHRAE Trans.*, Paper number TO-98-25-2, 1998, pp. 1368–1372.

[76] Fisette, P., "Housewrap vs. Felt," *Journal of Light Construction*, Nov. 1998.

[77] Minkovich, R., "Installing Water-Managed Synthetic Stucco" *Journal of Light Construction*, Sept. 1998.

[78] Straube, J. F. and Burnett, E. F. P., "Vents, Ventilation and Masonry Veneer Wall Systems," *Proceedings of the Eighth Canadian Masonry Symposium*, Jasper, Alta., Canada, May 31–June 3, 1998, pp. 194–207.

[79] Straube, J. F. and Burnett, E. F. P., "Field Measurements of Masonry Veneer Exposure Conditions," *Proceedings of the 8th Canadian Masonry Symposium*, Jasper, Alta., Canada, May 31–June 3, 1998, pp. 208–221.

[80] Boyd, J. M. and Scheffler, M. J., Eds. *Water Problems in Building Exterior Walls: Evaluation, Prevention, and Repair, ASTM STP 1352*, ASTM International, West Conshohocken, PA, 1999.

[81] Carll, C. G. and Highley, T. L., "Decay of Wood and Wood-based Products above Ground in Building," *J. Test. Eval.*, Vol. 27, No. 2, March 1999, ISSN: 0090-3973.

[82] "Comparative Analysis of Residential Construction in Seattle, WA., and Vancouver BC," CMHC Research Highlights Technical Series Report 99-111, 1999.

[83] Hosni, M. H., *ASHRAE RP-864—Controlling Moisture in Walls Exposed to Hot and Humid Climates*, Conducted: April 1996–March 1999, on-line at www.ashrae.org.

[84] Lacasse, M., et al., Eds., *Durability of Building Materials and Components 8-SL/AM IT, Proceedings of the 8th International Conference on Building Materials and Components (8DBMC)*, held in Vancouver from May 30 to June 3, 1999.

[85] Beall, C., *Thermal and Moisture Protection Manual*, 1999, pp. 154–159.

[86] Straube, J. F. and Burnett, E. F. P., "Rain Control and Design Strategies," *J. of Thermal Insulation and Building Envelopes*, July 1999, pp. 41–56.

[87] Tonyon, T., et al., "Water Management and Moisture Transport in Direct-Applied EIFS Assemblies," *J. Test. Eval.*, Vol. 27, No. 3, 1999.

[88] "Wall Moisture Problems in Alberta," *CMHC Technical Research Highlight 00-112.*, Dec. 2000.

[89] "Determination of Water Vapour Diffusion Across Brick Masonry Treated with Water-Repellent Sealers," *CMHC Technical Research Highlight 00-113*, 2000.

[90] Quirouette, R., Marshall, S., and Rousseau, J., "Design Considerations for an Air Barrier System-OAA," CMHC, Nov. 11, 2000.

[91] Straube, J. F. and Burnett, E. F. P., "Pressure Moderation and Rain Control for Multi-Wythe Masonry Walls." *Proceedings of International Building Physics Conference*, Eindhoven, Sept. 18–21, 2000, pp. 179–186.

[92] "Indoor Air Quality 2001 Moisture, Microbes, and Heath Effects: Indoor Air Quality and Moisture in Buildings," *Proceedings of the ASHRAE Conference Papers*, California, ASHRAE, Atlanta, 2001.

[93] *Thermal Performance of Building Envelopes VIII, Proceedings of the ASHRAE/DOE Conference*, ASHRAE, Atlanta, 2001.

[94] "The Ontario Wall Drying Project Phase 2," *CMHC Technical Research Highlight 01-130*, 2001.

[95] "The Envelope Drying Rates Analysis Study," *CMHC Technical Research Highlight 01-139*, 2001.

[96] Straube, J. F., "Air Flow Control in Building Enclosures: More than Just Air Barriers," *Proc. of 8th Bldg. Sci. & Tech. Conf.*, Toronto, Feb. 22–23, 2001, pp. 282–302.

[97] Trechsel, H. R., Ed., *Moisture Analysis and Condensation Control in Building Envelopes, ASTM Manual 40*, ASTM International, West Conshohocken, PA 2001.

[98] Brennan, T., Cummings, J. B., and Lstiburek, J., "Unplanned Airflows & Moisture Problems," *ASHRAE Journal*, Vol. 44, No. 11, Nov. 2002.

[99] Kumaran, M. K., *ASHRAE RP-1018—A Thermal and Moisture Transport Database for Common Building and Insulating Materials*, Conducted: September 1998—July 2002, online @ www.ashrae.org.

[100] Lstiburek, J., *EEBA Water Management Guide*, Energy & Environmental Building Association, 2002.

[101] Straube, J. F., "Moisture in Buildings," *ASHRAE Journal*, Jan. 2002, pp. 15–19.

[102] Straube, J. F. and Schumacher, C. J., "The Role of Hygrothermal Modeling in Practical Building Design: Case Studies," *Proceedings of e-Sim 2002*, Montreal, Quebec, Canada, Sept. 11–13, pp. 185–192.

[103] Straube, J. F., Onysko, D., and Schumacher, C., "Methodology and Design of Field Experiments for Monitoring the Hygrothermal Performance of Wood Frame Enclosures," *J. of Thermal Insulation and Building Envelopes*, Vol. 26, No. 2,

Oct. 2002, pp. 123–151.
[104] Weston, T. A., et al., "Performance Testing of Window Installation and Flashing in Hot and Humid Climates," *Texas A&M University 13th Symposium on Improving Building Systems in Hot & Humid Climates Proceedings*, 2002.
[105] Johnson, P. G., Ed., *Performance of Exterior Building Walls, ASTM STP 1422*, ASTM International, West Conshohocken, PA, 2003.
[106] "Water Penetration Resistance of Windows: Study of Manufacturing, Building Design, Installation and Maintenance Factors," *CMHC Technical Research Highlight 03-124*, Nov. 2003.
[107] "Water Penetration Resistance of Windows—Study of Codes, Standards, Testing and Certification," *CMHC Technical Research Highlight 03-125*, Nov. 2003.
[108] Bomberg, M., et al., "Weather Resistive Barriers: Laboratory Testing of Moisture Flow," *9th Canadian Conference on Building Science and Technology*, 2003.
[109] Straube, J. F. and Jeong, J., "Analytical Means of Assessing Ventilation on Crawlspace Performance," *Proceedings of 9th Canadian Building Science and Technology Conference*, Vancouver, B.C., Feb. 28, 2003.
[110] Teasdale-St-Hilaire, A., Derome, D., and Fazio, P., "Approach for the Simulation of Wetting due to Rain Infiltration for Building Envelope Testing," *Proceedings, 9th Canadian Conference on Building Science and Technology*, Vancouver, BC, Feb. 27–28 2003.
[111] *Thermal Performance of Building Envelopes IX, Proceedings of the ASHRAE/DOE Conference*, ASHRAE, Atlanta, 2004.
[112] "Summary of Research on Water Resistive Barrier," *CMHC Technical Research Highlight 04-124*, Aug. 2004.
[113] Quirouette, R., "Air Pressure and the Building Envelope," *CMHC Technical Research Highlight*, Revised Nov. 2004.
[114] Searle, N. D., "Harmonization and Optimization of Weathering Test Methods for Building and Construction Sealants and Adhesives," *J. ASTM Int.*, Vol. 1, No. 3, March 2004, Online ISSN: 1546-962X, Published Online: 10 March 2004.
[115] Boone, K., et al., "Wall Drying in Hot and Humid Climates," *Proceedings Symposium on Hot and Humid Climates*, Richardson, TX, May 2004.
[116] Tsongas, G., Spalt, H., and Hummel, G., "Laboratory Water Penetration Tests of Shiplap (Dropside) Hardboard Siding," *Proceedings, Conference on Wood-Frame Housing Durability and Disaster Issues*, Las Vegas, (to be published by the Forest Products Society), 2004.
[117] Weston, T. A., et al. "Water Resistance and Durability of Weather Resistive Barriers," *ASTM STP 1484 Performance and Durability of the Window-Wall Interface*, ASTM International, West Conshohocken, PA, 2006.
[118] Erdly, J. L. and Schwartz, T. A., Eds., *Building Facade Maintenance, Repair, and Inspection, ASTM, STP 1444*, ASTM International, West Conshohocken, PA, 2004.
[119] "Ice Damming Field Research," *CMHC Technical Research Highlight 05-104*, March 2005.
[120] Cornick, S. M. and Lacasse, M. A., "A Review of Climate Loads Relevant to Assessing the Watertightness Performance of Walls, Windows, and Wall-Window Interfaces," *J. ASTM Int.*, Vol. 2, No. 10, November/December 2005.
[121] Hardman, B. G., Wagus, C. R., Weston, T. A., Eds., *Performance and Durability of the Window-Wall Interface ASTM STP 1484*, ASTM International, West Conshohocken, PA, 2006.
[122] Huff, D., "Nondestructive Field Testing of Installed Weatherproofing Sealant Joints—Questions and Answers," *J. ASTM Int.*, Vol. 3, No. 8, Sept. 2006.
[123] Kumaran, M. K., Mukhopadhyaya, P., and Normandin, N., "Determination of Equilibrium Moisture Content of Building Materials: Some Practical Difficulties," *J. ASTM Int.*, Vol. 3, No. 10, Nov./Dec. 2006.
[124] Kumaran, M. K., "A Thermal and Moisture Property Database for Common Building and Insulation Materials," *ASHRAE Trans.*, Vol. 112, Pt. 2, Paper no. QC-06-044 (RP-1018), 2006, pp. 485–497..
[125] Strong, J. C., Kovach, J. R., and Eng, V. S., "Standards Development for Impermeable, Constructible, and Durable Waterproofing," *J. ASTM Int.*, Vol. 3, No. 2, Feb. 2006.
[126] Decareau, C. P., Kan, L., and Piñon, J. P., "Inputs and Analyses: An End User's Perspective of Heat-Air-Moisture Data," *J. ASTM Int.*, Vol. 4, No. 8, Sept. 2007.
[127] Godbey, R. J. and Thomson, M. L., "The Selection and Use of Natural and Manufactured Stone Adhered Veneer," *J. ASTM Int.*, Vol. 4, No. 1, Jan. 2007.
[128] Lewis, M. D., "Status on Development of Code Requirements for Exterior Stone Cladding," *J. ASTM Int.*, Vol. 4, No. 7, July/August 2007.
[129] Mukhopadhyaya, P., Kumaran, K., Lackey, J., and van Reenen, D., "Water Vapor Transmission Measurement and Significance of Corrections," *J. ASTM Int.*, Vol. 4, No. 8, Sept. 2007.
[130] Olson, E. K. and Taylor, J. A., "Retrofitting Barrier Exterior Insulation and Finish System: Methodology and Performance Assessment," *J. ASTM Int.*, Vol. 4, No. 10, Nov./Dec. 2007.
[131] Rudd, A. and Henderson, H. I., Jr., "Monitored Indoor Moisture and Temperature Conditions in Humid-Climate US Residences," *2007 ASHRAE Transactions*, Vol. 113, Pt. 1, Paper number DA-07-046, 2007, pp. 435–449.
[132] Wilkes, K. E., Atchley, J. A., Childs, P. W., and Desjarlais, A., "Effects of Drying Conditions, Phase Transformations, and Carbonation Reactions on Measurements of Sorption Isotherms of Building Materials," *J. ASTM Int.*, Vol. 4, No. 8, Sept. 2007.
[133] Yarbrough, D. W. and Graves, R. S., "The Effect of Air Flow on Measured Heat Transport through Wall Cavity Insulation," *J. ASTM Int.*, Vol. 4, No. 5, May 2007.

MNL18-EB/Oct. 2009

25

Quality Management in Design and Construction of the Building Envelope

Mario Tama[1]

1. Introduction—The Building Industry and Quality Challenges

Approach to This Chapter

THIS CHAPTER ADDRESSES CONTROL OF QUALITY in design and construction in the context of industry moisture control problems, building design requirements, and building owners' needs. The chapter is broken into ten sections covering the following topics:

1. Introduction—The Building Industry and Quality Challenges
2. Contracting for Building Design and Construction
3. Quality in Building Design and Construction
4. Managing Quality in Building Design
5. Specifying Quality Control in the Construction Contract Documents
6. The Construction Project Team—A Quality Approach
7. Communications Through Construction Project Meetings
8. Understanding Plans and Programs for Construction Quality Control
9. Developing a Quality Control Plan and Program for a Construction Project
10. Documentation Management for Construction Projects
11. Quality Management and Building Envelope Commissioning

In Sections 1 and 2, the composition and business practices of the building design and construction industry are reviewed. Section 3 includes a brief introduction to quality management of design and construction. The meaning of quality is discussed, as is the difference between quality control and quality assurance. The importance of proactive control processes vice reactive inspection processes is emphasized. Section 4 reviews the steps that go into developing an effective building design—a complete and unambiguous set of construction drawings and specifications. Peer reviews and quality reviews are emphasized. Section 5 addresses how owners can develop the scope of a contractor-managed quality control program in the building construction contract. Section 6 discusses the importance of effective collaboration between the building project participants—owner, designer, and construction contractor. Sections 7–10 provide detail on how contractors can effectively establish and manage project quality control programs, including organizational structure, quality control processes, and quality documentation. Section 11 expands the discussion to summarize the enhanced quality assurance process of building envelope commissioning.

Quality Processes

The emphasis of this chapter is on *processes that produce quality*, rather than providing "tips" to solve specific moisture control issues. The rest of the manual contains discussion of moisture control issues; their causes and remedies. For specific projects found in the building industry, individual designers provide moisture control details in their construction plans. Throughout this chapter, however, there are specific references to and *examples* of quality control measures, inspections, and tests that apply to moisture control at the building envelope (see section Paragraphs).

The Building Envelope

Moisture control measures are primarily concerned with the building envelope. The *building envelope* (or *building enclosure*) is the (exterior) barrier that provides protection against moisture, entailing the traditional building systems such as roofing, curtainwalls, doors and windows, floor decks and foundations. The building envelope includes the numerous kinds of materials that make up, interface with, and intervene between the systems comprising the envelope, such as thermal insulation, moisture and air barriers, vapor barriers, flashing, caulking, above and below-grade drainage, etc. Interior (inside the envelope) climate control, including moisture control, is the function of heating, ventilating, and cooling (HVAC) systems, and is also a concern of this manual and chapter.

The Players

The major participants in a building project are a *facility owner*, a *designer* (usually an *Architect-Engineer firm*), and a *builder* (normally a *Construction Contractor* or *Construction Manager*). Variations on the arrangement between the players are discussed. A view of this chapter is that the skill with which a building project is managed—and the way the participants work together—has as much an impact on the final quality and building performance as the individual technical competencies of the parties involved. The chapter is concerned with quality management of the design and construction process by these participants. The greater emphasis is on managing the construction phase of a building project, with specific focus on an industry-based quality control program for *construction contractors*. The chapter looks primarily at the *project level* of quality management and perfor-

[1] *Formerly with the Naval Facilities Engineering Command, Washington, D.C.*

mance, although owner and corporate quality strategies are briefly addressed.

Who is this Written For?

The intended audience includes facility owners and managers, and professionals, practitioners, and students of moisture control in design and construction. This is directed in particular to those who have had little exposure to quality control applications in planning and building facilities. The chapter also can serve as a quality control refresher for those in the design and construction fields who are already familiar with quality control programs. The construction and quality approaches espoused in the chapter have relevance throughout all types of construction, and are not limited to the building envelope.

1.1 Moisture Control Issues Confronting the Design and Construction Community

A Basic Need

Shelter from the elements is a primal human need, manifested from the time when ancient humans first sought shelter under natural rock outcrops and within caves. Today, despite our sophistication and technical capability, we still sometimes fall short in providing our modern structures with fully effective, integrated defenses against temperature variability, wind, and water. When we encounter failures in the category of moisture control, we are sometimes confronted with the reality of building owners and tenants whose sense of frustration and disappointment is based on a reasonable 21st-century expectation of adequate and comfortable shelter.

Expectations from Concept to Completion

Building owners rightfully expect that their facilities will withstand the forces of nature and time. They try to hire capable designers, counting on those architects and engineers to "go forth and do well"—to effectively turn a corporate vision into a viable plan for a functional building. Owners also strive to retain reputable construction managers/contractors to construct that facility, expecting them to "get-it-right" the first time and deliver a flawlessly completed edifice.

Typical Problems

When moving into a brand new building, these owners (correctly) do not anticipate or expect that they will inherit leaking roofs, drafty windows, porous walls, or below-grade spaces infiltrated with water. Yet, every day across the nation, these poor conditions—and others—show up in recently completed buildings. Perhaps you have encountered problems like these in buildings: condensation on interior surfaces; "sweating" pipes and ductwork; stifling dry-heat or "cold-zones" in winter; or withering interior humidity and "hot-spots" in summer. How about water damage to ceilings, walls, and flooring; or mildew or mold on finished surfaces—as well as mold concealed in the closed-in voids behind them? Some issues like these show up right away; and others may take awhile—even a few years—to become manifest. Many owners and tenants contend with conditions like these due to mistakes made in either the design or construction of a building.

Damage and Ripple Effect

The impacts of these problems range from annoying to catastrophic such as: Repetitive water damage to materials showing up in different places on successive occasions. Damage or destruction of equipment and sensitive electronics; repeated clean-ups; lost time and cost due to occupant disruption or move-out/move-in; delay of important program missions in the building…Repeated owner calls to the designer and to the contractor; finger-pointing and slow response toward the solution—who is responsible and who will fix the problem? Where will the tenant go while repairs and replacements occur? Which party will pay for the costs and the impacts to the occupant?…

Effect and Causes

The worst cases include significant repairs and replacements; time loss; expense and litigation involving the parties concerned. Owners and their tenants do not deserve this. They pay good money for good work, and should be able to start and maintain their normal operations in their new facility. Similarly, designers do not deserve contractors who fail to follow a competent design, and conversely, construction contractors do not deserve designers who fail to produce an effective design.

Design and Construction

The facility must be conceived considering the impact of climate, weather, and, importantly, location of the site. This includes considering the nature of the soils and substrata, water table, and topography; the nature of the terrain and surrounding environment; paved surfaces and structures; and exposure to the elements. An exposed seaside site will naturally require some different considerations than an inland city location, though many of the basic design considerations for moisture protection will be similar at both sites. The designer must follow the applicable design criteria in developing a good set of contract specifications for construction. The construction contractor needs to build in accordance with a competent design; following the appropriate plans and specifications, industry standards and applicable building codes. The work needs to be performed by capable prime and subcontract personnel, practiced in their respective trades.

Project Details are Crucial

Thermal, wind, and moisture control in buildings are often related, and the "devil is (literally, really) *in the details*." Was the insulation supposed to be only at the perimeter, or does it cover the entire area? Does the insulation belong on the inside or the outside? Which side is the vapor barrier on? How is this intersection flashed? Does the architectural masonry require a sealer? Are there weeps? Where are the head, sill, and through-wall flashing? Does the window frame require a thermal break? How are the doors sealed or weather-stripped? Is this gap to be caulked—and with what material? Is there a cricket, a curb, a cant needed?

Design Details and Field Implementation

Sometimes, design details are shown clearly and are followed very well in the construction. On other occasions, clearly shown design details are not followed during construction, leading to potential problems, disastrous in the worst case. On the other hand, if the design detail is unclear or nonexistent, the constructed outcome is likely to be uncertain in the best case, and again disastrous in the worst case.

Performance Issues

Good design and good construction are, of course, the goal. A less-than-complete design may not be salvageable or overcome by even the best contractor. A great design can be "savaged," and sunk, by a less than competent contractor. The latter two outcomes are each a "lose-lose" proposition for both the designer and the contractor. In each case, the job will have problems. The substandard performance of the one entity will then unfortunately tend to "drag-down" the reputation of the other entity because of association with a "problem-project." Both parties suffer and may fail to gain future business from the client (the biggest loser, in this scenario) and other potential clients. The failure of one entity to perform properly can have almost irrevocable consequences, with the potential to cause harm to the other entities.

All Parties Suffer when One Party Fails

Despite good efforts by some, all three parties (owner, designer, and contractor) tend to lose out ("lose-lose-lose") when a project has significant problems, especially when they are moisture-related. Uncontrolled, persistent water issues can be systemic, and are often hard to correct once the building is complete. Also, because of the number of occupants affected and the various trade subcontractors on the project, word of a negative outcome travels fast to other quarters of the industry and client base.

Another Way

This chapter focuses on establishing good communications between the players, and presents a program to manage quality during both the design phase and the construction phase. A *quality-management approach* can result in a successful project with a satisfied client, as well as a designer and contractor whose unimpaired, enhanced reputations help them to positively build up their portfolio of projects. We are talking about a potential "win-win-win" proposition here, but it requires "up-front" planning and downstream control to be successful.

1.2 Why Quality Management?

Developers and facility owners (and their investors) want a *quality project, delivered safely, on time and within budget*. This also happens to be the "mantra" of successful managers of design and construction.

Convergence of Project Aims and Goals for Owner, Designer, and Contractor

Facility designers and construction contractors need to be effective to stay in business. This means that architect-engineer firms must consistently come up with viable, effective, quality building plans, bringing them to fruition within the owner's time frame and budget. Similarly, it is in the vested self-interest of building contractors to construct the owner's building effectively, safely, and within the schedule and budget established in the contract. Necessary business goals, as well, drive developers/owners, designers and builders—the budget of one entity is the source of economic health and profit for the others—and in this sense there are some compelling, competing goals. Although each party has motivations that diverge from those of the other parties, the key unifying factors are the *common goals* of quality, safety, and meeting the schedule and budget. Quality management builds on those project commonalities, which are necessities for a fully successful project.

"Win-Win" Approach

A systematic quality management strategy introduces quality control processes that will likely "catch" problems before they occur or become systemic. This approach allows designers to minimize redesign during either the design or construction phase. The institution of quality control processes on the project site allows construction contractors to minimize re-work, "rip-out," and associated lost time and wasted labor. Quality controls save money and time for both designers and contractors. The planned, structured processes enhance the goals of staying within budget and on schedule. By meeting project goals, designers and contractors deliver positive results to a pleased customer. Designers and contractors become more likely to meet their economic goals of solvency and profit, and merit much greater consideration for future business from owners. Reputations are "made" or broken over the quality and success of a project. Effectively established quality control processes help all parties to benefit—the owner, the designer, and the construction contractor.

System of Proactive Problem Deterrence Versus Reactive—"Try to Fix After Broken"—Mode

A small investment of time and effort, made early, can reap huge dividends later in problem avoidance and cost avoidance. Most managers know this from the experience that has informed their intuition, but, when "caught-up" in reacting to project demands, may fail to have found the time to effectively plan for the next project milestones. By systematically adopting a structured, quality management approach before a project starts, by convincingly "talking the talk" and effectively "walking the walk" during the project, the management of project quality can be effectively integrated into the management of the production and schedule.

1.3 Roles and Norms Among the Four Major Players in the Building Industry

The design and construction of facilities takes place in a very competitive industry of (1) building owners, (2) architect-engineer (A-E) and engineering services (E-S) firms, (3) construction contracting, and (4) construction management (CM) firms. A fifth catagory—design-builders—are typically amalgams of AE firms and construction contractors/CM firms.

Owner's Role

Building owners look to design firms, construction companies, or design-build entities when they need a new facility. Owners with smaller-scale requirements contract with, and must rely on, these companies to manage the design and the construction with a minimum of owner oversight. Large-scale owners (private or public sector) with multiple facilities and several geographic locations, or both, may have an in-house staff that understands and manages design and construction. This staff contracts with the entities (engineering, design, construction, or design-build) to investigate the site and design and build the facility. The owner's staff provides some degree of overall management and quality oversight by working closely with, and coordinating between, the retained firms as necessary to achieve the intended result. Some large owners may instead retain and rely on a construction management (CM) firm to subcontract out the design or construction firms, or both. In this case, the CM provides the day-to-day oversight.

Architect-Engineer and Engineering Services Firms

A-E and E-S firms work within the realm of a large professional community of designers, including primarily architects and engineers, supported by drafting and other technical support staff. These firms are typically required (by the states they operate within) to be licensed based on the professional registration of the firm's principal and discipline leaders. There is some overlap in making a distinction between engineering services and architect-engineer work, as some do both. Generally E-S firms perform site investigations, technical investigations and studies, and independent testing. A-E firms develop a complete building design for a particular project based on the owner's stated needs. A-E firms vary greatly in their size and makeup. There are strictly architectural firms; engineering firms with one discipline (say, civil engineering or structural engineering) or with several disciplines (say, HV AC/mechanical, plumbing, and electrical engineering); and full-service firms of architects and engineers of all disciplines. A design project may be taken on by a full-service A-E firm or by collaboration between an architectural firm and one or more engineering firms. A-E firms also collaborate with construction companies to provide a project design under an owner's design-build contract. Initially the A-E develops a concept design; the design process then proceeds—usually in defined stages—to a final design. Each stage is subject to the owner's acceptance. The final design is a set of building drawings and specifications ("plans and specs") suitable to be bid for construction. A-E firms also provide construction support services, including consultations, submittals review and approval, quality verification and inspections.

Construction Contracting Companies

The construction community is very large and diverse, ranging from local "one-man outfits" to international behemoths with thousands of employees. General contractors contract with owners to build an entire facility as the *prime contractor*. General contractors are usually either "union" or "nonunion;" meaning that their trades-workers are all either union or nonunion. Larger companies often are "union;" while smaller firms often are not, but the situation varies with geographical location and local custom. General contractors rely on their own trades-persons to perform some of the work (say, carpentry), and they hire a number of specialty *subcontractors* to perform the multiplicity of other trades-work (say, concrete, masonry, roofing, sealants, HVAC/plumbing, and electrical). Sometimes a traditional subcontractor (say, a roofer) will bid as the prime contractor on a specialty project (say, a roof replacement on an existing building) because the firm has or can easily obtain all the resources necessary to do the specialty (roofing) work. Smaller companies doing smaller-scale projects tend to be run by people with a great deal of "hands-on" experience and less formal training. Larger general contractors tend to have some managers with formal education (typically in construction management, architecture, or engineering), but many managers in large firms have "come up through the ranks." Both types of backgrounds—training and education, as well as extensive construction experience—are necessary and valuable, and can provide some synergy to the management of a construction project.

Construction Management (*CM*) *Firms*

These firms are used by owners who want capable management of (a) both the design and construction process, or (b) the construction process alone. For owners, a primary advantage to retaining a CM firm is the temporary (one-time basis) provision of staffing expertise and valuable up-to-date industry experience—assets that the owner does not have in-house. Construction management firms provide budget, constructability, and schedule input to a project during its design. The quality of the construction documents is improved by the integration of design and construction expertise. The CM firm "takes over" (from the owner) the routine management processes that are crucial to keeping a project proceeding according to schedule and specified quality levels. This includes field quality assurance and inspections, and monitoring of safety. (Note that the designing A-E firms may also compete to provide some of these types of services during construction.) When providing management for design and construction, CM firms may operate at a number of possible levels, depending on the structure the owner wants. Following are several examples, though there are multiple other possibilities:

(1) *Owner contracts with the CM firm to provide the facility under a CM-design-build" contract:* The CM firm hires the A-E firm to design and prime construction contractor to build the project. The CM firm manages and pays the A-E and prime contractor; the owner pays the CM firm for the entire project.

(2) *The Owner has previously obtained the design from an A-E firm:* Owner contracts with the CM firm to manage and provide construction of the facility under a CM-construction contract, and the CM firm hires the prime construction contractor to build. The CM firm manages and pays the prime contractor; the owner pays the CM firm for the construction management and construction.

(3) *Owner has previously contracted with an A-E for the design; and owner will award the construction contract* (or, alternatively, *the owner has contracted with a design-build entity to execute the project*). Owner contracts with the CM firm to provide consultation—construction management oversight of the construction contractor (or design-build entity) building the facility, under an "at-arms-length" construction management (only) contract. The CM is a *consultant* to the owner. The owner pays the A-E firm for the design and any contracted field services, and the owner pays the prime construction contractor to build the project. (In the event of a design-build contract, the owner pays the design-build entity.) The CM firm provides routine CM services to support the construction processes and provides quality assurance and inspections, advising the owner in the construction manager's consultation role. The owner pays the CM firm for the construction management oversight.

(4) *Owner puts open bids out on a very large construction project:* The CM bids as a "super-prime" contractor, competing for the project on the open-market against other CM firms and prime construction contractors. The CM may subcontract to a general contractor who retains the subcontractors; or the CM may subcontract separately with a general contractor and each individual subcontractor.

1.4 Subcontracting and the Construction Trades

Construction contractors usually subcontract a much greater percentage of the building work than they perform with their own limited in-house trades-force. *Construction management* (*CM*) *firms* usually have no in-house trades-people, and will subcontract with prime contractors or subcontractors as previously indicated.

Role of Subcontractors

Subcontractors perform the largest role, literally, in a building project. They construct the project using experienced tradesmen who are the "heart and soul" of the construction production process. The planning of their work and execution of their workmanship is critical to the quality of a project. Larger firms (with some exceptions) will tend to have union workers, which means that the trades-persons have gone through extensive classroom training as well as mentoring on the job. Smaller companies (with some exceptions) typically tend to be "nonunion;" so the trades-persons usually have learned more through "on-the-job" experience than through formal training. In either case, good, reputable subcontractors have capable, experienced trades-persons that are the necessary source of high quality workmanship and, ultimately, the success of overall project quality.

Workmanship Role of Tradesmen/Journeymen/Craftsmen

Trades-people are the ones on the project that ultimately have to get the job done—they "make it happen." The construction trades are full of capable and creative people who are very experienced in what they do. Effective contractors and subcontractors tap into the practical genius of their better tradesmen, and allow them to do their job the right way. These blue-collar practitioners of the art of construction are often not sufficiently recognized for the value that they bring to a project, and they labor in the shadows of the managers who depend on them and the professionals that (unfortunately) sometimes look down on them. These traditional tradesmen can produce the workmanship expected and take pride in their work. There are new generations of good craftsmen still being developed in the trades because building is fulfilling work, allowing one the chance to see the fruits of one's labor in concrete terms every day. Job satisfaction can be high.

- *Skill Pool Decline:* As institutions and generational attitudes change with time, however, there seems to be a smaller proportion of the "traditional" tradesmen around. Some people on the job are not as skilled; and a few are not as committed to good workmanship. This can be exacerbated by cyclical building booms that bring many newer, less skilled workers into the trades to fill the worker gaps. When looking at some of the more difficult, labor-intensive jobs with difficult environmental conditions, such as roofing, insulation and vapor barriers, waterproofing, painting, sealing and caulking (all critical items for the building envelope), the labor pool tends to be less skilled.
- *Time and Money Pressures:* The final element of stress on the production of good workmanship is time, and its corollary, money. Time stress to meet the schedule may be heightened because the subcontractor has several projects and not enough crews, so he starts late on *your* project, and could cause impact to the schedule and subsequent work if he does not finish expeditiously. He, in turn, has to get to the next project to avoid delaying it. So the job gets hurried and the quality of work suffers. In addition, the very high level of competition for business in the construction arena leads contractors and subcontractors to "shave" their bids as tight as possible—this is not a new phenomenon. The natural result is that even the best prime and subcontractors may cut corners to save time and get the job done with less labor expense. When considering the importance of moisture control measures to the project success, these realities put adverse pressure on obtaining the necessary quality of the building envelope.

1.5 Building Industry Challenges

Uniqueness of the Construction Industry and the Building Process

The construction of buildings is a unique process—a "one-of-a-kind" amalgam of multiple building systems put together by a nonhomogeneous group of technical specialists assembled for one particular project at one particular time. When the project is completed, the parties dissemble, and probably will never again work together in exactly the same way, if they work together at all. Therefore, each project is a creative exercise with different players in the mix, all, one would hope, to some degree focused on completing the project in accordance with the contract requirements. Even "cookie-cutter" designs, like some fast food buildings, have differences in geographical location, environmental conditions, and site characteristics; and a different subcontractor mix will assuredly be assembled at different times and in disparate locations. Managing this controlled chaos can be a tall order, but is a challenge that seasoned construction professionals relish.

- *Quality Management Challenge:* Part of the organizational challenge is the management of quality, especially on a large project, with numerous subcontractors moving in and out of the picture between the ground level and the roof. Many of the traditional trades are either involved in, or impinging in some way, on the building envelope. It is hard for a manager to be everywhere at once to make sure that the work is going on in the way it is supposed to be accomplished.
- *Quality Control Context—Construction Site versus Manufacturing Facility:* Performing quality verification on a construction project is quite unlike traditional quality control programs in the manufacturing industry, where there is a fixed set of repeatable processes that usually occur successively in the same successive locations each time the series of processes is performed.

Toyota and Ford can rely on many repeatable operations in developing their QC program in a fixed, enclosed (weather-protected) plant setting. A construction contractor has a much more diverse and less predictable playing field than a manufacturer. The game plan for production and quality control has to be structured enough to bring a semblance of order to the chaos, but flexible enough to adjust for schedule delays and weather issues.

- *Integrating the Management of Schedule and Quality:* The special conditions and high risks characteristic of building projects—and the basic need for integrity of the moisture-controlling building envelope—argue for a well-planned schedule around which a well-planned quality control (QC) program can be developed. Quality concepts are introduced in Section 3; and quality control in construction is addressed in Sections 5–11.

Field Perceptions and Attitudes

Integrating quality control into management processes is one thing; integrating regular quality checks into the building site culture is quite another challenge. Tradesmen are responsible to produce the quality of workmanship required in a project—they and their foremen/superintendents usually know how to do this. But it is human nature to resist those "looking over your shoulder" to see if you are "doing right." On many projects, the entire culture on the building site tends to reflect this understandable attitude, from laborer to the job superintendent and project manager. Quality control efforts tend to be looked upon as unnecessary oversight and interference that will cause progress to be compromised. Part of the quality management challenge for construction contractors is to provide positive leadership that can effectively promote the value of quality control checks as ultimately beneficial for all production staff and workers (inculcating long-term vice short-term thinking). Good, committed leadership helps to instill a perception shift that can foster some degree of cultural adjustment on the jobsite. A generally positive (or even a benign) jobsite attitude toward quality control measures will help managers to (almost) seemlessly integrate the quality processes into the production schedule and work effort.

Adversarial and Cooperative Roles

The construction industry traditionally has tended to some extent embrace an adversarial contractual culture, with tight-fisted owners watching every penny; their inspectors inspecting to find mistakes (after the work was done), and requiring the contractor to rip-out defective work. Construction contractor management would often take an offensive stance, actively looking for design mistakes leading to change orders and pursuing claims in the case of owner contractual oversights. There is nothing inherently wrong with this strong-minded approach, each party correctly and assertively pursuing project priorities and protecting its contractual rights. The trouble comes when the primary approach to project administration, communications, and construction management becomes consistently adversarial, and when old-fashioned hard-nosed honesty and fairness turns into an atmosphere of "win-at-all-costs" for one or both parties. Quality will suffer and progress will stall as each party stakes out a rigid, sometimes untenable position. This culture still prevails in some sectors of the industry, but modern management on both sides have started to do what good, seasoned construction field practitioners on both sides have informally done for years—try to find a reasonable and rational way to communicate and resolve problems together despite initial contractual differences. This informal "teamwork" across the contractual divide, commonly called cooperation, is now often referred to as *partnering*.

1.6 Partnering

In today's parlance, "partnering" refers both to *informal* cooperation between the parties to a contract, as well as to a *more formal, structured "partnering process"* established in some of today's construction and design-build contracts. Formal contractual partnering is written into the language of some contracts and is usually supported by the resources of the parties to the contract, but is contractually nonbinding. The purpose is to set common goals for project success, to establish real (versus feigned) cooperation, and to implement smooth avenues for communications and contract processes. Partnering conferences are held between all stakeholders after contract award and before the design-build or construction work starts, and at regularly established intervals (or as needed) during the project duration. Stakeholders include representatives of the owner, the architect-engineer, the construction manager, and the contractor, subcontractors, and suppliers. The meeting sessions are usually facilitated by a trained facilitator, either a disinterested outside party or, alternatively, by a member of one of the contractually-involved organizations who is not involved in the particular project being "partnered" and is acceptable to all the parties involved. Some team-building exercises unrelated to the project may be used to "break the ice" and break down communication barriers. A virtue espoused is open and honest communication minimally tainted by "agendas" intended to primarily benefit only one party. A mission statement is developed and signed by all parties, and process flows are developed and agreed upon. Additional discussion on the importance of establishing good relationships and communications across project stakeholder "boundaries" is found in Section 6, The Construction Project Team—A Quality Approach. The concept of quality control performed by the producer of the work, the construction contractor, dovetails well with the partnering goals. The contractual efficacy of a contractor-managed QC program for construction is reinforced by the cooperative strategies inherent in the partnering process.

2. Contracting for Building Design and Construction—The Facilities Contracting Process

2.1 Public Sector (Government) Contracting

Governments need and consequently order a very large percentage of the facilities and infrastructure designed and built in this country. A multitude of local, state, and federal government entities, such as highway departments, court systems, administrative agencies—and the public that they serve—all need mobility and access, space to work and conduct business, a conditioned environment, and a roof over their heads. To obtain the facilities they need, such agencies predominantly contract with firms that can provide project consultation, design, and construction. Thus, public-sector contracting heavily relies on the private sector as the agent to get the needed work done. Government contracts are drawn up to clearly define the project requirements. Depending on the nature of the contract (A-E, construction, design-build, etc.), qualified companies compete by submitting a proposal and price, or both, for the project. Once a firm is awarded the contract for the work, it is incumbent on the company to perform it diligently based on the government contract criteria, which is usually strong in the domain of quality. Most government contracts are structured carefully to protect the interests of the government agency, while at the same time being fair to the company doing the work. Contractors are virtually assured that they will be paid for work that complies with the contract terms. The contractual structure is governed by statute, based on law protecting the public interest. As a result, there tends to be a greater emphasis on documentation in the public sector. Many designers and contractors like the predictability and structure of the government contract administration processes and fair payment policies, but they must be prepared to deal to some extent with a bureaucracy, and the attendant paperwork. Other companies shun government work because it does not suit their management style.

2.2 Private Sector Contracting

Commercial and private entities that need a facility built go through a similar, but likely less cumbersome process than do the government entities. These owner entities develop relationships with firms that design, companies that build, and consulting groups to determine if there is working compatibility as well as assessing if the firms can "do the job." Private or commercial contracts are developed based on the owner's requirements for the building project, and they may be (1) awarded outright by negotiating performance and cost with a highly preferred single source, (2) bid to and awarded from a select group, or (3) bid on the unrestricted open market and awarded to the low (or otherwise qualified) bidder. Private and commercial contracts may have either stringent or not-so-stringent performance requirements, but they tend to be strict with regard to completion time and penalties for failure to perform or complete timely. Most commercial contracts are based on a commercial code of the applicable state, based on applicable state law. The commercial contract contains provisions to protect both parties, but tends to be weighted toward the owner who is paying the bill. Many design firms and contractors appreciate the importance given in the private sector toward developing strong, favorable business relationships with suppliers and service providers that provide good management, quality, and schedule discipline. Such firms then become "favored" repeat providers for the facility owner, and the A-E or construction firm has incentive to continue doing well for the "favored" owner client. The potential for a positive collaboration, greater flexibility, and lower intensity of paperwork in the private sector appeals to these companies. Many design or construction companies, however, compete for projects both in the public and private sector.

2.3 Contracting Methods

Variety of Methods

The basic contracting approaches and the more complex contracting approaches are described. Some of the more sophisticated contracting methods described below tend to be most applicable to building owners with multiple properties and dispersed locations, such as large corporate entities and government agencies. These entities have a need to award a number of design or construction contracts every year to keep up with organizational expansion and change, or to provide repairs and replacements to buildings and systems that are well into or at the end of their life cycle. These large owner entities need to have available different contracting strategies that will best suit the *size, complexity, and risk* of the contemplated project, and will dovetail best with the current pulse—the intensity of activity—of the building industry.

Quality Implications of Contracting Methods

The *quality of the procurement method* used to pick a designer or contractor has immediate ramifications that will ultimately affect the *quality of design and construction*. Whether the contract is for design or construction, the quality of the final product, a building design or the completed facility, is dependent on *the right people doing the job*. Contracts for design or construction can go to the *lowest-price* "qualified" bidder, or they can be awarded to the "*most*" *qualified* bidder, depending how the procurement strategy is structured. "Best-value" strategies assess both price and capabilities. The owner needs to realistically assess the level of quality he needs for his project against his budget, and then find the best provider of design or construction that he can for his money. Various procurement strategies can help "narrow the field" of contenders so that the probability of getting "the right guy" is increased. By judiciously picking the most advantageous procurement strategy for their situation, owners give themselves potential *quality leverage* before the project even starts.

- *Contracting for the Building Envelope:* When a building project is contemplated that includes the building envelope, whether an entire building or a component of the envelope, owners need to use a procurement strategy and contract methodology that will be most likely to give them the building moisture control that they need—designers that understand how roofs, walls, and foundations go together to keep water out, and contractors that have the right experience and know how to put the components together properly to control moisture. It may seem like a simple order, but it isn't necessarily so. *Procurement of competent and capable firms is the* (often overlooked but) *vital first step on the road to quality*.

2.4 Contracting for the Building Design

The selection of an Architect-Engineer firm to design a building project is based on several factors, including: (1) firm qualifications; (2) price; and (3) in some cases, a design proposal. In the case of the Federal Government (the "Brooks Bill") and some states, A-E firms must compete in the open market to be considered qualified, then selected for, and eventually awarded an A-E contract for a specific project, or projects. A "two-step" process is mandated: (1)

first, competing A-Es must each provide their firm's qualifications and experience. The proposing firms are then culled down to a "short-list" of only a few firms, those considered "highly qualified," by the owner's representatives. Interviews are then conducted with each firm on the short list, and a single "most highly qualified" or "best-qualified" firm is selected by the owner's panel. (2) The best qualified firm submits a proposal with a design strategy and a price to perform the work. An acceptable price is then negotiated. (If an acceptable price cannot be achieved, the owner goes back to the next most highly qualified on the short list for a proposal and subsequent negotiations.) Private sector owners may select A-E firms with this type of rigorous approach, or they may have a more informal way of picking the firm they consider the best for the project. In some cases, such as a formal design competition or the design portion of a design-build contract, part of the process may include a concept design proposal.

- *Moisture Control Concerns—Building Envelope Design:* Owners who contemplate retaining a designer for a new or existing building that will include building envelope systems and components should consider a strategy that "flags" the importance of moisture control. Owners can mitigate their design risk by making sure that their A-E selection criterion includes demonstrated design competence in the moisture control arena, specifically with the type of building envelope systems and components that are contemplated for their particular project. These aspects of a project design are often not particularly emphasized in the A-E procurement documents, because of the inaccurate general assumption that all A-E firms are versed in the "apparently" very basic and rudimentary systems such as *roofing, flashing, sealants and caulking, and waterproofing, etc*. These systems all, of course, require simple but subtle details to be effective.

2.5 Concepts of Design and Construction Contracting Strategy—"Design-Bid; Build (D-B-B)" vice "Design-Build (D-B)"

Before bidding either the design or the construction, the facility owner must reach an essential decision on contracting strategy:

1. *"Design-Bid-Build:"* Does the owner want to (a) award a *design contract* to an A-E firm for a complete design, and then (b) use the construction documents from the design to *bid* and award a *construction contract* for *building* to a construction contractor? The advantage of a separate design contract is the owner's high degree of control over the evolution of the design, and a full designer focus on developing an optimum, complete design. On the other hand, there may be less practical construction-side input into the "constructability" of the design.
2. *"Design-Build:"* Alternatively, does the owner want to merge the responsibility for design *and* construction by awarding a *design-build contract* to a design-build firm? A design-build approach has the potential advantage of putting the entire responsibility for the design-construction process in the hands on a single entity—streamlining contract administration for all parties and eliminating the owner's onerous role as adjudicator in "we-versus-they" issues between a separate designer and builder. The design-build process may allow a quicker timeline between project concept development and construction completion because instead of two contracts [award of (1) design and then (2) construction], the owner awards a single design-build contract. In addition, under *design-build*, the design and construction can sometimes be "overlapped" or "fast-tracked," if the benefits versus risks are considered advantageous. This reduces schedule time and related costs. D-B offers the potential for some synergistic convergence toward cost-effective or best-value design solutions, as designers and builders contribute collaboratively to the evolution of the project. Conversely, a concern about the D-B process is that designers may have less "clout" than the constructors on the team, increasing the potential for design cost-cuts. Owners may manage such risk by specifying life-cycle cost evaluation in contracts when added cost is justified.

2.6 Owner's Design Strategy and the Construction Project Documents

The complexity of the project has a lot to do with the design and construction strategy. Several design development strategies may be employed to develop different levels of design—from simply developing design criteria, to developing a concept design or a partial design, to developing a complete design for construction. The decision made on completeness of the design depends on the owner's needs and perceptions of what the competitive industry can effectively deliver. Factoring into this decision are the owner's building requirements, budget, cost control, time constraints, risk potential and risk tolerance, and the relative amount of work currently being proposed upon or bid in the industry. (For example, how competent, how busy, and how "hungry" are the likely available players in the broader building industry community of architect-engineers, construction contractors, and design-builders?) The *owner's design* approaches connected to the two respective contracting strategies, (1) design-build versus (2) design-bid-build, are summarized below.

Owner's Design Approach for Design-Build Contracts

- *Owner's A-E (in-house or contracted) Develops Design Criteria Only*—The design criteria, performance, and aesthetic requirements, but no level of design, is developed in accord with the owner's basic needs for the building. The owner in this instance has no preconceived scheme for the building, and is mainly concerned that the final product will be functional and look appropriate in its setting. This approach is most feasible when a simpler structure without complex systems is desired. After the design criteria is established, the owner bids and awards a *design-build contract* based on the criteria. The design-build contractor then initiates, develops, and completes the design to the final stage of construction plans and specifications, and builds the project accordingly.
- *Owner's A-E (in-house or contracted) Develops a Concept Design*—A set of rudimentary design documents is developed: a concept design shows the owner's general intent for size, scale, appearance of the building, and general types of building systems. The owner in this

instance needs only some basic control over the general direction of the design. After the concept design is generated, the owner bids and awards a *design-build contract* based on the concept. The design-build contractor fully develops and completes the design to the final stage of construction plans and specifications, and constructs the building in accordance with those documents.

- *Owner's A-E* (*in-house or contracted*) *Develops a Partial* (*"Bridge"*) *Design*—A set of incomplete design documents is developed. A partial or "bridge" design takes the owner's requirements to perhaps a 35 % complete design, where configurations, building systems, and materials are delineated, but drawings and details are incomplete. The owner in this instance needs some control over the general direction of the design. Within the content of a largely 35 % stage of building design, some specific systems within the building that are critical to the operation may require even more mature development (to, say, 100 %) for that particular portion of the design. After the concept design is developed, the owner bids and awards a *design-build contract* using the owner's partially completed design. The design-build contractor completes the project design to the final stage of construction plans and specifications, and builds the project as delineated in the documents. The need for this approach is questionable from a strategic and cost point of view—why have one design firm (the owner's) take the design to the 35 % stage or so, and then "abandon" them to employ a new designer that is part of the design-build team? This approach may have virtue in the case where the owner has a limited design team on hand, but finds it necessary to get the design started off in a direction that is certain to satisfy the owner's operational requirements. The design then gets "handed-off" to a design-build firm that has the depth and capability to finish it expeditiously in the "fast-track" design-build environment.

Owner's Design Approach for Design-Bid-Build Contracts

- *Owner's A-E Develops a Fully Complete Design*—A set of construction plans and specifications that is complete and ready-to-bid and construct. In this scenario, the owner requires complete design control over the materials, systems, and configuration of the building. He needs to know ahead of time exactly what the building will look like and exactly how the systems should perform. This approach is applied most prevalently for more complex and sophisticated facilities. Once the plans and specifications are completed, a *construction contract* is awarded using the construction documents. The construction contractor builds the project in accordance with those plans and specifications.
- *Owner's A-E—Designs for Multiple Projects*—Owners with multiple facilities may need an almost continuous A-E presence over time in order to keep up with a recurring design demand. Typically, the need is for construction documents to implement the necessary repair and replacement of deteriorated or outdated building systems, interior reconfigurations and re-vamps, and for occasional building additions and smaller-scale buildings. An effective design strategy that deals with an owner's evolving need for design of *routine small to medium scale projects*, including those involving the building envelope, is for owners to select one architect-engineer firm to handle this general category of recurring work. Typically, this type of design procurement strategy is accomplished through an *indefinite quantity contract* (*IDQ*). IDQs are usually awarded for an initial term of up to one a year, typically with options to extend on a yearly basis up to three years or five years. There is usually a guaranteed minimum award amount and a maximum not-to-exceed limit to the potential total contract value, per year and per total contract, or both. Individual "work orders" are issued for each project, giving the design scope and duration, and a price is negotiated for each. The A-E selection process is similar to the method described earlier in the paragraph "*Contracting for the Building Design*," with the additional criteria that the A-E firm has the capacity and resources to handle a specified volume of work yearly. There are many advantages to this approach for an owner challenged with managing many building projects: (1) the contract is tailored to the owner's long-term needs. (2) An effective investment of owner time in developing selection criteria and in the selection process has the *potential to deliver highly-leveraged quality results*. The quality of an A-E firm, selected only once, is infused into each successive project as the necessary project work orders are awarded. (3) The administrative burden is significantly reduced when compared to the competition, award, and administration of individual separate contracts. (4) A longer-term partnering relationship can be nurtured to the benefit of both parties. (5) The owner can opt out of the option years if performance of the A-E is not satisfactory. A downside is the potential for "cost-creep" because the A-E firm is somewhat "locked-in."
- *Multiple Projects for Specific Types of Design Work*—An offshoot of the owner IDQ strategy is to select an architect-engineer firm to handle a *specific recurring category of work* (for example, the moisture control categories of roofing, flashing, and waterproofing). This approach gives an owner the opportunity to fine tune his stable of A-E resources to bring specific expertise to bear on a particular category or discipline that may be considered of potential high risk.

Owner's Design Role

The owner does not relinquish influence on the project design in any of the scenarios outlined above. The design process in all the instances discussed is, by contract, always contingent on the owner's review and acceptance as the design process evolves.

2.7 Contracting for the Building Construction or Contracting to Design and-Build

The difference between a construction contract and a design-build contract is implicit in the names given. These two types of contracts are alluded to above in the discussion of different owner strategies to deliver the design.

- *Construction Contract:* The construction contractor is awarded the contract with a fully-developed set of construction plans and specifications. The contractor is responsible to construct the project in accordance with the plans and specifications, and is fully responsible for the effectiveness of his management and the quality of construction of the building. Note that the construction contract is the second contract of a two-stage project contracting process: (1) a building design prepared under the owner's contract with an A-E firm to develop a complete set of construction plans and specifications for bidding purposes; (2) a building constructed under the owner's contract with a construction company, based on the set of construction plans and specifications. This process of two successive contracts—one with an A-E for design, and one with a contractor for construction—is sometimes referred to as "*Design-Bid, Build*."

- *Design-Build Contract:* The design-build (D-B) entity is awarded the contract with the owner's design criteria, or concept design, or partial design, as determined by the owner. The contract also contains construction criteria mandated by the owner. The design-build entity's team consists of design architects and engineers and construction staff. The design-build entity may be a design-build firm using all in-house personnel, may be a construction firm that has subcontracted the design work to an A-E firm, or may be a joint venture between a construction contractor and an A-E firm. In any case, the project contract requires the D-B entity to be a single legal entity for contractual purposes. The full responsibility for project design and construction resides with the design-build team. Quality is infused into the design by both the designing staff and construction staff during design. The process of an owner using a single contract to encompass both the design and construction of a facility is, of course, "*Design-Build*."
- *Construction Management Contract:* Construction management firms can serve the owner by representing the owner during the project development, from concept through design to building completion. Construction managers have the design and construction background to provide a project with budget control, schedule control, safety assurance, and quality assurance, as necessary, both during design and construction. Owners retain construction managers because CMs have the expertise and staff (that may be lacking or currently unavailable to the owner) to capably manage the project design and construction on the owner's behalf. Owners need to assess well ahead of time if they will need this asset, and budget accordingly for a CM presence.

2.8 Procurement Strategy—Method of Solicitation for Construction and Design-Build

Some of the common methods for contract delivery of construction and design-build projects are described as follows:

- *Invitation for Bid ("Hard-Bid" or "Low Bid"):* The project documents are competitively bid by the owner, through an invitation for bid (IFB) either (a) on the open market or (b) to select, prequalified firms. The lowest qualified bidder gets the contract award, and has the responsibility to construct the project per the quality designated in the documents, standards, and codes. This approach is most prevalent and effective for projects, large or small, with a low level of complexity. It is used primarily for construction contracts, though it may be used for simpler design-build projects when there is a preestablished, select bidding pool.
- *Request for Proposal ("Best-Value"):* The project criterion (either design criteria, design documents, or construction documents, as applicable) are published with a request for proposals (RFP), either (a) on the open market or (b) to select, prequalified firms. Proposal selection criteria are established in the RFP, and usually boil down to (1) industry references assessing past performance; (2) relevant (similar) project experience; (3) effectiveness of a technical proposal based on "technical" elements required by the RFP; (4) proposed price; and (5) the relative "weight" given to the firm's past performance, related experience, and technical proposal *vice* the price. (In the case of an RFP issued to select bidders, the effectiveness of a firm's past performance may have already been prequalified in the previous establishment of the select bidder pool, so that criteria may or may not be used.) "Offers" are received, and an owner team subjectively evaluates the proposals against the technical and cost criteria. Award is made to the qualified "offeror" that represents the "best-value" to the owner, considering the mix of past performance, relevant experience, technical merits, and cost. This procurement approach is most useful and effective for projects, large or small, with a higher level of complexity. It is used primarily for design-build contracts, though it may be used for complex or high risk construction projects.
- *Moisture Control Concerns—Building Envelope Construction:* Owners are rightfully risk-averse when construction is involved. *The potential for inadequate construction of the building envelope poses high risk to an owner.* A prudent strategy is to make reasonably sure, in advance, that the eventual contractor for a new or existing building contract will likely be capable and competent to properly build moisture control into the building envelope (per "plans and specs"). Owners can do that well "up-front" by setting up the right procurement process. They should assure that their procurement method allows some effective contractor screening criterion to be set up in the procuring documents, including bidder's past performance and relevant experience with projects similar in size and scope to their particular project. Experience with the specific building envelope systems and components in the construction documents should be singled out as criteria in the procurement. This type of procurement approach has been rarely used in the past for traditional contracts involving the building envelope, because of the additional administrative effort, possible additional cost, and the unfortunate perception that "basic" systems like *roofing and flashing, sealants and caulking*, or *waterproofing* are "simple" and do not need special attention. In fact, these systems, while simple in concept, must be built or installed with proper attention to the subtle design details that will "make or break" the moisture control integrity of the building envelope.

Multiple Procurement Strategies

Owner organizations that need to execute multiple routine contracts for minor construction or rehabilitation and repair may implement *Indefinite Quantity Contracts* ("IDQs"), with recognized good construction performers that have the capability and depth to effectively manage and perform multiple contracts of all categories or of specific categories (e.g., roofing). The owner's procurement organization needs to develop the right contractor criteria and then select a well-qualified contractor based on the criteria through a contract proposal (RFP) process. These RFPs are usually structured as a form of "Best-Value" contracting—the contractor selection is based on the best value to the owner when the factors such as past performance, related experience, content of a technical proposal, as well as proposed prices, are considered. Once the owner awards the IDQ contract with an initial "task," subsequent tasks are issued as needed and performed by the contractor. Many IDQ contracts are awarded for a year, with several subsequent option years awardable to the same contractor if the performance is good and if the owner has the need and the funds. If the IDQ contract goes well as the duration unfolds, the owner will partner and can nurture a long-term relationship, ultimately a "win-win" proposition for the involved parties when handled fairly and above board. The IDQ approach can be a *quality multiplier* for organizations, minimizing the administrative effort of separate competitions for each routine project. Some common examples of types of IDQs issued by large owners are outlined below.

- *Repair/Replace IDQ*—Prepriced Job Order Contracts (JOCs)
- *Minor Construction IDQ*—Task Order Contracts (TOCs)
- *Major Construction IDQ*—Multiple-Award Construction Contract ("MACC")—A form of "select-bidder" procurement, uses IFBs and RFPs, construction and design-build. A selected group of contractors (say, five firms) is awarded the privilege of competitively proposing (under owner-designated RFPs) or competitively bidding (under owner-designated IFBs) against contract "Work Orders" for one or more years, with several option years. In order for contractors to ascertain the potential size of the contract, there is a stated minimum guaranteed amount that the owner intends to award to the group as the aggregate sum of awards made to different individual firms competing for each task order. Similarly, the owner will state a maximum (nonmandatory) aggregate amount that could possibly be awarded. Individual "Work Orders" competed and awarded for each project.

2.9 Contract Cost Structures

Construction and design-build contracts are put together with certain cost and payment criteria that, when properly written, are intended to both protect the interest of and limit the advantage of either party. Most projects are fixed-price contracts, but unique situations where a greater-than-normal risk is borne by the contractor may be cost structured differently.

- *Fixed Price:* The contractor performs the work for an agreed-upon (proposed or bid) price in accordance with the contract plans and specifications, including a fixed completion time from award. Late penalties may apply for finishing behind the specified completion schedule. If the plans and specifications are changed ("change orders" are issued for various reasons), additional fixed-price contract modifications are negotiated, agreed, and added to/included in revised contract terms, changed contract price and, possibly, a contractual time extension.
- *Fixed Price* w/Incentives: Similar to fixed price, except the disincentive of a late penalty is complemented by a potential added price incentive for finishing early. Used when the owner has a strong interest in a rapid completion.
- *Cost-Plus:* The owner pays the contractor his actual documented cost, plus an agreed upon percentage of profit. Used where the total scope is uncertain and contractor risk is high. Not usually used in construction, although in some cases a higher risk "cost-plus-component" of an otherwise fixed-price contract could be isolated as a separate bid item within the contractors' bids or proposals for the entire work. For example, in the quality arena, this approach could apply to a special contractual requirement for a prototype of a "one-of-a-kind" building envelopes, or for a unique structural frame. This type of high-level quality strategy could be separately provided for in the contract as a "cost-plus" bid item. The cost-plus format would lend itself to this quality control methodology to distribute the risk of this significant aspect of a unique project to both the owner and the contractor.
- *"Construction Manager* (*CM*) *at Risk:"* When the owner decides to use a construction management firm to manage his project, he may want to consider this cost approach. A *Guaranteed Maximum Price* (GMP) can provide an owner with the control of budget with the required quality. For example, a "Construction Manager (CM) at Risk" provides a GMP to an owner to provide an upper-end "cap" to project costs. Construction-management firms cannot afford to under-bid this type of contract, so the greatest value for the owner is likely achieved through a "best-value" RFP to select a well-qualified CM firm.

3. Quality in Building Design and Construction—Overview of Quality Concepts

What does quality mean in the context of building design and construction? What is quality control, and what is quality assurance? These concepts are addressed as follows.

3.1 What is Quality?

We all have a sense of whether something is of good quality; we look at an object and, based on our experience, judgment, and aesthetic sense we usually can come to some conclusion on the quality that we perceive, its intrinsic value to us, and perhaps its monetary worth, as well. Our judgment may or may not be "accurate" when held up against others' views of the same item. Is beauty is in the eye of the beholder; is one man's trash another's treasure?…Is quality relative, or is there some absolute standard of quality that all can agree on? How do we judge quality when we can only see the surface, and not what's inside, or hidden?

Dictionary Definition of Quality

Dictionary definitions of quality—in the sense most closely applicable to design and construction—essentially boil down to "*the basic or essential character or nature, etc., of* *something*;" and "*the degree of excellence*" of something.

3.2 Obtaining Quality in Building Design

A building design is a sophisticated and complicated undertaking, depending on skilled and experienced architects, engineers and technicians who marshal their collective talent to produce, electronically and on paper, images and words that need to exactly capture the essence of the owner's requirements, translating them into construction drawings and specifications that can be clearly understood by the builder. Site plans, utility plans, existing conditions, building plan views, elevations, sections, and details, details, details… the essence of design is those carefully rendered clear pictures that each can be worth a thousand words. Complementing the essential drawings are the technical specification sections, explicitly worded paragraphs and subparagraphs that describe the needed equipment, material, and workmanship, the substance that buttresses the essence. In the best case, the documents for construction must be complete, clear, and unambiguous.

- *Building Design Quality—What is It?* All the careful design work described above, when really done well, boils down to a simple bottom line definition—*design quality* means *meeting the owner's stated needs by providing the information necessary to build to those needs*.
- *Building Design Quality—How to get It?* Although the definition above is a subjective statement, the quality of designs can be objectively verified by a thorough *design review process*. A structured management program for design, including design reviews, enhances the potential that architect-engineers will achieve the needed degree of design quality. The program is described in Section 4, Managing Quality in Building Design.

3.3 Quality of Building Construction

Although the building process is sometimes messy, dirty, and labor-intensive, it is, like the design, a complex, coordinated effort, using the time-honed skills of managers, foremen, and tradesmen who work together to construct a building that complies with the owner's specified needs. The builder and their staff need to have the capability and experience to clearly understand contract drawings and specifications. They need to carefully read and review the site plans, utility plans, existing conditions, building plan views, elevations, sections, and details to know what is required and to plan how to put the building together. *They really need to pay close, explicit attention to the details on the drawings*. They need to read and understand the requirements of the technical specification sections. Builders then must proceed to provide the right equipment and material, and to build, assemble, and install the multiple interfacing building systems precisely in accordance with the construction (contract) document requirements. Ideally, the construction of the building will be well coordinated; the systems well integrated; and the workmanship, exposed or hidden, flawlessly executed. Presumably the completed building will look as good and better in actual light of day than in the architect's original color rendering hanging back in the owner's office.

- *What Do the Experts Say About Quality?* Here are some observations:
  Crosby—Quality is a sense of the *relative* worth of things.
  —Requirements must be clearly stated.
  —Measurements are then taken continuously to determine conformance to those requirements.
  —The nonconformance detected is the absence of quality.
  Deming—Quality is defined only in terms of the "*Agent*," the person doing the work is the only one who can actually produce the quality product—no one else can do it for him. If that is so, then…who is the "*Judge*" of quality?
  Feigenbaum—Quality is a customer determination. Not an engineer's, not a marketing manager's, not a general management determination; it is based upon the customer's actual experience measured against requirements—stated, unstated, technological, operational, or entirely subjective.
- *The ASCE Manual "Quality in the Constructed Project"* emphasizes the adequacy of the design, and the preparation, planning, competence, and performance of construction contractors in correctly implementing the requirements of the contractual documents.
- *Building Construction Quality—What is It?* Good builders construct good buildings by "building-in" *construction quality*, which is defined as *meeting the owner's stated needs by building in conformance with an adequately prepared set of construction plans and specifications*.
- *Building Construction Quality—How to Get It?* Although the definition above is a subjective statement, the quality of construction can be objectively validated through a comprehensive quality checklist process. A structured quality management program for construction—including quality checklists—significantly increases the probability that builders will obtain quality construction. The major building blocks for a construction quality program are addressed in Sections 5 through 7. The program is described in Sections 8 through 10.

3.4 Assessing Construction Quality—Inspection, Quality Control, and Quality Assurance

The paragraphs below, concluding this section, discuss the separate but related concepts of *inspection, quality control, and quality assurance*. The chapter ultimately focuses to a great degree on *quality control* processes, as they are usually the responsibility of the immediate *producer* of the work, design or construction. *Quality assurance*, also very important, is conducted by others, offset at more or less an arm's length from quality control practitioners. *Inspections* are usually performed at the behest of the owner to determine acceptance or rejection.

The three basic categories of quality assessment are reviewed below.

3.5 Inspection

Inspection, in the context of building construction, is the act of *confirming the adequacy of equipment, materials, and workmanship and the functional adequacy of systems against the standards established in the contract documents*. Inspections can be performed (1) *in process*—either (a) at certain pre-established stages (witness points or milestones), or (b) randomly, as the construction proceeds; and (2) at the *completion or final stage* of a building project, or completion of a particular system or element within the project. Inspections are intended to establish the acceptance or rejection of a particular part of the work; and final inspection of a complete building determines whether or not the owner will accept the completed building at that time. Inspections are performed by professionals or technicians who are qualified by training, certifications, and experience to pass judgment on the adequacy or fitness of a building system, element, or component, and are frequently required to be furnished by third-party firms. The inspections (including related tests) are conducted on behalf of the owner to strictly and with finality determine if the project and its component parts have been built in accordance with the owner's needs as expressed in the construction contract documents. Since visual observation alone will not necessarily determine contractual compliance, testing is also performed when required. Inspections and tests can be specified as part of the producer's quality control process or as a validation tool in the owner's quality assurance process. *Inspections are absolutely necessary and crucial to determining whether an owner has gotten what was contracted for*.

- *Reactive Process:* However, inspection is *reactive* in nature, and while it is a *fundamental and necessary* tool to assess quality, experience tells us it should probably not be the *only* tool to determine the adequacy of construction. The traditional, historical building industry approach—wherein owner and contractor rely *solely* on inspection to confirm quality—has had some counterproductive results.
- *"The Old Way:"* In the past, quality was (attempted to be) "inspected into" a project. Inspections of field construction found the absence of quality. In response contractors removed and replaced the deficient work, causing crew inefficiency, delays, and lost revenues.
- *The Basic Difference Between "Inspection" and "Control" Processes:* A control process is performed *before and during* an activity; an inspection or test is performed *after* an activity or portion of an activity is finished. (This is a "rule-of-thumb," not a "hard-and-fast" edict—project control and inspection does overlap, as discussed below.)
- *"The New Way:"* Modern construction management employs *preventive quality control and assurance processes* to ensure that subsequent inspections will go smoothly. *The proactive quality control and quality assurance approaches anticipate and complement the reactive inspection process*. Inspections, in fact, are optimally integrated into and become a counterpart to the in-process quality control and quality assurance program. Quality control, inspection, and quality assurance are essential complementary management "tools" in the project management toolkit.

3.6 Quality Control

Quality control is a management program that allows systematic quality verification processes to be integrated alongside production processes. Quality verifications are performed to ensure compliance with the contract documents. Project quality control is normally performed by representatives of the entity producing the design and the construction: the A-E's quality manager conducts processes to verify the quality of the construction plans and specifications as they are developed by the A-E firm. The construction contractor's quality manager conducts processes to verify the quality of the construction as the building work progresses. Quality control (QC) consists of quality plans, quality management processes, and documentation. QC for design and construction is the day-to-day quality monitoring of the design production and building production work and includes design reviews, quality checks, inspections, and tests. The A-E firm or the building contractor may use experienced in-house staff, a third party A-E consultant, and a construction management firm, or a combination thereof, to perform these roles. Production folks are the "doers." QC types are the "watchers" of the "doers."

- *Design Quality Control* verifies that the construction documents prepared by the A-E accurately reflect the owner's stated requirements for the building project. The minimum requirements are found in the:
  1. project architect-engineer scope of work and specifications;
  2. the applicable building codes;
  3. the applicable referenced design standards.
- *Construction Quality Control* verifies compliance with the established minimum standards for materials and workmanship found in the following:
  1. project construction specifications and drawings;
  2. the applicable building codes;
  3. the applicable workmanship standards.
- *Some Quality Control Precepts:*
  - ○ Quality is a result that must be planned and executed.
  - ○ Quality cannot be inspected into a design or a building project.
  - ○ Quality control utilizes planned "quality reviews" and "quality checks" as the design evolves and as "in-process" construction proceeds.
  - ○ Quality control integrates the inspection of materials and workmanship installation as a basis for the acceptance or the rejection of completed field work.
  - ○ Visual observation alone is insufficient.
  - ○ Quality control includes testing performed to determine whether construction procedures are producing the desired contractual product.
  - ○ Quality control programs are project-specific: construction projects are unique due to the variation in design, materials, location, workforce, subcontractors, schedule, costs, and weather.

3.7 Quality Assurance

Quality assurance is a management initiative to systematically validate that production and quality control processes are effective. Periodic reviews of the producer's quality control processes and documentation, and occasional scheduled and random validation checks, inspections, and tests are performed to ensure that the producer's QC program is achieving compliance with the contract documents. Project quality assurance (QA) is normally performed by representatives of the owner. The owner's quality assurance manager instigates reviews of the A-E's design quality control efforts and the construction documents to validate that there are QC processes in place to manage the design quality. The owner's quality assurance manager uses a QA plan to implement periodic QA assessments of the workings of the building contractor's QC program through quality audits, attendance at the contractor's QC meetings and conferences, and occasional validation inspections and tests of high-risk building systems. The QA manager takes the lead for the owner in witnessing acceptance inspections and tests of specific building systems and final inspection of the building project, making recommendations for acceptance or rejection. QA for design and construction consists of validating the quality control processes of the design producer and construction producer. The owner may use experienced in-house staff, a third party A-E consultant, or a construction management firm, or a combination thereof to perform these roles. If QC types are the "watchers" of the "doers," then QA operatives are the "overseers" of the "watchers."

QA—Quality Oversight

Quality assurance provides a "second-layer" of quality management, only slightly removed from the daily interaction between the quality control operatives and the design draftsmen or construction tradesmen involved in production. Quality assurance is not intended to duplicate quality control, but to play a "watchdog" role, usually for the owner, ensuring that the producer really has an effective "system" to achieve quality. If the contractor's QC program is adequate, the owner's QA enterprise should involve much less manpower and effort than the QC program. If the QC program is inadequate, the QA effort identifies the systemic issues, and the owner seeks remedies from the contractor to replace personnel or otherwise "beef-up" the QC program.

Quality Assurance Operates at Different Levels

The discussion has been focused primarily on construction quality assurance by the owner as oversight on quality control by the construction contractor. Quality assurance provides oversight in other relationships and at other levels, as well:

- ○ Designer's home office assurance; coordination and peer reviews of specific projects;
- ○ Construction contractor's home office assurance; oversight on QC of individual projects.

3.8 What is the Impact of Not Implementing a Quality Control Program During Design and Construction of a Building Project?

A building with moisture infiltration is a dysfunctional structure that impacts both the owner and its occupants.

- *Building moisture problems* can cause huge costs, impacts, and ripple effects, as previously discussed. (See Section 1, Paragraph 1.1, Moisture Control Issues Confronting the Design and Construction Community. Refer also to the chapters in this manual regarding "Troubleshooting" and "Case Studies.")
- *The effort invested early in a Quality Control program is highly preferable to dealing later with major design or construction problems and impacts that will require rework and redesign, or both*.
- *Cost Issues*: The monetary considerations for quality include the relatively predictable—quantifiable and estimable—effort that can be put into quality control, vice the high risk of unpredictable, unknown but fairly certain costs that will occur if quality "goes south." Owners, designers, and builders who commit "up-front" to invest in a project quality control program have in their hands a prudent strategy to mitigate risk, providing "quality leverage" and cost avoidance as the project proceeds.
- *Latent Problems are Very Problematic*: Can a project afford to find out after construction is complete that the building envelope does not perform because deficiencies are detected "after-the-fact," such as in the following?…the masonry base flashing is not lapped and sealed; the masonry window lintel flashing has no end dams; the metal panel to panel sealant joints are not installed; the EIFS has no window head flashing; the weather resistive barrier is absent behind the column covers; and the end dams at the jambs of the vestibule exterior doors are not installed. These *simple but subtle details*—inexpensive to install while the work is going in—are expensive to rip out and replace in an occupied (or unoccupied) building. They are very costly in time and money to the contractor, and costly to the owner in impacts and related effects.

3.9 Process Failures Impacting the Building Envelope

Although a mistake may be a "one-time" occurrence, repeated mistakes can be an indication of a sustained project culture lacking in the necessary attention and commitment to "getting it right," a portent of potential systemic problems. Several failures in the functionality of a completed building, be it the building envelope or other system, are often symptomatic of a process failure. A project with moisture issues has three likely sources of the problems:

1. The design;
2. Material or workmanship;
3. Operation and maintenance.

Following are examples of building enclosure moisture issues. They provide some insight into the negative effect of failures in the design details, the construction execution, or operation and maintenance procedures. Systemic preventive measures—*proactive* design and construction processes to avoid the types of problems represented by each example, are offered:

Causation 1—Design

Although vapor retarders and insulation are usually specified, the details of interior vapor retarders and insulation are often missing from drawings. Example—Spandrel glass above a drop ceiling in a structural steel-framed building where there is insufficient accessibility to install the insulation and the vapor retarder due to the position of both the steel beams and steel columns which are located four inches from the exterior wall.

Solution 1: Design Process—Preventive Measure

A *building enclosure review* of the A-E's plans during the design review phase, performed by one or more of the following: the (1) A-E's cross-discipline staff, (2) a third-party design review team, or (3) a construction management team. The CM team has the advantage of bringing "hands-on" construction experience as well as design knowledge to this effort. This multi-discipline review can solve this particular issue during design by scrutinizing the contract drawings to find the potential for "thermal breaks" in specific locations.

In addition, the comprehensive building enclosure review will systematically detect constructability issues for the entire building envelope by checking the design documents for material specifications, installation details, clearances, and tolerances of all materials and systems within the envelope.

Causation 2—Construction Materials and Workmanship

Masonry base flashing requires the installation of inside corners, outside corners, laps, and end dams. The proper installation of the flashing requires compatibility with adjoining materials and sealants, correct terminations, and integration with the waterproofing systems. Example: Insufficient lap, the incorrect mastic, and poor workmanship will lead to the leakage of installed masonry base flashing.

Solution 2: Construction Process—Preventive Measure

Before the masonry work starts, (1) a *preparatory phase conference* is held by the prime contractor with the applicable subcontractors, such as masonry, concrete, and waterproofing, to review and discuss the contract drawings, details, and specification requirements for materials and workmanship. The materials on site are verified for compliance with the specification and the technical submittals previously sent to the prime. As the work starts, the prime holds (2) an *initial phase conference* with the foreman and crew at the location of the work, making sure that the installation and workmanship gets off to a good start. During the rest of the masonry work, the contractor (3) *follows-up* by observing the critical details as they are built into the work; using a "quality checklist" developed in a *quality plan* and expanded in the preparatory and initial phase conferences. When the masonry flashing work is complete, the contractor conducts a *final follow-up* check to ascertain the compliance of the final product. This process is replicated for other systems in the building project.

Causation 3—Operation and Maintenance (O&M)

The service life of caulking/sealants is limited (5 to 12 years). The dependency of the building envelope on the durability of sealants is a key to the envelope's ability to perform.

Solution 3: O&M Process—Preventive Measure

Owners should develop an *operations and maintenance plan* for their buildings. Maintenance of buildings must provide for the periodic inspection and replacement of failed sealants at interfacing materials of the building envelope

3.10 Third-Party Building Envelope Coordination in the Design and Construction Process

Owners should consider investing in and retaining third-party expertise when the technical risk or contractor performance risk is high. Under the pressure of "getting the work done," (a) the A-E firms that provide building designs, and (b) the contractors constructing the buildings often will inadvertently overlook important details, interfaces between systems, and the coordination between disciplines or trades. Sometimes it takes another, an outsider, a new "set-of-eyes," to notice problems in design or construction that will go unrecognized by someone deeply engaged and immersed in the particular process. Unbiased design and construction expertise can be brought to bear by retaining "third-party" expertise. Design firms, consulting firms, inspection and testing firms, and construction management firms can provide the right kind of review and oversight to assist owners, designers, and contractors, as appropriate to the contracting scheme. Third-party expert firms can perform a one-time service, function in a day-to-day quality control role, or serve specific quality assurance endeavors, as needed by the project parties.

- *Building Envelope Design Oversight*: The integration of design details for the building envelope—within each system of the envelope, and at interfaces between the differing materials of adjacent systems comprising the envelope—is paramount to creating a functioning building. To this end a third party review of the interrelated details for the building envelope provides the necessary quality control to assure that the design is complete and correct; that the proper selection of materials has been made; that the tolerances permit installation; and that the submittals/shop drawings provide materials which are durable, functional, and meet the specifications.
- *Building Envelope Construction Oversight*: Third parties typically are engaged to perform field inspections and testing. This approach has a long-standing tradition in the construction industry, and is often explicitly specified in owner's construction contract documents. Unbiased third parties are used in order to ensure the performance of the installed materials on the building envelope, from the below grade waterproofing through the roof. Building System *mock-ups* (refer to Paragraph 9.9, Testing, Section 9) may be assembled on-site to (1) allow assessment (tests and inspections) of a representative sample of the building envelope, (2) to compare different options for materials, and (3) weigh alternative approaches to the work sequence and workmanship process.

3.11 Building Envelope Commissioning

- *Assuring Environmental/Moisture Control at the Exterior of the Building:* "Commissioning" of the building envelope takes the owner's quality assurance regimen up another notch. The building owner selects a third-party expert to implement a formalized quality assurance program that oversee integration of the various building systems comprising the envelope of the building. This *building envelope commissioning program* for management and coordination of the building envelope is led by a designated consulting firm/individual with demonstrated technical knowledge, and a track record of successful application of expertise to the construction of exterior building systems. The firm/individual leading the commissioning program is referred to as the *building envelope commissioning agent/building envelope commissioning agency, or BECA*. The BECA is best involved during the planning and design phases, as well as during construction. The BECA develops an appropriate commissioning plan and program, and during construction conducts incremental QA checks, inspections, and tests of the building systems (and mockups) as they are assembled and then built together as an integrated whole envelope.
- Section 8, Paragraph 8.6 of this chapter briefly addresses

commissioning plans in the context of coordination with project quality control plans. *Section 11*, Quality Management and Building Envelope Commissioning of this chapter presents a summary of the processes involved in *building envelope commissioning*. The National Institute of Building Science (NIBS) has developed a program for owners to use for planning and oversight during design and construction of the building envelope. Processes are included for "commissioning" of the building envelope. The NIBS is developing a series of guidelines for "Total Building Commissioning (TBC)," and the relevant document that specifically covers the building envelope is commonly referred to as "TBC 03." Refer to NIBS Guideline 3-2005, Exterior Enclosure Technical Requirements for the Building Process.

3.12 HVAC Commissioning

- *Assuring Moisture Control Inside the Building:* Heating, ventilation, and air-conditioning systems need to be properly designed, and should be specified to be balanced and then tested by a qualified third-party testing and balancing firm. When the stakes and risk are high, owners should consider a more elaborate, costly HVAC management and oversight process that can incorporate the design, construction, testing and balancing, acceptance and life-cycle operations and maintenance parameters under the over-arching umbrella of an HVAC commissioning process. HVAC Commissioning guidance has been developed by the American Society of Heating, Refrigeration, and Air Conditioning Engineers (ASHRAE) under ASHRAE Guideline for *Commissioning of HVAC Systems*. In either case—testing and balacing or commisioning—the moisture control characteristics of a building's HVAC system can be evaluated by qualified specialists using procedures or variations of procedures established by the ASHRAE.

Construction Documents

Commissioning may be crucial to assuring the successful realization of a building's intended function. The commissioning programs and each player's role (owner, third-party expert, designer, and builder) must be explicitly specified in the project construction documents developed by the architect-engineer for the owner [under either (1) the design-bid-build or (2) design-build process].

4. Managing Quality in Building Design

Design Quality

The quality of design for a building starts with the effectiveness of the Architect-Engineer firm commissioned by the owner to translate the owner's stated needs into the construction specifications and drawings for the project. The A-E's challenge is to assemble and lead a design team with the necessary variety of disciplines, then draw on the capability and experience of each individual on the team, integrating the effort of each to meld the design into a seamless whole. As good as any firm or individual is at what they do, mistakes and oversights will occur. An A-E well serves the firm's fortunes, as well as the owner's, by integrating design reviews and quality checks, a quality control process, into the design processes.

Design Quality Control

The design process typically involves a number of reviews by the project stakeholders (to be discussed later) at preestablished stages or milestones in the evolution of the design. As such, these reviews already inherent in the standard design process constitute a "built-in" quality verification element; the "extra eyes" are a form of control of the quality. However, design reviews by individual stakeholders with varying backgrounds and levels of knowledge are not always systematic, thorough, or knowledgeable regarding design and construction. When the A-E takes the extra step of introducing internal or external *peer review* to the design process, the drawings and specifications of each individual discipline will get reviewed by an experienced practitioner of the same discipline; this constitutes quality control. Peer reviews can be conducted by (1) A-E in-house discipline experts/mentors; (2) third party A-E consultants; or (3) multi-discipline construction management (CM) firms with both design and construction expertise.

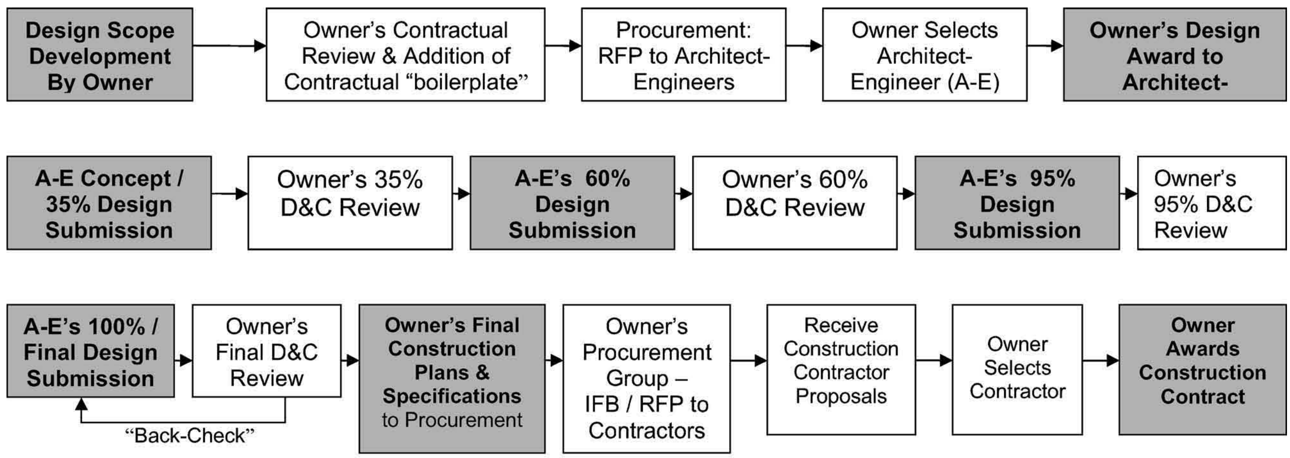
4.1 Integration of the Design Team and the Construction Team

Pulling Together Designers and Constructors

It takes an adroit collaboration of expertise to effectively design and build a facility. Design professionals team together to make sure that all the systems in the project are coordinated together clearly on the project drawings and are unambiguously presented in the project specifications. The collaboration of *design* talent is vital to the success of the project, but what is just as importantly needed is *construction* expertise "weighing-in" to the design effort. Experienced construction practitioners bring to the table the practical knowledge of what works well in the field (and what does not); they can help in determining the relative cost implications of one system vice another, and provide value engineering approaches that otherwise might not be considered. The earlier in the design process that construction knowledge is factored into the design, the higher the probability of a successful project from the point of view of design, construction, and long-term use. The way that design and construction professionals engage together during the project design phase depends on the construction contracting method, as summarized below. Normally, the owner will specify that the A-E institute a design QC methodology for his project, and the owner may specify how he expects the A-E to bring this about.

(1) *Design-Bid-Build* (*D-B-B*)—The A-E is developing the building design for the owner without necessarily knowing which firm the owner will eventually select for the construction phase of the project. The A-E can integrate building expertise into the design by using (a) field support staff on the in-house payroll; (b) the expertise of a CM firm; or (c) when applicable, the knowledge of construction managers on the owner's staff.

(2) *Design-Build* (*D-B*)—The design-build contractor has under his direct control a design team and a construction team and is in an optimal position to effectively combine the two skill pools in executing the design.



***Design Review Entities** for Design Submissions by A-E (35%, 60%, 95% and 100% Design Stages)*

- *Owner's Reps (as applicable): Planning; Design / Engineering; Operation and Maintenance (O&M).*
- *Owner's Construction Management and Quality Assurance (CM / QA) Organization (in-house or 3rd-party).*
- *Owner's Customer: Client, User, or Tenant.*
- *A-E's internal (in-house or contracted 3rd party) QC / QA Reviewers.*
- *Local and Institutional Authorities as necessary or required: Security, Safety, Fire Prevention, Environmental, etc.*

Fig. 1—Design development and review process.

(3) *Construction Management (CM) Firm*—A CM firm can be retained by the owner to (a) provide construction consulting input to an A-E's project design; (b) provide construction consulting oversight to a design-builder's design; or (c) as CM/prime contractor, provide both the design and construction through a design-build contract, integrating construction expertise into the design.

4.2 Managing Design Reviews

The design process is normally broken down into phases or stages. There is a project stakeholder review at the end of each stage of design. The owner (or owner's representative or CM) manages these reviews. Although milestones may vary by organization and by project, they typically are similar to the following:

(a) *Concept Design*—elementary plans of building configuration; building system descriptions; list of specification sections;

(b) *35 % Design*—rudimentary plans and outlined specification sections; building systems design calculations;

(c) *60 % Design*—plans and elevations mostly complete; specification sections "fleshed out;"

(d) *95 % Design*—sections and details finished; "specs" complete, including submittals and a submittal register; some incomplete pieces;

(e) *100 %/Final*—construction drawings and specifications ready to issue for bidding or proposals; become contract documents upon award to successful bidder.

4.3 Project Players and Types of Design Reviews

Project stakeholders involved in the reviews of the A-E's design at each stage include the owner and the owner's representatives; the owner's staff involved in design and construction management; the building users/tenants; building site managers and operations and maintenance representatives; applicable safety and fire officials; local building code officials, etc.

Third-party peer reviews: If the A-E has an in-house or third-party quality control program, these design (and construction) professionals perform a *quality control review*. If the *owner* has retained a construction management firm or third-party consultant, they provide oversight with a *quality assurance review*. The firms and staff doing this kind of quality review—design or construction—need to be reputable, well-credentialed, and experienced. These professionals are often referred to as "the gray-hairs."

Figure 1, The Design Development and Review Process, summarizes a typical large owner's design evolution, including an internal and external review process. This flow chart depicts the major design milestones; the key project participants during design and their roles; and the unfolding process of design preparation, reviews, and approvals between the designer, owner, and other stakeholders in the design review process.

Categories of Design Review

The stakeholders include some familiar with design, engineering, construction, and operations, and some not. The professionals and technicians/tradesmen perform the more technical reviews; the building owner and occupants are looking for the functionality and aesthetics that they requested in their charge to the designer. Below are the four primary categories of reviews performed at each stage:

(a) *Building Function Review*—Does the building meet the stated needs of the owner/client/tenant. For example, building configuration and layout, space, circulation; access/egress; function and operation of each space; operation of each system; building and site esthetics.
(b) *Design Review*—Is the technical design adequate? Are the design calculations for each building system correct? Does the building comply with applicable codes?
(c) *Coordination Review*—Have the individual disciplines designed their respective systems so that they are coordinated, integrated? Structural, architectural, mechanical, and electrical systems must be checked carefully to ensure that they do not interfere with, inadvertently penetrate, or adversely overlap each other in the contract drawings. The systems will thus eventually fit together and integrate seemlessly in the three-dimensional reality of the soon-to-be-constructed building.
(d) *Constructability Review*—Are the existing site conditions and existing structures accurately shown? Can the building systems, components, and materials be built, assembled, and installed as shown and specified? Is there a better way?

Building-Enclosure Coordination and Constructability Review

A building-enclosure coordination and constructability review is a structured way of looking at the building envelope design to determine how complete it is and if there are flaws. Section 3, Paragraph 3.10 of this chapter briefly discussed this concept in the context of prevention of moisture issues in the envelope. If an owner is really serious about reducing his risk exposure to difficult-to-repair moisture infiltration problems, he should consider implementing this intensive corollary to the design review process. The people that are most effective at doing this type of a review are those professionals and practitioners of design and construction who have a strong background in both the design details and field installation of building envelope systems. The major systems include roofing (insulation and vapor retarders), flashing, curtainwalls, doors and fenestration, sealants and caulking, and below-grade waterproofing/diversion. There are many roofing systems and curtainwall systems out there, and new systems and products change the market and challenge the installers. Owners need the right consultant or CM to do this kind of detailed review.

Design Quality Checklists

Review isn't just "looking" at the design and constructability of buildings. Effective design review practice entails systematic use of quality checklists for design, building system coordination, and building "constructability." The professional *peer reviewers* and their *quality control/quality assurance* counterparts usually make extensive use of *quality checklists* based on "lessons-learned" about what can go wrong. This is particularly true of those—usually with construction experience, who focus on coordination and constructability reviews. Quality checklists for building design, coordination, and constructability—as well as construction—are an essential "staple-of the trade" for *CM firms*.

4.4 How to Get Good Construction Contract Documents

Preparing Effective Drawings and Specifications

The Owner's Role

The owner knows what he wants from the building he envisions. He needs to be able to clearly and accurately convey the result he expects to his designer: aesthetics, space, tenant requirements; user operations and needs; and system functionality. If the owner's needs are still evolving as the design proceeds, the A-E is placed into a difficult position—how are changes in scope and cost accommodated and integrated into an already-established design configuration? Owner's whose needs are well-defined from the start have the best chance of getting what they need within their budget. Owners who invest the time early to "get-it-right," and continue to collaborate effectively with their designer as the design stages progress are going to be ahead of the game. Of course, some late changes may be unavoidable as prospective users/tenants and their operations may change. In some industries (with deep pockets), constant change is the prevalent operating dynamic; and these owners and their designers and builders need to be effective and agile in accommodating the pace of change. The productivity of the owner—A-E relationship (including early A-E collaboration with construction expertise) is a hallmark of successful project dynamics and a positive harbinger for a successful end result.

A-E's Primary Role

As the building designer, the AE's major task for the project is to develop construction documents that will be the basis for the construction of the building. It is important that the designer develops a design with the *appropriate* kinds of building systems, materials, and equipment that will adequately, and in the best case optimally, *meet the owner's needs and budget*.

Just as important is the designer's obligation to accurately and clearly *express* the design in the construction specifications and drawings. The clarity and completeness of the construction documents is crucial in at least two respects: (1) the effect on potential builders who will bid or propose to construct the building—they each need a "level playing field" in order to estimate the project cost; and (2) the potential effect on the building process, with related cost and time implications.

Contractual Impact of Lack of Clarity in the Contract Documents

The intent of the project design must be translated into unambiguous black-and-white terms (literally and figuratively) in the drawings and specifications. If not, multiple bidders or offerors may legitimately (or illegitimately) interpret them differently from the intent of the designer. Some or all of the prices submitted with proposals or bids will be based on something other than that which the owner expects, so the bidding process is compromised for the owner and the offerors. If award is about to be made and an unsuccessful offeror suspects he has been prejudiced by the lack of design clarity in the bidding process, the bidder may file a protest, further impacting the project prospects. If a discrepancy is discerned after construction contract award, additional work and cost may have to be negotiated, or the lesser (bid/proposed) solution accepted. If a design problem is not detected early after award, the building may be constructed incorrectly until someone figures out the discrepancy between the contractor's intent and the designer's intent. This can lead to rip-out and replacement, along with greater added cost. The bottom line is that the "designer's intent" has little value during bidding and after contract award if the contract documents are, in fact *actually* unclear. In the worst-case scenario (see the chapter "*Legal Considerations and Dispute Resolution: The Water-Related Construction Failure*"), if there are unnegotiable disagreements or unresolvable disputes between the parties that evolve from such discrepancies, "designer's intent" is not a crutch that the A-E or owner can lean on if an unbiased administrative adjudicator or court determines that the documents are, indeed, unclear, incomplete, or ambiguous. As with all aspects of a project, if we invest time and effort in the early stages of design to "get-it-right," we will reap rewards in the ultimate quality of the project and in the avoidance of wasted time and cost.

4.5 A Few Precepts for Developing the Building Construction Documents

Listed below is some general guidance for the owner's design investment and the designer's preparation of construction plans and specifications.

Owner's Considerations

- The Owner's project needs and goals are to be understood, defined, and "locked-in" *early*;
- Owner to invest in a design that includes soils investigations and soil borings to establish equitable basis of bid; forestall the potential for future claims;
- Owner to make sure that a design review process is employed, including the project stakeholders;
- Owner should consider investing in an A-E that will implement design quality control through peer discipline reviews;
- Owner to make sure that genuine construction expertise gets integrated into the design; ensure that coordination and constructability reviews are performed;
- Owner should consider mitigating risk of moisture infiltration by requiring a *Building Enclosure Coordination and Constructability Review* using personnel or consultants with the appropriate (often rare) design and construction expertise in building envelopes, such as CMs.

Designer's Considerations

- Optimum selection of appropriate Building Systems/materials for project budget;
- Use the right Building Codes and standards;
- Use the appropriate industry workmanship standards;
- Adequately show existing site conditions;
- Adequately show existing work to be removed, built upon or tied into;
- Provide explicit details at the interface between adjacent systems;
- Perform a coordination review that checks for conflicts between building systems;
- Check for conflicts and ambiguity—within the drawings, within the specifications, between the drawings and specifications;
- Other factors as necessary due to local conditions and local seasonal weather considerations.

Assembling a Construction Specification—CSI Format

A project design is organized in accordance with the technical disciplines appropriate to the systems contemplated in the building design. Construction specifications capture the project requirements using a format of *16 divisions* representing different disciplines/trades; each division of the specification is broken down into individual *specification sections* that each represent and describe a particular system in detail. This standard format for construction specifications has been developed over time and has been in use for many years. The Construction Specifications Institute (CSI) is the standard-bearer for the building design and construction industry on specifications. Owner organizations and designers go to CSI to obtain a detailed specification template to work with; large organizations develop their own "guide-specifications"—templates that are generally based on the CSI format but incorporate their own particular needs into the requirements. The chapter "*Contract Documents and Moisture Control*" in this manual provides additional information on the structure and format of the construction specifications.

4.6 Use of Building Codes

Building codes regulate building construction to protect the health, safety, and welfare of people. They establish minimum standards for construction. The project designer needs to consult the appropriate building code for the characteristics and location of their particular project, and integrate the code guidance into the construction documents.

Building Systems

Codes establish minimum standards for the following categories of building systems:

- Fire Safety
- Sanitary Facilities
- Electrical
- Lighting
- Building Construction
- Building Materials
- Ventilation
- Plumbing
- Energy Conservation

Model Building Codes

Codes are written in an attempt to address all conditions and building system categories described in the list above. Some of them focus primarily on residential construction, and incorporate other standards (National Electric Code, American Institute of Steel Construction, American Concrete Institute, etc.) by reference. To date there have been four "model codes."

—*BOCA*–Building Officials and Code Administrators International

—*ICBO*–International Conference of Building Officials

—*SBCCI*–Southern Building Code Congress International

—*CABO*–Council of American Building Officials

Community Codes

A specific building code must be adopted by a specific community in order to apply to that community. A community will select a model code, but may then modify as they deem appropriate, adapting it to the needs of their community. Designers need to be conversant with the exact terms of the code adopted by the community they are working in.

County and State Codes

In many cases adjacent communities will collaborate to adopt a uniform code. This is very often done at the County level. In addition, collaboration across larger geographies has resulted in State building codes—17 states have adopted "state-wide" codes.

Integration of Model Codes; ICC—International Code Council

In 1997 representatives of BOCA, ICBO, and SBCCI compiled the *first draft* of a comprehensive code that could apply across the United States, with potential future ambitions for international use:

—*IBC*–International Building Code (1997). Adoption and use of the IBC is elective to the specific jurisdiction (state, county, city).

The IBC is an attempt to integrate model codes into a single body of regulations to bring uniformity in the use and applications of codes and to maximize the health, safety, and welfare of people and their exposure to construction operations and buildings.

NFPA—National Fire Protection Association

Virtually all model codes and local codes defer to the NFPA Code and adopt it by reference.

Building Code Characteristics

The following list briefly summarizes the key characteristics of the current building codes in the United States:

—Building codes are written by architects, engineers, fire marshals, inspectors, manufacturers, builders;
—Complex set of rules covering all disciplines;
—No uniform building code across the United States currently exists;
—Four separate model codes have dominated specific geographies;
—Some communities may develop a unique code, while some have nothing;
—Regulations—written, rewritten, adopted, interpreted by local communities.

References to the Code Agencies are provided in *Appendix A*.

4.7 Industry Workmanship Standards

Standards for quality of workmanship are necessary to establish a uniform way of evaluating the installation of construction materials across the industry and geography of the nation. The workmanship standards are established by industry-supported independent agencies or trade groups, such as the American National Standards Institute (ANSI), ASTM International, American Society of Civil Engineers (ASCE), and American Concrete Institute (ACI), to name a few.

References to the industry workmanship standards for the installation of materials in construction are provided in *Appendix* B.

4.8 Specifying Construction Submissions for the Project

What are "Construction Submittals"? *Materials, Equipment, and Systems*

The construction specifications prepared by the project architect-engineer (the *architect-of-record*) require the building contractor to provide a certain level of quality of materials and equipment that comprise the building systems in the project. The owner and the architect-engineer need to be sure that the specified quality will be met. The contractor therefore must be required by the specifications to submit, in advance of procurement and installation, printed (or electronic) information on the materials, equipment, and systems proposed to be incorporated into the construction. This type of information includes product descriptions and data, manufacturer's system specifications and calculations, fabricator's system "shop" drawings, and samples. They are called *construction submittals*. They are normally submitted by the building contractor after a construction contract award has occurred.

Plans, Processes and Procedures

Some construction submittals do not describe the characteristics of items proposed for installation, but are owner-mandated requirements which require the contractor to describe the specified programs, processes, or operational procedures, such as a "quality control plan;" a "sheeting and shoring plan," or a "roofing demolition and installation plan." These administrative and operational submittals are needed in time for approval or acceptance before the construction, program or operation commences.

Test results: Some types of construction submittals occur at different stages in the procurement and building process—say testing information, for example: (1) *manufacturer's test data* for an established standard product (e.g., wind resistance and air and water infiltration data for a type of window) may be required before procurement; (2) *a fabricator's tests* (e.g., concrete strength test during casting of a precast wall panel) may be required during factory fabrication of system components; and (3) *field test results* (e.g., water infiltration tests on the curtainwall/fenestration system) provide pass-fail documentation during and after installation of a system. Field tests occur from beginning to end of construction.

4.9 Submittal Processes

Building Contractor's Initial Obligation

The *submittals* are to be obtained by the prime contractor from suppliers and subcontractors. The construction specifications should clearly state that such submissions then must be *reviewed by the contractor to assess contract compliance*. If the submitted documents are accepted by the prime contractor, the next step depends on the contract terms.

Approval Authority

The construction specifications may require the *contractor* to retain a qualified submittals *approval authority*; and/or may designate a submittal *approval authority* for the *owner*. This will depend on the contracting strategy that the owner selects, including *Design-Bid-Build* vice *Design-Build*. The process also varies significantly when the owner chooses to explicitly specify a *construction quality control* (*QC*) *program* to be implemented by the contractor. (See Section 5, "*Specifying Quality Control in the Construction Contract Documents*.") The submittals process needs to be clearly specified in the construction specifications to allow offerors to properly bid the project. Below are a few of the possible variations on this process.

- *Design-Bid-Build* (*No QC Program Specified*)—*Construction Submittals*–The *owner* is the designated approval authority and will retain an A-E firm (normally his project designer-of-record) to act on the owner's behalf as the professional entity that will review and recommend approval or disapproval of the submittals.
- *Design-Bid-Build* (*QC Program Specified*)—*Construction Submittals*–The *contractor* (*QC manager or submittals manager* in the specified QC program) is the designated approval authority for most routine submittals. The *owner* is the designated approval authority for major, complex building systems that are considered "extensions" of the A-E's design; the owner will retain the A-E firm (his project designer-of-record) to act on the owner's behalf as the professional entity that will review and recommend approval or disapproval of the submittals.
- *Design-Build* (*No QC Program Specified*)—*Construction Submittals*–The *design-build contractor* is the designated approval authority for all submittals. The design-build entity uses their internal A-E partner (the project designer-of-record) to act on their own behalf as the professional team that will review and approve or disapprove of the submittals. The owner will receive from the D-B entity information copies of all submittal actions. (The owner has the option of checking these submittals for compliance using his own internal resources or a retained A-E consultant.) The owner may opt (in the specifications) to retain sole final approval authority on some special systems, samples, and colors.
- *Design-Build* (*QC Program Specified*)—*Construction Submittals*–The *design-build contractor* (*QC manager or submittals manager* of the specified project QC program) is the designated approval authority for all submittals. The design-build entity uses their A-E partners (the project designer-of-record) to act on their own behalf as the professional team within the QC program that will review and approve or disapprove of the submittals. The owner will receive from the D-B entity information copies of all submittal actions. (The owner has the option of checking these submittals for compliance using his own internal resources or a retained A-E consultant.) The owner may opt (in the specifications) to retain sole final approval authority on some special systems, samples, and colors.
- *Construction Manager* (*CM*) *Role*–A CM firm can act in a number of contractual roles in relation to the project owner; thus the CM's role in the submittals process depends on the contractual role the CM firm provides. As a consultant to the owner, a CM firm can serve as the owner's designated submittal review/approval entity or, alternatively, provide a second-tier quality assurance review of submittals to detect and correct discrepancies. As a manager of design and construction contracted with the owner, the CM firm can provide the review expected of the construction or design-build entity, or provide the contractor's quality control services, including submittal review.

A Time-Critical Process—Submittal Log and Scheduling Requirement

Submittals must be expeditiously furnished by the contractor and promptly reviewed and approved or disapproved by the designated approval authority. The idea is that the submission, review, and approval process takes place in advance of the procurement and installation of materials, equipment, or systems. This is advantageous to owners and reassuring to suppliers, subcontractors and the project prime contractor. *Construction specifications should be written to require building contractors to perform as follows:*

(1) Submittals of materials, equipment, systems, and contractor/subcontractor plans and procedures must be prepared reasonably *ahead of time* for review and approval by the approving authority before the contractor *purchases and incorporates* the submitted items or plans in the construction.

(2) The contractor prepares and maintains *a submittals tracking system*, using a *submittals register and log* that consists of a list of all of the submittals required in the project. (Some owners will provide the listing of submittals that are required of the contractor, with the understanding that the contractor is responsible for filling in any submittal "gaps.")

(3) Maintaining an on-time project performance per the project construction schedule is crucially important for all parties. Project operations are dependent on timely materials and equipment delivery, which is directly dependent on submittal and approval of the contract submittals. Submittals must be coordinated with and included on the *construction schedule*, and construction specifications should mandate that approach.

Figures 2(*a*) and 2(*b*) are flow charts graphically depicting—in simplified form—the construction submittals process for a building project during construction. Figure 2(*a*) addresses the situation when the owner has chosen a *design-bid-build* process (separate design and construction contracts). Figure 2(*b*) depicts similar information on the construction submittals flow for a *design-build* project.

Why are Submittals Needed?

In summary, submittals are documents or material samples which the contractor prepares, reviews, accepts, and recommends for approval—or approves outright, and—depending on the contract terms—submits to the architect-engineer or owner for review, approval, or other appropriate action. The submittals are a tool for the owner, A-E, CM, general contractor, and subcontractors to do the following:

—Identify products and systems
—Describe physical and performance criteria
—Detail shop and field-fabricated materials
—Coordinate component interface(s)
—Identify color, texture, finish characteristics
—Verify compliance with contract requirements
—Provide manufacturer's installation instructions for materials and equipment to assure manufacturer's issuance of warranty
—Delineate component costs
—Plan critical work processes
—Plan and schedule the work

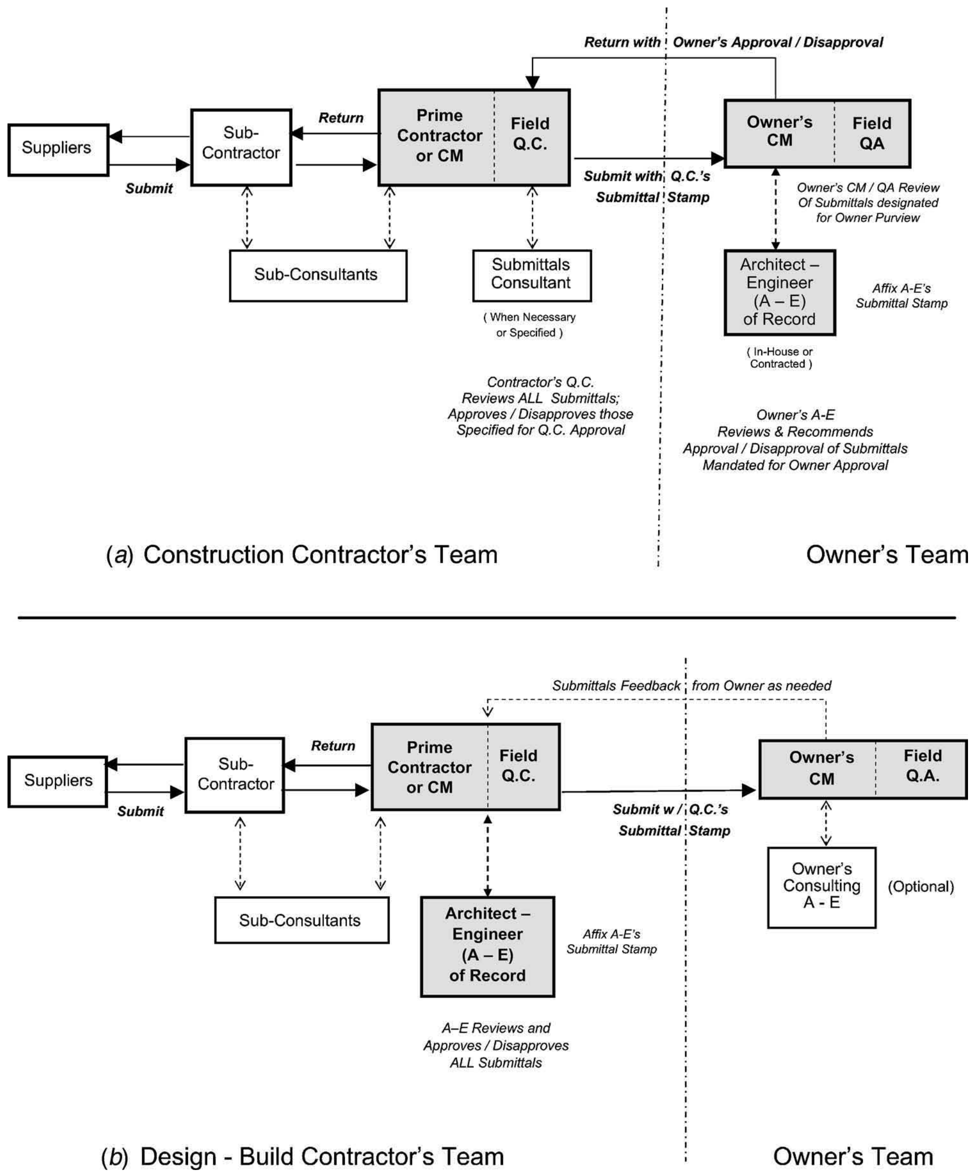


Fig. 2—(a) Construction submittal process for construction contracts. (b) Construction submittal process for design–build contracts.

4.10 An Overview of Specifying Submittals in the Construction Specifications

Categories of Construction-Phase Submittals

A few examples of construction submittals were given earlier. Generally, construction submittals are broken down into the following categories:

- Product data (catalog info/brochures, MSDS, manufacturer's certified tests);
- Engineering/technical information and calculations;
- Certifications (manufacturer and installer);
- Shop drawings and coordination drawings;
- Samples, field samples, and mock-ups;
- Test reports (manufacturer, fabricator or field);
- Operational (construction processes and procedures);
- Administrative (program plans and processes);
- Quality Assurance/Quality Control;
- Construction progress schedule updates;
- Construction photographs and videos;
- Closeout submittals.

Informational Content of Construction Submittals

The characteristics of several of the most frequently used submittal categories are described following:

- *Product Data:* Illustrations, standard schedules, performance charts, instructions, brochures, diagrams, and other information furnished by the contractor to illustrate materials or equipment for some portion of the project.
- *Shop Drawings:* Drawings, diagrams, illustrations, schedules, or other data specifically prepared for the project by the contractor, subcontractor, manufacturer, supplier, or distributor to illustrate portions of the work to be installed and to validate understanding of the contract documents. The purpose of shop drawings is to show the following information:

○ Compliance with contract requirements
○ Field conditions
○ Dimensions
○ Construction means and methods
○ Installation instructions for materials and equipment
○ Quantities
○ Coordination with adjacent materials/components

- *Coordination Drawings* show integration and coordination of multiple systems and interdisciplinary work. These drawings are very valuable to the construction process. They are time-consuming and costly to produce (especially the MEP), but when done well provide leverage in quality, time, and cost. Specifiers should seriously consider requiring these on projects of higher risk or high complexity. They are usually applied to the following two categories of inter related or integrated systems.
  ○ *Building Enclosure*—the building skin, from below grade waterproofing through the roof;
  ○ *Mechanical, Electrical, Plumbing* (*MEP*)*, and Fire Protection*—preplanned coordination in plan, section, and orthogonal where necessary.
- *Material Samples and Sample Construction/Mock-Ups:* Physical examples that illustrate materials, equipment, workmanship or component assemblies, and establish quality standards by which the project will be evaluated.
  ○ *Material samples* (material, color, texture, etc.) are normally small-scale versions;
  ○ *Sample construction and mock-ups* usually use full size component materials;
  ○ *Sample construction* is usually built in place and often remains as permanent work;
  ○ *Mock-ups* are normally constructed separate from the permanent work.
- *Operational Work Plans:* Contractor work plans for high-risk construction give the contractor an opportunity to plan for difficult operations, and give the owner/CM/A-E the opportunity to review, provide feedback, and expand their "comfort zone" with the builder. Examples of operational work plans that can be specified when risk is high include the following:
  ○ *Demolition and removals* of existing structures;
  Hazardous materials handling and removal (asbestos; lead; PCBs; petroleum; toxics);
  ○ *Excavation Plan*;
  ○ *Shoring and Sheeting Plan*;
  ○ *Roofing Plan* (removal and new work).
- *Administrative/Management Plans:* These include the important *progress schedule*. In addition, specified contractor management plans for construction give the contractor an opportunity to plan for required programs that are needed to comply with laws or statutes for environmental protection, occupational health and safety, or for contractor quality management. The owner/CM/A-E will review, provide feedback, and monitor the builder's performance against an approved or accepted plan. Examples of management plans that can be specified when considered necessary include the following:
  ○ *Progress Schedule and monthly updates*;
  ○ *Environmental Protection Plan*;
  ○ *Storm-water Management and Sediment Control Plans*;
  ○ *Waste Management Plan*;
  ○ *Occupational Health and Safety Plan*;
  ○ *Accident Prevention Plan*;
  ○ *Quality Control Plan* (*see Sections 8 and 9*) includes the following processes and documentation/tracking tools:
  —submittal process and log;
  —control process and log;
  —testing and inspection process and log;
  —deficiency and rework process and log;
  —completion and closeout processes and log;
  —documentation processes and sample reports.
- *Quality Control Submittals* document the project from the standpoint of quality status, and verify that it meets specified requirements:
  ○ Daily Quality Control Reports;
  ○ Preparatory and Initial Phase Conferences; Preinstallation Conferences;
  ○ Project Meetings (Progress; Production; Quality);
  ○ Reports and Certificates (inspections and tests).
- *Closeout Submittals* occur near and at project completion, and consist of:
  ○ Project record drawings
  ○ Operations and maintenance manuals
  ○ Operational and Acceptance Test Data
  ○ Training Records of Owner O&M Personnel
  ○ Spare Parts
  ○ Keying
  ○ Written notice of substantial/final completion
  ○ Building Warranty commencement
  ○ Lien releases and waivers of debts
  ○ Consent of surety to final payment
  ○ Final application for payment.

4.11 Designer Field Support

Once the construction starts, the A-E or CM's A-E staff normally provides (under contract with the owner) *field support services*, including consultation, review of contractor submittals, and site visits to assess quality or review construction issues. This type of service ensures continuity of design knowledge and design intent between the design and construction phases of the project. This type of expert support to the field is generally seen as *construction quality assurance* support for the owner.

Note: During the preparation of the building concept, the owner, collaborating with his designer and construction manager, should address the degree of quality control that will be needed during construction. Section 5, following, deals with how to contractually specify a contractor-managed quality control program for a building project.

5. Specifying Quality Control in the Construction Contract Documents

Do We Want Quality Control?

Owners must decide whether to specify a builder-implemented quality control (QC) program for the construction phase of their building project. They need to consider the nature and complexity of the project and the efficacy/quality of their procurement/contracting process in delivering construction competence, and assess their *risk*. They then should look at the potential cost (in the bid or proposal price) of a contractor quality control manager (with or without supporting QC staff) against the project risk. Owner risks resulting from building construction include the potential in any project for short or long-term building quality issues and for resultant schedule delays that can cause disruption to the owner. These types of common industry issues were addressed to some degree in the Introduction of this chapter. Builder-caused quality shortfalls during construction can lead to lost production, rework, and cost and time impacts to the builder. While these impacts should not contractually be absorbed by the owner, the owner and client will often unavoidably experience related (difficult to recover) internal costs and overheads, delays in occupancy, impacts to tenants and users, and ripple effects on the building user's operations. Investment in a contractor quality control program can mean long-term cost avoidance for the owner.

Clarity of Quality Control Documents

The importance of good construction documents was previously discussed. As in other aspects of the construction documents prepared for bids/offers, when an owner chooses to require a contractor-managed quality control program for his project, there must be adequate definition of the desired QC program in the construction specifications. This will enable contractors to fairly estimate and adequately and competitively bid the contract, quality control included. A quality control program is usually specified in a separate specification section—dedicated solely to quality control—under Division 14 of the CSI specification format. (The industry format for construction specifications is briefly mentioned within Section 5 of this chapter, and is discussed in detail in the chapter entitled "Contract Documents and Moisture Control.") A clearly written quality control (QC) specification (01400 series) minimizes the risk for all parties. Clearly defining a QC program in the project specifications will provide the bidders—among them the successful contractor—guidance that should be unambiguous. This provides a "level playing field" for those competing for the project, while at the same time giving the owner greater confidence that he can obtain what he expects in the contractor's management of the project quality.

What is a Quality Control Program and QC Staff?

Typically, a QC program includes a QC plan, a dedicated QC manager and, when considered necessary, expert QC specialists or submittal reviewers (of specific trades or disciplines), and/consultants, and independent testing and inspection agencies. The QC manager (and staff when specified) manages and performs QC processes, including (1) submittal review (and approval when specified); (2) phased, proactive control activities paced with production; (3) tests and inspections (as specified in the individual technical specification sections for each system/trade/discipline); (4) deficiency identification and correction; (5) completion inspections; and (6) attendant documentation processes.

The QC Specification Explicitly Describes the intended Contractor QC Program

The facets of a QC program—submittals, control activities and deficiency tracking, test and inspection approaches, as well as the needed QC staff and responsibility for specific quality documentation, need to be specified in the *quality control specification* prepared for the construction contract. The requirement for a full-time on-site quality manager and the explicit duties should be stated here, along with the responsibility of the QC manager to lead and manage the QC program while having the authority to require the removal and replacement of deficient work. During construction, the clarity of the QC specification will support the needed line of authority and responsibility for control processes, testing and inspections, and documentation.

Determine the Appropriate Level of QC Effort

Those charged with writing the quality control specification for a project must consider the project parameters and look at some of the typical project variables such as size, cost, and complexity. The composition of the QC team and breadth of the QC program depends on an evaluation of the project characteristics such as those listed in the following, along with a judicious assessment of the accompanying risk of failure to achieve the project goals.

(a) Needs and financial resources of the client;
(b) Project parameters and variables such as:
 (1) Size and cost;
 (2) Adequacy and completeness of the design;
 (3) Project scope and systems complexity;
 (4) Capability of the contractor pool and local trades;
 (5) Market conditions; and
 (6) Impact of site and weather on the ability to achieve a quality result.

The project design, size, complexity, and the possible attendant risk of project parameters and variables are addressed in the following.

5.2 Approaches to Specifying Quality Control Programs by Assessing the Risk for Projects of Varying Size, Scope, and Complexity

Project Size, Scope, and Complexity

The quality of the design, the experience and expertise of the contractor pool that will be bidding or proposing for a project, and other factors will affect the risk to the owner. These factors, in turn, will determine the consequent makeup and extent of the specified contractor QC program. Following are some ways to look at the characteristics of a project when trying to determine the extent of the contractor-managed QC program that may be required.

- *Project Size:* The project cost usually varies along with the size of the project. For purposes of this chapter and as of this writing (2009), project size is defined roughly as follows:
  —*Small Project:* up to $1M+;
  —*Medium-sized Project:* $1M–$9M;
  —*Large Project:* $10M and above.
- *Project Scope and Complexity:* For purposes of this discussion, project scope and complexity is defined approximately as follows:
  —*Less Complex Project:* Up to 10 building trades; no specialty trades/disciplines.
  —*Moderatly Complex Project:* 10–25 trades/disciplines, including both building trades and specialty trades/disciplines;
  —*Complex Project:* over 25 trades/disciplines, including both building trades and specialty trades/disciplines.

Project Risk

For purposes of this discussion, "risk" is defined as *the potential or probability that something will go wrong and adversely affect the project in some measurable or intangible way*. Usually, the *risk* is of a failure in management or building process which inhibits or precludes the ability to achieve the usual *project goals*. Managers strive to achieve a *quality* project, built using well-coordinated and integrated trades-forces; performing production processes that are smooth and *safe*; delivering the project within the scheduled *time* and budgeted cost constraints. In summary, the owner and his specification writer need to consider what are the project risks that could impact *quality, safety, time*, and *cost?* Some of the typical project risk variables and characteristics to consider are as follows:

(1) Project size;
(2) Project scope and complexity;
(3) Quality of the design;
(4) Contractual procurement method the owner has chosen;
(5) Qualifications of available contractors;
(6) Capability of the available construction trades;
(7) Relative competitiveness in the construction market at the time;
(8) Expected (or potential for unexpected) weather during the contract;
(9) Local and other factors.

Assessing risk beforehand is very subjective and depends on a multiplicity of factors—the risk variables and the individual potential risk of each variable may change with time and market conditions. *Every project will contain a "mix" of risk variables that suggest low, moderate, or high risk for that particular variable. The project risk is a subjective amalgam of the relative weights of the individual risk variables*. Using the risk variables enumerated above, some possible characteristics of projects of (a) *lower risk*, (b) *moderate risk*, and (c) *higher risk* are listed below.

- *Project Variables of Possible Lower-Risk:*
  —A smaller project;
  —Design is considered good;
  —Building envelope design thoroughly and fully developed and complete;
  —Project includes less-complex systems;
  —Contractor proposals are to be evaluated by the owner's team;
  —Well-qualified or "Select" contractor pool will be bidding or proposing on project;
  —Well-qualified construction trades pools are available in the area;
  —Market conditions show a "lean" pace of construction business activity;
  —"Good weather" seasons coincide with much of the anticipated schedule for outdoor / exterior work.
- *Project Variables of Possible Moderate-Risk:*
  —A medium-sized project;
  —Design is considered adequate;
  —Building envelope design considered complete;
  —Project includes systems of moderate complexity;
  —Contractor proposals are to be evaluated by the owner's team;
  —Generally qualified contractor pool bidding or proposing on project;
  —Generally qualified construction trades pools are available in the area;
  —Market conditions show a normal pace of construction business activity;
  —Benign weather seasons coincide with much of the anticipated schedule for outdoor / exterior work.
- *Project Variables of Possible Higher-Risk:*
  —A larger project;
  —Design below normal standards or incomplete;
  —Many owner changes were made during design;
  —Design was "rushed;"
  —Building envelope design which is not thoroughly detailed or not complete;
  —Adjacent building envelope systems are lacking in coordination;
  —Building envelope design by generalists rather than specialists;
  —Project includes several complex systems;
  —Proposals to be bid on the open market;
  —Qualifications of the bidding or proposing contractor pool are variable or uncertain;
  —Qualifications of available construction trades pools are weak or uncertain;
  —Construction trades tend to be fully booked on other projects;
  —Construction market activity characterized by a high number of projects "on-the-street" and frenetic bidding; a high number of projects currently under construction;
  —"Bad weather" seasons coincide with much of the anticipated schedule for outdoor / exterior work.

The definitions in this paragraph are not considered "hard and fast," but are more about establishing approximate soft thresholds to enable project specification writers to categorize their particular project— and then apply their best discretion to determine the breadth and depth of the needed QC program in terms of personnel, processes, and documentation. Often specified intuitively, an objective approach can supplant the inherent knowledge that specifiers apply, and may help avoid QC misjudgments.

While some large projects may be complex and some small projects may be less so, it is important that specification writers not confuse size and complexity. There are small projects of higher complexity and large projects of low complexity. Also, a project that is primarily noncomplex may have one specialty system of high complexity or risk that requires close oversight by a qualified expert assigned to the QC staff. Section 6—The Construction Project Team—A Quality Approach, Paragraph 6.7 contains a discussion of specific approaches to establishing the appropriate level and mix of quality control personnel on projects of varying size and complexity.

5.3 Composition of the Contractor's Construction/ Quality Team

The contractor's construction management team will typically include (a) home office project management, (b) field office project management and superintendence, and (c) field quality control management, each with associated staff.

The typical quality control staff positions were mentioned previously in this section, and their roles are described in Section 6. The owner's specifying authority (A-E or construction manager or both) needs to assess the project characteristics and risk. Based on this assessment, the specifier should come up with a specification for the QC team that is adequate in breadth and technical depth for the project, and therefore can be expected to be cost-effective. The specification writer needs to require that the contractor provide the *right quality control expertise* for (1) the most crucial portions of routine construction work and (2) the critical elements of complex systems in the project. However, over-specifying technical qualifications and numbers of quality control specialists should be avoided—the owner will be paying for something that is not needed and may likely not be provided. The A-E or Construction Manager preparing the specification must convey to the owner the reason for recommending specific quality positions in the QC specification, and outline the expected project cost of such recommendations to the owner. *Remember, the quality control positions will usually not be in a contractor's bid and will typically not be filled by the construction contractor unless the owner assures that he specifies* (*and provides project funds for*) *the needed QC positions*.

Figure 3(*a*), *Contractor's Project Organization Chart*, shows the management, production and quality control positions for a typical contractor organization. Figure 3(*b*), *Owner's Project Organization Chart*, shows the typical management and quality assurance positions for a typical project owner. The owner must budget for such a staff to effectively manage a large project or several simultaneous projects.

5.4 Overview of the Components of Field Quality Control

The owner's quality control specification for a contract/project should spell out the aspects of quality control that the owner expects the contractor to manage—and the owner must be prepared to budget accordingly for the project contract. Field quality control can be broken down into *three operational categories:* (a) *organization, management, and administration*; (b) *quality control processes and procedures*; and (c) *process tracking and documentation*.

The three operational categories typically contain the subcategories, or QC program *elements* listed below each operational category that follows:

(a) *Organization, management, and administration:*
- (1) Organizational structure;
- (2) Established QC staff positions;
- (3) Qualified individuals on the QC staff;
- (4) Delegation of Authority to QC staff;
- (5) Outside consultants;
- (6) Independent agency for construction material tests and inspections.

(b) *Quality control processes and procedures:*
- (7) Project Submittals;
- (8) Proactive, Preventive Quality Controls;
- (9) Testing and inspections;
- (10) Identification and correction of deficiencies;
- (11) Completion Inspections.

(c) *Process tracking and documentation for the following activities and processes:*
- (12) Documentation Management
- (12a) General Documentation: Project schedule; QC plan; daily project activities, etc.
- (12b) Submittal procedures; (relates to 7 above)
- (12c) Quality control effort; (relates to 8 above)
- (12d) Testing and inspection effort; (relates to 9 above)
- (12e) Deficiency monitoring effort; (relates to 10 above)
- (12f) Completion inspection effort; (relates to 11 above)
- (12g) QC Staff responsibilities and effort (relates to 1 through 11 above).

5.5 Overview of the Components of a QC Plan

It is important for owners to specify that contractors shall provide a detailed *Project Quality Control* (*QC*) *Plan*. A QC Plan describes the contractor's planned quality control program for the project at hand. The plan should show the quality organization, processes and procedures, and documentation that the contractor plans to use, based upon the contract specifications and contractor experience. Quality control plans are essentially broken down to outline and describe the three operational categories and twelve elements of the QC program. The basic requirements that should be stated when specifying a quality control plan are listed below.

(a) *Description of organization, management and administration—along with required documents that support the credentials of the proposed QC organization and staff:*
1. *Contractor's production and QC organization*—Organizational chart;
2. *List of QC staff positions for the project*—Includes a summary of the duties, responsibility and authority of each position;
3. *Qualified individuals proposed for the project*—Resumes summarizing the individual qualifications, education, and training of the proposed QC staff.
4. *Contractor's appointment of proposed QC Staff*—Individual letters of appointment for each QC staff member describe that individual's responsibility and authority, as delegated by appropriate company official.
5. *Proposed consulting firms, proposed consulting staff, describing disciplines and expertise*—Includes credentials of consulting firms and staff.
6. *Proposed independent testing and inspection agencies/laboratories; proposed test and inspection staff, describing disciplines and expertise*—Includes credentials of testing agency/lab and staff.

(b) *Description of management approach to quality control processes and procedures:*
7. How the contractor will manage the inception, transmission, review and approval of *submittals;*
8. How the contractor will implement proactive QC processes and procedures—How the *three-phases of control*—(1) *preparatory*, (2) *initial*, and (3) *follow-up* will be integrated into the project schedule;
9. How the contractor will perform and validate the *testing and inspection processes*;
10. How the contractor will *detect and correct defects;*
11. How the contractor will manage and integrate into the *three stages of final inspection*—(a) *punch-list inspection*, (b) *pre-final inspection*, and (c) *final inspection*.

(c) *Documents used to track and record production and quality control processes:*

12a. *General production and quality documentation: Project Schedule* and updates coordinated with quality processes in the QC Plan; *Project Meeting* agenda format; *Daily Reports; Transmittals*, etc.

12b. Project-specific *Submittal Register* (Log) (relates to 7 above);

12c. Project-specific list of *Schedule Activities* (*"Definable Features of Work"*) *subject to the three-phase QC process; Preparatory and Initial Phase Checklists* for each DFOW; etc. (relates to 8 above);

12d. Project-specific *Testing Plan and Log* (relates to 9 above);

12e. *Deficiency/Rework Log* (relates to 10 above);

12f. Project-specific *Completion Inspection Matrix* (relates to 11 above);

12g. Project-specific *Quality Matrix*—a cross-reference of QC staff responsibilities for submittals, quality control phases, inspections and tests (integrates key information relating to 3, 5, 6, 7, 8, 9, and 11 above).

The operational categories and elements of a comprehensive QC plan are summarized in Figure 3(*c*)—*Key Elements of a Contractor's Quality Control Plan*.

Quality Control Programs and Plans are further detailed in Sections 8 through 10. Also, Section 8, Table 1—Elements of a Project QC Program and Corresponding QC Plan, relates the components of a QC program to the development of a contractor quality control plan.

6 The Construction Project Team—A Quality Approach

Best Practices

The remaining sections of this chapter describe a method of managing construction quality, with emphasis on larger and more complex construction projects. The program and processes outlined are based on best practices in the industry as espoused by many top contracting firms, and are similar to those stipulated in many public-sector contracts with these companies. These construction quality control programs and their processes are a proactive, structured way to help contractors elicit the best results from the knowledgeable trades and crafts talent on the project site.

Construction quality has as its basis the team that designs, manages, and builds the project. This section focuses on the quality team and the teamwork necessary to make a good project "happen."

Establishment of a Quality Culture

Good quality construction requires a genuine commitment to a quality culture from the top-down in a contracting firm. At the project level, field managers need to provide strong leadership focused on the end result of a quality project. The field leaders need to have a sound depth of general construction experience, and the workers building the project must exhibit competence in their disciplines. Prime contractors can use these QC processes as an effective way to manage subcontractor performance.

The purpose of the quality control program at the project level is, of course, to provide facilities and infrastructure that meet the quality requirements of the contract for a particular construction project. Quality means that the provided materials, equipment, fabrication, workmanship, as well as construction and operations (when specified) comply with the plans and specifications for the project.

Use of Proactive, Structured Quality Processes

Both prime contractors and subcontractors have found that the structured quality control processes enable them to keep their trades-people and subcontractor craftsmen focused on the goal of doing the work right "the first time." As noted previously (in Section 3), it is worth repeating that *quality cannot be inspected into a project*. When control inspections at the end of a specific trade activity discern major problems requiring correction, it means that any purported "quality control" efforts have failed. This underscores the earlier statement (also in Section 3) that *quality is a result that must be planned and executed*.

Depending on the manner in which the project is specified, the project quality control program consists of several quality control procedures and processes, starting with the establishment of a QC organizational structure, appointment of a project-based quality control manager, and development of a project-specific quality control plan. Other components to the QC program include appointment of QC staff when specified or necessary; regular quality-centric meetings; review of submittals; examination of delivered materials and equipment; a three-phase quality control process; inspections and tests; a deficiency identification and tracking process; a final inspection process; and documentation and certification procedures. These processes (described in Sections 7 through 10) are all related, and represent a continuum comprising the field quality control program for a large or complex project.

6.1 The Importance of Project Relationships in the Field (Owner, Design Team, Quality Team, and the Construction Team)

Differing Roles

The roles of the major players in a construction project were discussed earlier (in Section 1). The *owner* knows what he wants—a facility that meets his needs—but he may or may not necessarily understand how the final product is achieved. To assist him, the owner may retain a construction management (CM) firm as his agent, sometimes for design oversight, more often for construction contract administration, construction management, and quality assurance/inspection. The *designer*, typically an Architectural-Engineering (A-E) firm, will ideally have designed a project that meets the owner's needs and can be built efficiently. The *contractor* provides the capability and expertise to build the project as specified by the designer in the contract documents. The contractor's on-site production team is usually led by a *Project Manager* and a *Project Superintendent*. The contractor's quality control team is on board to assist the contractor in meeting the quality specified in the contract documents, while helping the contractor to avoid costly mistakes. The on-site QC team is usually led by a *Quality Control Manager*, also described in some cases as a Quality Control Representative. (The text uses the terms "QC manager" or "quality manager" as synonymous with "quality control manager;" these terms all refer to the project-level position

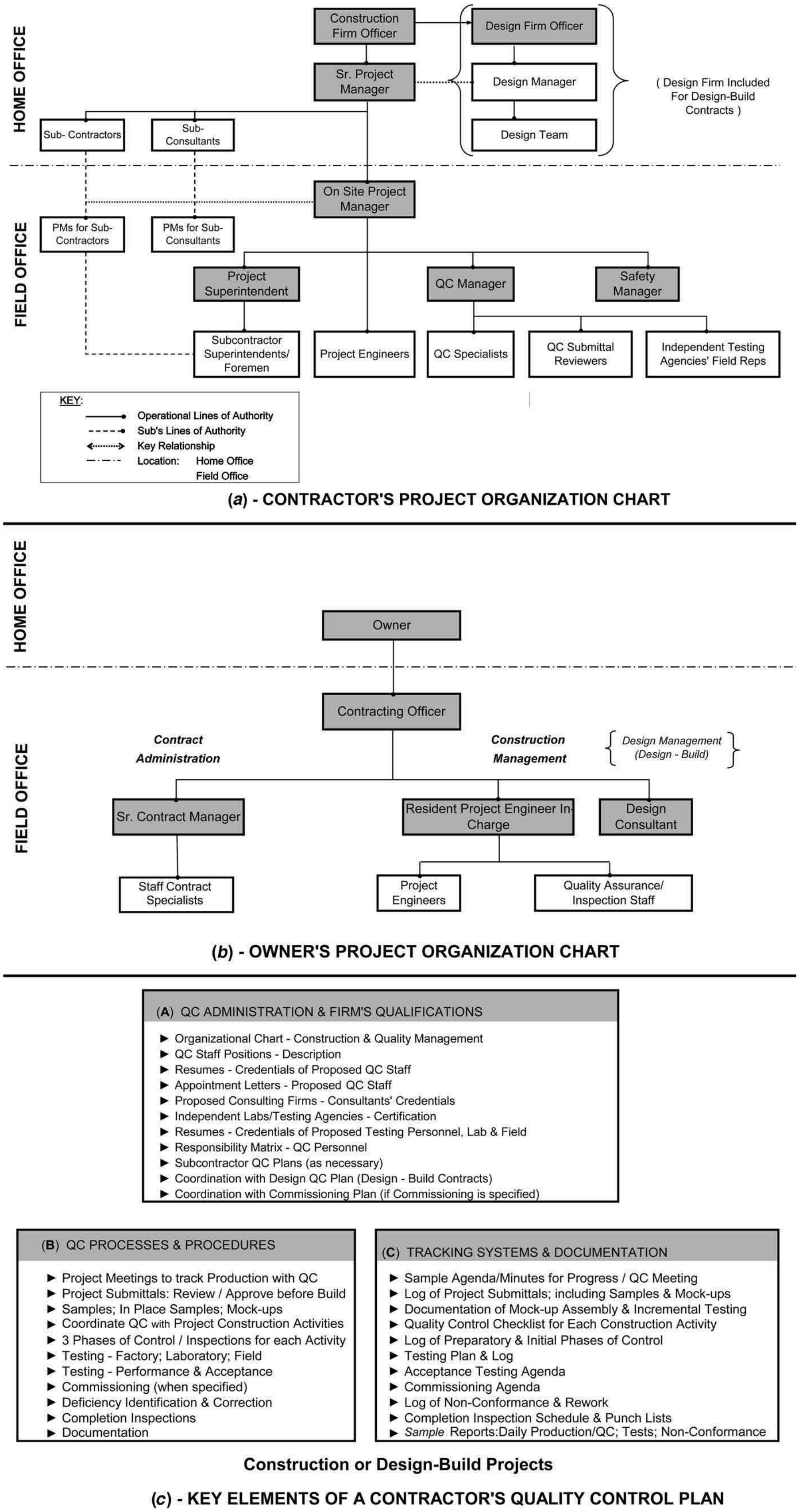


Fig. 3—(a) Contractor's project organization chart. (b) Owner's project organization chart. (c) Key elements of a contractor's quality control plan.

of Quality Control Manager; they mean one and the same.) Figures 3(*a*) and 3(*b*), respectively, show the typical contractor's and owner's project organization chart.

Common Goal

All parties are concerned that the project, as built, will incorporate their requirements, accommodate their procedures, and meet their expectations. The CM firm, A-E firm, and construction contractor want to effectively serve the owner, respectively enhance their own reputations, and earn repeat business. It is in the mutual interest of all that the project is of good quality, built safely, on time, and within budget—the construction management mantra. Though all of the parties have the same common interest in a good project, the stresses of contract requirements, project complexity, time, and budget often lead to differences between the parties that are difficult to resolve.

Project Partners

The tradition of informal partnering and the advent of formal "Partnering" processes have been described previously (in Section 1). A formal Partnering effort should help kickoff and enhance the working relationship between the involved parties. In the absence of that, all entities of the project should encourage an attitude of cooperation among their respective staffs which would, in effect, represent the tradition of informal partnering.

Numerous construction challenges are the norm on large projects, and the method of their resolution is often the source of intense discussion, frequent disagreement, and occasional discord. Civil discourse among the project team members is important to the ongoing relationships during the long (often 2 + years) construction process, and is one key to ultimate project success.

Importance of the "Other Guy's" View

Listening to the other party's point of view (a sometimes unnatural behavior that can be learned with a bit of practice) has proven to be an important part of the successful deliberative process, even when there are strong opposing opinions. Such "active listening" is an empathic behavior that incorporates a habit of "seeking to understand before you seek to be understood" (Stephen R. Covey, *The 7 Habits of Highly Effective People*, 1989 and subsequent editions, Simon & Schuster). This type of fair-minded behavior may seem "soft" and intuitively wrong to wizened designers or hard-nosed construction types, but—especially when practiced by both sides—can be an effective aid to bargaining and negotiating an acceptable solution to technical issues (which usually also have monetary dimensions). Sometimes, just the fact that one party demonstrates an authentic attempt and ability to recognize the other's position, and so states it, will open the avenue to agreement with the "opposing" entity. Parties across the table from each other (sometimes only) want the "other guy" to "hear them out," give them a "fair shake." Active listening is a useful step in the path toward achieving a fair and reasonable accommodation to disputed technical terms of the contract.

An Approach to Problem-Solving

When a problem surfaces on the construction site that will cost additionally to fix, a rule of thumb is that designers pay for reasonable rework costs of improper design, and contractors pay for rework costs of improper construction. Contract terms vary, but this is the usual case. Owner's pay if they request additional work. When differences in contract interpretation arise, legal and contractual principles may require that one or more of the parties take a strong stand, without compromise, and this is sometime very necessary and appropriate. Often, however, the real situation is not always that clear a case of black-and-white. Compromise, in the sense of a fair and rational accommodation by both sides appropriate to the situation, is a necessary reality in fast-moving, large and complex construction contracts, where the contract documents, the design or the construction are never perfect.

Though the term "compromise" has an unsatisfactory ring to it, rational technical solutions that may vary from the original intent of the contract documents and do not impair the quality or ultimate function of the facility may be a prudent means to move ahead when there is a "stumble" either in the preparation of the contract documents or in the design or the construction. This especially applies when there are errors contributed by different sides in the argument. This does not mean that either side "gives away the store." Occasionally, technical revisions result in a "win-win" for both parties. The goal, of course, is an effective technical solution for the project team that does not contradict the owner's intent for appropriate materials and good workmanship—the owner's satisfaction with the project quality is the ultimate goal.

Disputes

All problems are best resolved at the lowest level, assuming that the competence and authority lies there. If disagreement is essential to maintaining the integrity of each party's divergent position, the best course is, as amicably as possible, to "agree to disagree," and move the dispute to the appropriate next higher level. If the contractor is under contract with a public-sector entity, the government agency's designated contracting officer is the appropriate higher authority. In the case of most entities, the contracting officer has the written contractual recourse to keep the project moving by directing a solution that the contractor must implement. In such cases, the contractor often must technically proceed per the government entity's direction, but may seek relief, monetary or otherwise, via government administrative remedy or a Court's legal decision. (For further information, refer to Chapter 26, *Legal Considerations and Dispute Resolution—The Water-Related Construction Defect*, which contains discussions of claims and disputes arising from failures in moisture protection.)

6.2 Obtaining Building Quality: Contractor Integration of Efforts of the Construction and Quality Control Teams

Make the Quality Commitment Early in the Project

Contractors serve their best and highest long-term interests when they select a good quality control manager for their project, and get him or her on the job-site quickly. It is important to have effective quality leadership on the construction jobsite as soon as the project work starts, preferably before then. Proactive means being early, being "on-top-of" what is going on; vice being, in effect, "late"—reacting to what is happening (and to that which may not have been anticipated). Experience has shown that project QC programs are most successful when a competent quality manager is established on site in the very early (and usually less intense) stages of the project. This brings their presence and structured processes to bear on the project before the jobsite quality culture has the possibility of slipping, leveraging their influence and multiplying their potential for success.

Construction and Quality

Construction Challenges

Most construction projects are "one-of-a-kind," which suggests that almost every project is a creative exercise. For the same reason, most construction projects have a "learning curve," resulting in lower production in the early stages of a project and each of its various components. Construction contracting by its very nature is a risky endeavor, where different subcontractors are garnered together for each project and expected to work together in a seamless, coordinated fashion. These facts mean that there is risk of some degree of failure in every project. While the genuine intent of most construction contractors, subcontractors, and trades-people is to build with quality, the pressures of cost, time, weather, and unanticipated problems frequently have a tendency to take precedence over quality. The best-intentioned practitioners of the craft can make inadvertent mistakes while trying to meet a tight schedule, or may feel forced to compromise the level of workmanship to stay "out of the red."

Background of Contractor-Managed Quality Control Programs

This challenge has given rise to the establishment of contractor-managed quality control efforts on construction project sites. This concept was pioneered by a very large owner's agent—the construction management leaders within the Army Corps of Engineers—who were also seeking to ratchet down their sole dependence on government inspection to assure quality. They sought out the best quality practices in the construction industry and started specifying them in their contracts. The Naval Facilities Engineering Command soon followed suit, further refining the concepts. The practice is now rather widespread in the construction industry, primarily in government contracting but also within large scale private sector construction contracting.

Quality Control Independent of Production

In setting up the ground rules for project quality programs, owners have made the following general (and probably correct) premise—in order for contractor quality not to be compromised by production considerations, the quality control decision-making and QC effort needs to be independent of undue influence by the managers of production. Therefore, driven both by owner's concerns (reflected in the specifications) and some contracting firms' prudent self-interest, contractor-appointed quality managers are given the responsibility to lead quality control efforts and the authority to enforce quality requirements—independently of project production management. Naturally, therefore, project production management and project quality management have two differing and often conflicting roles.

Previous Misapplications of QC Principles

In the earlier days of implementing contractor quality control on site, the line separating the production and quality functions on the job-site was a "hard" one—a project superintendent (working for the contractor) and a QC Manager (also working for the contractor) were not co-located. The contractor's QC manager was often expected (by the owner's agent) to behave like an owner's inspector. This could lead to a reactive focus on inspection for defects, vice the proactive management of quality control. Historically, such a jobsite climate might mean that quality meetings with the owner exclude the superintendent, and might tend to limit open conversation between the "QC guy" and the "Super." Project superintendents tended to be suspicious of and dismissive toward QC managers: suspicious because the "super's" authority was "threatened"; dismissive since contractors at that time often appointed unqualified individuals to QC positions—owner's specifications did not mention any qualifications for the position. These (sometimes pervasive) attitudes tended to artificially constrain constructive dialogue on the contractor's team and with the owner, and created an unnecessary adversarial climate in place of firm, responsive and responsible interchange between the project players. This was a result, on both sides, of skepticism over the concept, and unfamiliarity with the intent, of contractor-managed quality control. Traditional roles were threatened, and people on both sides, owner and contractor, were placed in unfamiliar roles. A residue of this skepticism and counterproductive approach remains today.

The Current Environment for Construction Quality Control by the Contractor

Today, a contractor's on-site QC manager typically still has the important authority to enforce quality requirements, along with the quality control responsibility, and is able to act independently of the contractor's production managers. The authority and responsibility are now more recognized in the industry, and thus its application is more effective and more of a reality. What has changed is a greater recognition on both sides that the key contractor positions in the field—project manager, project superintendent, and QC manager—each with a different role, need to work more closely together to achieve the mutual mission of quality, in a safe manner, on time, and within budget. Owner's contract specifications typically cite minimum qualifications for the QC positions, and better-qualified quality managers tend to have a greater degree of personal clout backing up their delegated authority. Contractors and their project managers and superintendents realize that a qualified QC manager on their payroll can help them do their job more effectively, meaning satisfying the owner while earning a reasonable profit.

Partnership Between Project Superintendent and QC Manager

The QC manager is responsible for quality, must have complete quality authority, and needs to be the final arbiter regarding quality at the project level. On the other hand, the quality manager needs to work hand-in-glove with the on-site project superintendent (vice versa applies as well), establishing a good working relationship early in the project and nurturing an effective collaboration until project completion. This effectiveness of this relationship is absolutely crucial for a project to be a success in terms of quality and schedule, and can also positively influence the goal of remaining within budget.

The superintendent needs to know what processes the quality manager will be implementing and when; conversely, the quality manager needs to understand what work activities the superintendent will be managing and when. Though the superintendent leads the production effort while the quality manager leads the QC program, the positions are mutually dependent.

6.3 Integrate the Scheduling of Production and Quality

Construction Schedule

The key to the superintendent's plan is a well thought out construction schedule. An effective construction schedule is crucial to the project, and an understanding of the schedule is also crucial to the quality manager's success. The contractor's project manager and superintendent must manage procurements, subcontractors and construction activities such that they will not compromise quality or planned quality processes. Conversely, the quality control processes described below must be structured so they are conducted on time, such as not to compromise or delay a properly thought out construction schedule. The project team, comprised of project manager, superintendent, and quality manager, needs a good schedule, and each member needs to execute his respective area of responsibility timely to follow the schedule. The project team must keep their heads together continuously, coordinating their efforts in a synergistic way.

Scheduling Quality Control

The project schedule typically shows the critical "up-front" efforts—submittals, procurement, fabrication and delivery—that ultimately control the start of work on each construction activity. One important innovation to consider is to *add the major quality control activities alongside the related construction activities on the project schedule*. This simple coordination exercise increases the project team's awareness of each other's (production vice quality control) role, helping to enhance and improve mutual preparations for construction activities as the project progress unfolds. Some owners are beginning to require this approach on their projects.

6.4 Role of the Quality Control Manager

Good, strong, quality leadership in the field helps the contractor to avoid technical problems (and related quality disputes) by proactively managing a quality program that seeks to preclude the use of substandard materials and avoid workmanship mistakes.

Technical Strengths

The Quality Control Manager (also referred herein as QC manager or quality manager) must thoroughly understand the construction plans and specifications, as well as the quality requirements within them. He must, for example, be (or rapidly become) conversant with the type of sub-grade waterproofing system, roofing system. or curtainwall system, as well as the many other building materials and systems specified. (On occasion, based on field experience, the quality manager may be able to discern a problem in the design that can be solved among the necessary parties before the inadvertent "wrong" materials are purchased or "substandard' installation occurs.)

The QC manager needs to understand the project components and how they will be built; how they interface and the sequence in which they will be put together. For example, the quality manager must understand the proper sequencing of and coordination between penetrations (mechanical, plumbing, and electrical) through structural framing and decking; the built-up or membrane or other roofing; flashing; and other systems with interfaces crucial to moisture protection within the building. He or she needs to know about the specific type of wall system specified, be it tilt-up precast panels or aluminum curtainwall systems; and the type of glazing and sealants, etc. Not only do the correct materials need to be used and installed with good workmanship, but the right sequence of construction needs to be followed to assure watertight integrity, both during construction and for the building's expected life.

Field Quality Management Focus

Although the project QC manager is responsible for producing, reviewing, and approving a great amount of quality-related documentation, he is foremost a leader and manager of the quality process for the project. The quality manager should not normally be involved in managing procurement or production, and is not normally involved in negotiating costs of changes with clients of the contractor. QC Managers that solely become field-office-based "paper-pushers" and fail to frequently get out in the field to manage on-site quality cannot properly support their project, and should get additional clerical and technical staff, or both from the contractor. The quality manager's focus is intended to and needs to be on construction quality.

6.5 Selection of the Quality Control Manager and QC Staff

Get the Right Experience

Contractor selection of the project QC Manager and QC staff is, in part, based on minimum criteria often spelled out in the quality control specifications of large construction contracts. Usually, a certain level of field technical experience is required, and in some cases educational background is specified as well. The selection criteria for QC personnel are based on the size, complexity, and nature of the project. This approach is relatively common in Federal Government contracting, particularly under branches of the Department of Defense (Army, Navy, Air Force), and has been adopted by other government and private-sector contracting entities. Determination of criterion is addressed under the previous Section 5, Specifying Quality Control in the Construction Contract Documents.

The contractor usually submits the qualifications of a proposed project QC manager and staff to the contracting agency for acceptance. The contracting agency may exercise the option of interviewing proposed QC staff before conferring acceptance.

Project success and contractor success depend on having the right people on the jobsite—including leadership with real, boots-in-the-mud experience. Successful contractors have skilled construction management staff on hand (or available through subcontract) with experience as project managers, superintendents and QC managers. Most are generalists, but some (either generalists or specialists), have special discipline skills, such as roofing/waterproofing; building envelope integrity; foundations/structural; mechanical or electrical, etc. This is the talent pool from which good QC persons are made. On the other hand, selecting inexperienced or technically unqualified persons is an invitation to major quality problems.

QC Leadership Counts

Contractors with a view toward long-term success will fine-tune their quality staff to deliver the technical skills that match up with the technical nature of the project. Effective QC managers and QC staff need to have the right background, the technical field experience, a penchant for detail, ability to document information, and a commitment to quality. The quality manager, in particular, also must be able to exert leadership, manage well-defined quality processes and people, and apply good interpersonal skills. A strong QC Manager, one who can "hold his own" and stand for quality in the face of production pressures, is a long-term asset to the project. A QC manager that stands up for what is right may appear to some contractors as a detriment to progress, but such thinking usually reveals a short-term view. By using an effective quality manager, a contractor's skilled craftsmen are enabled to build quality into the building for the life of the building, satisfying the customers, enhancing the contractor's reputation, and earning more business from the better clients.

6.6 Responsibility and Authority of the Quality Control Manager

The quality control manager is responsible to implement and manage the construction quality control program for the contractor on a specific, single project. The position is normally considered (and usually specified) as a full-time, on-site job. The intent is that the QC manager should only be involved in quality-related work. Owner's contract specifications often explicitly specify that the quality manager perform no other work (such as procurement or production).

In order to effectively manage quality on the project, contractors need to give their project QC managers the complete *authority to enforce quality*. Contract specifications usually require such authority to be granted. Effective contractors today exhibit faith in the notion that a QC manager with authority to "do the job" will save the contractor money by avoiding costly rework and the associated money-draining delays.

Responsibilities

QC Plan

Ideally, the project QC manager develops the project-specific *quality control plan*, which includes both (1) the standardized, structured QC processes, and (2) project-specific technical procedures to be used in maintaining quality on the building project. The "Three Phases of Control" (described subsequently) is the most important structured process, and encompasses other well-defined processes such as submittals review, inspections and tests, and deficiency tracking. Under this standard process, three phases of control are applied to each separate technical category of work in the project. The QC Plan is developed around the three-phase-control structure by (1) reviewing the different building systems specified in the contract, and (2) developing and stipulating project-specific QC procedures to be performed for each category of work. These procedures include (a) the specified inspections and tests, and (b) field QC checks based on both the specifications and experience.

QC Program Implementation

When construction starts, the quality manager is responsible to implement (per the QC plan) the structured quality control processes and project-specific procedures to ensure that the project complies with the contract plans and specifications. The QC manager has on-site responsibility for the management of all persons performing quality-control work on the jobsite, including QC technical discipline specialists; QC submittal reviewers (on or off-site); and inspection and testing personnel provided to the prime contractor by subcontractors, manufacturers, or inspection and testing firms. He or she manages the quality control documentation and certifications required by the contract and the QC plan, including overseeing all paperwork required of subordinate QC personnel involved in the project. The QC Manager schedules and leads QC program "kickoff" meetings and regular project quality control meetings. In summary, the QC manager is responsible for all project quality control activity, both on-site and off-site.

Managing Quality by Ensuring it is "Built-in"

Three Control Phases

The QC manager employs the structured quality control process known as the "three phases of control" as a sort of overarching quality template, a standard process of "preparatory," "initial," and "follow-up" phases that is applied successively to each different category of work or construction activity, such as excavation, foundations, framing, wall systems, roof systems, plumbing, electrical, and mechanical work. (For purposes of discussion, the construction activities listed are oversimplified.) The *preparatory phase* for a specific category of work occurs before that construction activity starts, and includes a study of the plans and specifications for that work activity, review and approval of submittals, and the validation of delivered materials. This phase culminates in a "*preparatory phase conference*" to go over the quality plan for the specific construction activity. The initial phase of control for a specific category of work primarily entails an "*initial phase conference*" that occurs on the construction site as that construction activity begins, getting the work off to good start. The *follow-up phase* for a specific category of work occurs during the entire remaining duration of that construction activity, and culminates in a *"final follow-up"* inspection of that category of work.

In the case, for example, of a roofing system specified for the project, submittals of materials information and data and layout drawings are provided to the prime contractor by the roofing supplier via the roofing subcontractor. The prime's QC manager (or subordinate reviewer) reviews and approves/disapproves—then distributes the roofing submittal. When the roofing materials are delivered to the jobsite, the QC manager (or subordinate specialist) will check the materials for compliance with the specification and the approved submittals, and ensure that the roofing subcontractor properly protects the stored insulation and roofing membrane material from the weather.

The quality manager understands the specification requirements for the roofing system; he monitors the schedule and knows when the roofing work is planned to start. He schedules a *preparatory phase conference* for a date before the roofing work starts, and on that day meets with the project superintendent and the roofing subcontractor to review the contract requirements for the roofing work and "get on the same page" regarding the methodology of executing the roofing work. Subcontractors with critical interfacing work may also be involved in this meeting. When the roofing work starts, the QC manager has the *initial phase conference* with the project superintendent and the roofing subcontractor's foreman, reviewing the work of the roofing crew on the project site as the roofing is initially installed to make sure that proper materials and workmanship go in from "day one." As the roofing work continues, the quality manager monitors the work continuously, as necessary (the *follow-up phase*), to ensure that the quality standards for the roof work (established in the contract documents, discussed at the preparatory phase meeting and demonstrated/implemented during the initial phase meeting) are maintained by the roofing foreman and his crew.

The QC manager ensures that specified tests, such as roofing/insulation core samples, water infiltration, roof leader flow, etc., are performed at the appropriate locations and times by the roofing subcontractor or approved testing firm. Deficient work or failed tests are documented and correction made by the contractor, and the deficiency-rework process is tracked. When the roofing activity is complete, the *final follow-up inspection* is conducted by the quality manager to identify any remaining deficiencies, and he monitors and ensures their correction. Some large or complex projects may require appointment of a roofing QC specialist, delegated the above responsibilities; this specialist will then perform and document most of the above quality processes under the supervision of the QC manager. When a long-term manufacturer's warranty is specified by the contract documents, a manufacturer's representative will need to be on site either periodically or continuously, depending on the nature of the roofing system and the length of warranty. The QC manager must understand the requirements and ensure that the appropriate QC individual is there when required.

Off-Site Quality Management

The contractor's QC manager also is responsible for quality oversight of major systems that are fabricated offsite, such as the components of pre-cast concrete wall sections, of major curtain-wall systems or large quantities of glazing, windows, or doors. This is, in effect, quality assurance applied by the contractor on the manufacturer. In such cases, the quality manager's responsibility is to ensure that the fabricator's internal quality processes are effective in fabricating a product that will meet the contract specifications, for example, the gage of thickness and cross section of extruded stock; welding of joints; thermal conductivity/resistance; weather-tightness/water-tightness; wind loads, etc. The quality manager needs to validate and ensure, preferably prior to but certainly early in the procurement, that there is an effective manufacturer's in-house QC process capable of satisfying the specification requirements. Several observation visits may be necessary for the quality manager to validate that the contractor will get what is specified from the manufacturer/supplier.

Authority

The project Quality Control Manager typically has the authority to enforce all of the contractually specified quality requirements on the project site on behalf of the contractor. When assessing quality and making decisions on quality, the quality manager needs to have clear authority over the superintendent and other contractor/subcontractor personnel on site. The QC manager also typically needs to have the authority to disallow the building of new work (or closing in of subsequent work) over deficient work. In addition, QC managers typically have the authority to approve submittals, with the exception of submittals that are reserved for the owner's approval under the contract. The aforementioned "authorities" are usually spelled out in the owner's contract with the construction contractor.

Owner's contracts may specify that the project QC manager reports to an officer of the construction contracting firm, and is not subordinate to either the on-site project manager or the project superintendent. In general, if the organizational relationship is not specified, the quality manager needs to have at least equal project status as the project superintendent in the project hierarchy in order to be effective organizationally. However, in matters of quality, the QC manager normally should not have equal status nor be subordinate to the project superintendent. (An exception is found in some public-sector contracts for large public works projects at more remote sites, where the project staff is more self-contained and the QC manager reports to a "project-manager-like" superintendent who is responsible for both construction and quality.)

Owner's Remedies for Performance Problems

If a QC manager either does not effectively perform his responsibilities or exert authority over quality, or is prevented from doing so by the contractor's management, the owner will usually step in and require the appropriate quality measures to be applied and corrections made, based on the contract terms. Also, the owner will usually have the authority (under the contract) to require the removal of ineffective or incompetent personnel, including the project manager, superintendent, QC manager or others. (In the case of the large public works projects cited parenthetically above, contracts typically state that the project superintendent—who supervises a QC manager—is responsible for quality and, if quality suffers, the owner may find cause to order the removal and replacement of the project superintendent. (Most contracting firms would loathe the removal of a superintendent, but may have less concern over the removal of a QC manager.)

6.7 Size of the QC Team and Roles of the Team Members

The size and composition of the QC team will vary according to the project size, complexity, and the nature of the work.

Large Projects of Lower Complexity

For example, an on-grade road project or a major reroofing project could be relatively large in size, but each may not be unduly complex. This type of project primarily consists of several operations conducted in sequence, with the same sequence repeated in a more-or-less continuous process.

QC Manager
Such projects usually can be served by a QC manager (a "dirt and pavements person," a "roofing guy") with knowledge and experience in the technical disciplines of the project scope, and the QC specification should contain language to that effect.

Alternate QC Manager
Because of the importance of the position, owner's specifications usually mandate that the contractor appoint an alternate who will be available to temporarily assume the duties of the QC manager in the event of the QC manager's absence. The requirement is usually that the alternate QC manager should have qualifications similar to those specified for the QC manager. (This is usually the case for all types of projects—large, small, complex, or otherwise.)

QC Team
Depending on the size of such large but less-complex projects, the QC manager may be supported by a limited QC team:

- *QC Specialist* (*when considered necessary*)*:* The quality control specification may call for a full-time QC specialist/inspector (a discipline/trade expert) to continuously monitor the work as it goes in; and
- *Independent-Agency-Furnished Inspection and Testing Personnel:* The technical specifications usually will require inspection and testing personnel from an independent laboratory to periodically check the work and take samples/conduct tests. This type of project, for example, typically could require such personnel under the following specification sections: *Earthwork; Roadway Base; Bituminous Concrete Pavement; Concrete Pavement*, etc.
- *Manufacturer's Representative* (*when considered necessary*)*:* Applicable when specified, in order to obtain more precise quality control or to receive a longer-term warranty on a particular installed product. For example, under specification sections for bituminous built-up roofing, torch-applied membrane roofing, or fluid-applied waterproofing membrane.

Large Projects of Higher Complexity
For example, *a large R&D/laboratory facility with concrete grade beams and piers on pilings and structural steel framing; complex HVAC and electrical systems, UPS System; specialized functions include RFI shielding, computer rooms, clean rooms, fume hoods, lab gases; high bay assembly areas with bridge cranes; and vaulted lobby with five-story glazed, aluminum-framed curtainwall, and extensive administrative spaces day-lighted with clerestories and skylights, etc. The roofing design is complex, with extensive flashing details. Facility is designed to achieve a "Green" Building rating, and includes a "moat-like" storm-water management pond with an inner perimeter against a waterproofed foundation*. The project is both large and complex. This type of project will include many different trades; initially several will be on site, eventually dozens of trades will be scheduled and coordinated by the production team. Many production operations of many trades will occur simultaneously.

QC Manager
Such complex projects will need a QC manager (typically a savvy construction generalist with many solid years of field experience and a degree in architecture, engineering, or construction management) with a working knowledge of most of the major building systems in the project scope. The quality control specification typically will require such an individual.

Alternate QC Manager
For the large and complex project in the above example, the requirement to have an available alternate with the needed strong credentials and experience is important.

QC Team
The QC manager should be supported by a full-scale QC team, and specifications typically will spell out the composition of the team. Unless properly supported, QC managers on large projects can get "buried" in the time-consuming but necessary paperwork flow and submittals process, leaving little time to properly cover field quality control. Typically, the QC team for a complex project (such as the above example) may contain the following types of positions:

- *Assistant QC Manager*—This position is specified when it is clear that the combination of paperwork and field work is extensive, or when QC leadership is needed for shift work. Credentials and experience should be commensurate with the project needs.
- *QC Submittal Manager*—The QC submittal manager position should be specified when the submittals process will be voluminous. Specifiers should require the position be filled by a skilled, degreed (preferably professionally registered) architect or engineer. Due to field coordination needs, this position is probably most effective on-site, but could be partially off-site.
- *QC Submittal Reviewers, by Disciplines*—These positions (architectural, civil, structural, mechanical, HVAC, plumbing, electrical, specialty disciplines, etc.) are specified when the building systems under specific discipline categories are extensive or complex. Specifiers should require that these positions be filled by a skilled, degreed (preferably professionally registered) architect or engineer, as applicable. This position could be mostly off-site, and are typically not full-time assigned to the project.
- *QC Administrative Assistant*—Large complex projects need a full-time, on-site clerical/secretarial assistant to handle routine quality control paperwork and inquiries, freeing the technical QC management and staff to make judgments and decisions. Specifiers should require that these positions be filled by well trained individuals with technical knowledge and field work experience in their particular discipline/trade/specialty.
- *QC Specialists, by Disciplines*—These positions (architectural, civil, structural, mechanical, HVAC, plumbing, electrical, and specialty disciplines such as building enclosure, roofing, waterproofing, curtainwall, etc.) are specified when the building systems under specific discipline categories are extensive, complex, or have a history of problematic trade performance. These positions are most active on-site when the QC meetings, three phases of control and trades-work for that particular discipline is performed. The positions are on-site (or in as fabricator's shop as necessary), and (with some exceptions) are typically not full-time assigned to the project.
- *Subcontractor-Furnished Inspection and Testing Personnel*—The technical specifications may require some rudimentary testing that is customarily performed

by the subcontractor performing the work. Under this project, for example, such tests could be included under the following general construction specification sections: Exterior Water Distribution; Sanitary Sewer System; Interior Plumbing; HVAC Systems; Interior Electrical Wiring; Life-Safety Systems, etc. With regard to the building enclosure, tests need to typically be included under the following contract specifications: roofing and roof flashing; masonry and masonry flashing; windows and window flashing; building flashing; foundation and deck waterproofing; etc.

- *Independent-Agency-Furnished Inspection and Testing Personnel*—The technical specifications usually will require inspection and testing personnel from an independent agency or laboratory to periodically check the work and take samples/conduct tests. This project, for example, typically could require such personnel under the following specification sections: *Earthwork; Concrete Foundations; Structural Steel; Underground Electrical Distribution; RFI-Shielding; HVAC Testing, Balancing and Commissioning; Clean Rooms; Fume Hoods; Roofing, Waterproofing, etc.*
- *Manufacturer's Representative*—Applicable when specified, in order to obtain more precise quality control or to receive a longer-term warranty on a particular installed product. For example, under specification sections for fume hoods, curtainwall/glazing, roofing system, waterproofing, etc.

7 Communications Through Construction Project Meetings

7.1 Project Meetings

Good communications and clear understandings between the key players involved in a construction or design-build project are vital. This includes the owner and his construction management representatives, the owner's client/tenant, the designer, and the contractor, as well as subordinate entities to and organizations that may interface with the major participants. Regular discussions at designated project meetings keep the flow of information going on fast-moving and constantly changing projects, where the "good, bad and ugly" need to be effectively sorted out along with the benign.

7.2 Pre-Construction Conference

This initial project meeting, referred to commonly as the "*Pre-con*," is normally held by the owner upon the contractor's request. It is convened to kick-off the project immediately after award of the contract. The conference sets down the ground rules for administration of the contract and management of the construction, the lines of authority and responsibility for all parties, and introduces the major participants—including the owner and any major tenant or user, the architect-engineer, the prime contractor and major subcontractors, and other involved parties. Each participant should be represented by one or more key persons that have a management role in the home office or the field office.

- The contractor will often have a similar meeting with his major subcontractors and suppliers, as well as mini "pre-cons," held separately with each subcontractor and supplier to discuss their specific role in the project and the ground rules of the subcontract or vendor contract.

7.3 Quality Control (QC) Plan Meeting

The "QC plan meeting" is normally held by the owner and his construction management representative with appropriate contractor representatives—after contract award to the builder, but *before the contractor submits the quality control plan*. The architect-engineer may attend if there are significant technical challenges anticipated in the construction of the project.

(Related references in this chapter: Quality control programs were previously addressed in Section 5, in the context of how an owner should specify a contractor-provided QC program for a building project. Paragraphs 5.4 and 5.5 elaborate on the necessary specification requirements for quality control plans in the construction contract. The format and content of QC plans are also addressed in detail in Sections 8 through 10. Figure 3(*c*) is applicable, as well as Table 1 of Section 8.)

Ideally, the contractor representatives at this meeting should include *home office and field office management*, as well as the key contractor player—the *contractor's quality control manager*. The owner's construction management representative reviews the contract specification requirements for the quality control program with the contractor representatives. This includes expectations for the content of the project-specific QC plan based on the quality control specifications, technical specifications, and nature of the construction. Ideas are exchanged on the management, processes, and documentation required for a successful QC program that will effectively address the systems and characteristics of that particular building project. In the best-case scenario, the owner walks away from the meeting having effectively conveyed concerns for a quality project; and the contractor departs in a better position to develop a QC plan and program that will meet the owner's needs, while also having brought forth ideas and innovations for a quality building process.

7.4 Coordination and Mutual Understanding Meeting

This meeting occurs *after the QC plan is submitted*, and should include the managers and technical staff from the contractor's project management, on-site production and quality control operations, and subcontractor representatives as appropriate, as well as the owner's representatives. Once the contractor develops and submits the QC plan to the owner's representative—and after the owner's rep has reviewed the plan and agrees that it is acceptable or close to being acceptable—the meeting is mutually convened by the contractor and owner. The purpose of the meeting is for the *contractor to present the QC plan*, reviewing the management, personnel, quality processes, and documentation in the project-specific QC program. Particular emphasis is placed on quality challenges within the entire spectrum of different construction activities needed to build the project, looking at each separate activity on the construction schedule associated with a specific building trade or technical discipline. These disparate construction activities are also referred to as the project-specific *Definable Features of Work*. The adoption and use of the *three phases of control* for each definable feature of work is emphasized in this meeting. The three-phase control process is the under-girding principle resonating throughout all aspects of a well-managed contractor quality control program.

(Related references in this chapter: The concept of three phases of control was previously mentioned in Section 5, Paragraphs 5.4 and 5.5 as the proactive, preventive quality control element to be required when specifying a quality control plan. The QC Manager's role in implementation of the three phases is described in Section 6, Paragraph 6.6. Project attendees at the Preparatory and Initial Phase Conference are addressed in this Section, Paragraph 7.6. Section 9, Paragraph 9.8 explains the concept of designating the distinctly separate building systems and components as definable features of work (DFOWs) and elaborates in detail on the "three phases of control.")

During the QC plan meeting, the owner's construction management representative conveys any outstanding concerns and comments from the prior review of the QC plan, and offers constructive feedback on the contractor's presentation. This coordination meeting between the owner and the contractor (and major subcontractors) should result in mutual understandings regarding the operation and documentation of the QC program, and is intended to firm up lines of authority and communication on production and quality matters. Typically, owners allow construction to commence after approval of the QC plan and successful convening of the Coordination and Mutual Understanding Meeting.

7.5 Project Status Meetings

Once construction starts, regular status meetings are conducted either on a weekly or bi-weekly basis. The major categories for discussion are *progress*, *production*, and *quality control*. The meeting leader on large projects is often the project manager, but the superintendent, and QC manager each play leadership roles, covering their respective areas of responsibility. Key players include the contractor and subcontractor superintendents or trade foremen performing the work at that time, as well as the QC specialists that are assessing the quality of the work. The owner's representative for construction management and quality assurance usually attends, and the end-user / customer may attend.

- *Emphasis on Quality:* The meeting, of course, helps facilitate communication, planning, coordination, and progress—and provides a venue to resolve problems in a semi-formal way before they unnecessarily escalate. It is important that quality management has a prominent place in the meeting agenda, allowing the QC manager an effective platform to convey the status of the QC effort, emphasize the areas that need attention or correction, and provide a "look-ahead" at the planned QC activities. The contractor is responsible to timely submit the minutes of the meeting, providing a copy to the owner / contracting officer and other attendees. Usually, either the contractor's project manager or QC manager develops the minutes for the contractor.
- *Meeting Agenda:* Following is a typical agenda for a regularly-recurring status meeting on projects that incorporate a formal quality control program. It is similar to status meeting agendas for any construction project, covering the usual topics that need review. The format, order, structure, and detail of the meeting agenda would vary per project, depending on the owner's requirements, the contractor's needs, and the size and scope of the specific project. The list of topics below includes a brief summary of the nature of the discussion at such meetings.

1. *Minutes:* Review the minutes of the previous meeting. In addition to a review, this is the opportunity for participants to clarify and correct errors in the record of the previous meeting.
2. *Schedule:* Review the project schedule document, the actual work progress since the last meeting, and the current status of work (including any rework) accomplished. The schedule must be scrutinized to cover submittals, procurement, and fabrication and delivery activities, as well as the construction and QC activities. A thorough "scrub" of the schedule ensures that the effect on construction of all "up-front" actions and current work is clearly discerned, highlighting potential impacts and delays, so that they can be dealt with expeditiously.
3. *Submittals:* Review the status of submittals, including current submissions, reviews, approvals, disapprovals, and re-submissions that are pending.
4. *Production "look-ahead:"* Discuss the work to be accomplished in the next two weeks, along with the required documentation.
5. *Quality control "look-ahead:"* Discuss the preparatory and initial phase meetings to occur in the next two weeks, along with the required documentation. Ensure that the right people are lined up to be involved in the preparatory and initial phases of control for upcoming activities per production look-ahead.
6. *Production and Quality:* Address production issues, address quality control issues, resolve issues involving both production and quality control. These issues will often arise out of quality control oversight during the follow-up phase of control.
7. *Quality Control Plan:* Address items that may require a revision to QC Plan, and
8. *Safety Plan:* Review the safety plan for the upcoming work; discuss any revisions needed.

Note: Some owner-contractor teams may break their meeting into two separate sessions held in succession: (a) *A progress/production session* run by the *project manager* and *superintendent*; (b) followed by a *quality control* session, led by the *quality control manager*. The agenda would be revised accordingly. *Typically, each session would be attended* (with some exceptions), *by pretty much the same players, as the categories of production and quality control overlap and need to be coordinated together*. The issue of "one vice two" meeting sessions is discussed below:

- *Most Projects:* On the average project, small, medium, or large, there is a production team and a quality team; on many small-to-medium projects, the "quality team" is primarily a QC manager. These individuals are always (presumably) working together closely in the field. All are concerned with and need to be involved to a greater or lesser degree in the daily interaction between progress, production, and quality. (In this situation, splitting the meeting agenda into two separate categories—(a) progress/production and (b) quality control, each with a separate session—would seem to be unnecessarily compartmentalized, as the same participants would need to be in both.)

- *Very Large Projects:* Two separate sessions may work better on some very large projects, where large meetings with many participants having disparate roles and agendas can be unwieldy. In such cases, there may be a subgroup of players "less-involved" in quality processes, e.g., concerned primarily with materials procurement or subcontractor administration issues. This subgroup would attend only the progress/production session. This strategy would leave the QC session of the meeting more focused between the QC team and the field production team that must build to the quality specified. This approach also imbues the QC manager position with a greater sense of influence and clout, perhaps perceived, perhaps real. However, as noted above, the key participants of production and quality control need to be involved in *both* sessions.
- Because the sphere of influence of most on-site individuals and the typical agenda topics extend between both production and quality, most construction projects should probably have one integrated meeting session—as inferred by the above agenda—rather than two. The best approach for the nature of a particular project will usually be found between the contractor and the owner.
- On large projects, following the project status meeting, there may be "mini-meetings" among participants central to resolving a particular issue. "Preparatory Phase Meetings" (see below) can also be scheduled to follow a project status meeting, or can sometimes be "rolled into" the project meeting agenda on smaller projects.

7.6 Preparatory Phase Conference and Initial Phase Conference

These conferences, held on site for each *definable feature of work*, are scheduled in accordance with the project schedule and are led by the QC manager and QC staff, or both. The "preps" and "initials," as they are known in the field, differ from other types of project meetings in that they only cover a specific category or type of construction activity (or closely related activities). They are covered in depth. In addition to the key field managers of production, quality control and safety, the attendees are limited to the specific trades or technical disciplines involved in that activity. The format, content, and attendees for preparatory phase meetings and initial phase meetings are described in Section 9, Paragraph 9.8, where the three phases of control process is addressed in detail as an element of the project plan and program for quality control.

7.7 Pre-installation Conference—for Projects with No QC Specification, or for Smaller Projects

These conferences are very *similar* to preparatory phase meetings in that they focus on a particular category or type of construction activity. Preinstallation conferences in various formats are conducted by conscientious contractors who are concerned with project quality. They may occur in instances where the owner has not specified a formal contractor-managed quality control program, but the contractor is nevertheless concerned about "getting it right." When a formal QC program (requiring the preparatory, initial, and follow-up phases of control) has been specified in the owner's contract documents, the contractor's preinstallation conference gets "rolled-into" the preparatory phase meeting. In practice, there are differences in the industry in how these are handled, but the bottom-line is that these conferences—just like the formally-required "preps" in QC programs—are used to set the ground rules for a specific construction activity, "getting all the ducks lined up" by reviewing what is required for a particular trade or discipline before the work actually starts. Preinstallation conferences are, of course, effective for smaller projects as well.

- *The Project Team* attending each preinstallation conference includes involved members of the project team, such as the Architect/Engineer, CM, General Contractor, Subcontractors, Manufacturers and Suppliers, Consultants, and the Owner's representative.
- *Positive Engagement:* In order for the preinstallation conference to be of real value, the subcontractors, fabricators, and suppliers engaged in the particular category of work that is the subject of the meeting must attend and be involved in a positive way.

Building Systems That Have a Role in the Building Envelope or Moisture Protection

Listed below are some of the typical building enclosure subcontractors who should be included in the preinstallation conference for their particular category of work:

1. *Exterior Concrete*
2. *Exterior Precast Concrete*
3. *Exterior Masonry*
4. *Stone*
5. *Doors, Windows and Glazing, and Curtainwall* (*coordinated*)
6. *Curtainwall*
7. *Deck and Wall Waterproofing*
8. *Sheet Metal Flashing*
9. *Sealants*
10. *Roofing*
11. *Skylights*
12. *Exterior Insulation and Finish System* (*EIFS*), *Stucco*
13. *Exterior Studs and Sheathing*
14. *Expansion/Contraction Joints*
15. *Fireproofing*
16. *Miscellaneous Iron*
17. *Mechanical, Electrical, Plumbing, Fire Protection*
18. *Revolving Doors/Sliders*
19. *Hardware*
20. *Security*
21. *Acoustical Ceilings*
22. *Perimeter Insulation*
23. *Vapor Barrier*
24. *Fire-stopping*
25. *HVAC*

8 Understanding Plans and Programs for Construction Quality Control

Quality Control in Construction

Earlier, Section 4, Quality Control During Design, addressed the development of strategies to maintain and improve the quality of designs for buildings. We will now look more closely at the construction side of the quality equation to try to answer the questions, "how do we build a quality building, avoid accidents, and still finish on time—with a pleased client—and yet still some profit left over for the builder? How does the construction project team make this happen?"

The concept of a *contractor-managed construction quality control plan and program* was introduced in Section 5 in the context of how an owner can specify such a program for his contemplated project. Section 6 shows the importance of getting the right construction project team and establishing good working relationships. Section 7 shows how good, regular communications are established in the field—where the action occurs.

This section and the subsequent remaining Sections 9 and 10 of this chapter cover the two parallel concepts previously introduced for managing quality in construction contracts—(a) a *project quality control program*; and (b) the *Quality Control* (*QC*) *Plan* that is the foundation for the program. What are they and how are they put together and then worked—made to happen? Construction quality control programs are established by contractors to serve their best interests, or to satisfy the contract requirements imposed by their client-building owner or both. This section explains some basics regarding quality control plans and programs. Section 9 provides further detail on field implementation of the typical quality control processes within the QC program, as well as their treatment in an effective QC plan. Section 10 applies a well-established documentation approach to the standard construction management and quality control processes discussed in the previous sections.

8.1 Some Basics about Construction Quality Control

In this section, the *three basic operational categories* and the *twelve basic elements in a construction quality control program* are introduced; then the *differences* between a *general-purpose QC plan and a project-specific QC plan* are discussed. Importantly, several aspects of a quality control approach to *moisture protection for the building envelope* are presented. Finally, the often-stringent owner submission requirements for QC plan packages are summarized.

Operational Categories in a Construction QC Program

A QC program typically consists of three major categories of operation:

(a) An *organizational structure* supporting a *QC manager and QC personnel;*
(b) Quality control *processes*; and
(c) *Tracking and documentation* of QC processes.

The *QC plan* corresponding to the quality control program should address the operational categories of the program, primarily by describing each of the quality control performance elements within them.

Performance Elements of a QC Program and Plan

This chapter recommends twelve *major QC performance elements* spread among the three operational categories. These twelve or so elements should be described in the QC plan in sufficient detail that a clear "roadmap" for quality management emerges. The key participants in the contract (contractor, architect-engineer, and the owner's representative—typically a construction manager) will review the document. The field players on the project team will refer to the contractor's plan as the "quality bible" supporting the contract requirements.

Table 1 summarizes the major characteristics of a QC program and the corresponding QC plan. Depending on project size and complexity, the owner's specification requirements, and the contractor's internal policy, QC plans will typically include some or all of the performance elements listed in Table 1. These quality control elements are described in detail in Section 9. Also applicable is Figure 3(*c*), Key Elements of a Contractor's Quality Control Plan, in Section 6.

8.2 General-Purpose vice Project-Specific QC Plans

The purpose of and general approach to *construction quality control plans* are described in the following paragraphs. We will look at (a) *the QC plan structure*, followed by the different types of plans that evolve from the basic format for a construction QC plan. These include (b) *corporate QC plans*, (c) *project-specific/site-specific QC plans*, and (d) *commissioning plans*.

Note: Most owners will not allow construction to begin without a viable quality plan; therefore contractors must thoroughly develop and expeditiously submit their project QC plan, allowing reasonable time for owner review and approval prior to the start of construction.

Quality Planning

Good quality does not "just happen." Quality construction requires good *planning*. Prior to the start of work on a project, the contractor develops the Quality Control (QC) Plan. The QC Plan serves as the basis for the performance of the Quality Control Program on that project. Ideally, it should be prepared or final-edited by the contractor's QC manager for the project, based specifically on the project site and the systems and components to be constructed under the applicable contract.

A QC manager needs to understand *what* will be built and *how* it will be built *before* fully developing a viable project quality program. When putting together the plan, sufficient time must be allocated to the review of site conditions and the requirements of the contract plans and specifications. Initially, the overall project approach, building sequence, and construction methods should be discussed among the project leaders, including the project manager, construction superintendent, and QC manager. The QC Plan is the crucial first step in developing an effective quality control program, and is the *foundation* on which all quality processes are developed.

8.3 The QC Plan Structure

QC plans establish the quality control organization, processes, and methods to be used for a construction project, and identify the responsibilities of qualified individuals performing the quality control operations. In consort with the QC program approach reviewed above, a QC plan typically includes three major categories of quality doctrine: (a) organization, management, and administration; (b) processes and procedures; and (c) process tracking and documentation management. Also, the plan typically explains the func-

TABLE 1—Elements of a QC Program and Corresponding QC Plan

Operational Element of QC Program	Information in Section of QC Plan	Supporting Documentation in QC Plan
(A) *ORGANIZATION, MANAGEMENT, AND ADMINISTRATION*		
1. Organizational Structure	Contractor's Production and QC Organization	Organizational Chart
2. QC Staff Positions	List of QC Positions for the Project	Duties, Responsibility & Authority of Each Position
3. Proposed Names of Staff	Individual Resumes	Individual Qualifications, Education and Training
4. Delegation of Authority to QC Staff	Letters of Appointment to QC Staff	Letters Signed by Appropriate Official
5. Outside Consultants	Consulting Firms, Staff and Disciplines/Expertise	Credentials of Consulting Firms and Staff
6. Independent Agency for Construction Material Tests	Agencies/Labs, Staff and Disciplines/Expertise	Credentials of Testing Agency/Lab and Staff
(B) *QUALITY CONTROL PROCESSES AND PROCEDURES*		
7. Project Submittals	Submittal Procedures	See Documentation, #12b.
8. Proactive, Preventive Quality Controls	Three-Phases of Control—Establishment & Procedures	See Documentation, #12c.
9. Testing and Inspections	Testing Processes	See Documentation, #12d.
10. Monitoring of Deficiencies	Procedures to Detect and Correct Defects	See Documentation, #12e.
11. Completion Inspections:	Processes & Procedures—Three Stages of Final Inspection	See Documentation, #12f.
(C) *PROCESS TRACKING AND DOCUMENTATION*		See Documentation #12g.
12. Documentation Procedures		
12a. General Documentation		Schedule; Meetings; Daily Reports; Transmittals, etc.
12b. Submittal Procedures	Documents & Tracking	Submittal Register (Log)
12c. 3 Phases—Procedures	Documents & Tracking	DFOW*List; P&I Lists; etc.
12d. Testing	Documents & Tracking	Testing Plan & Log
12e. Deficiency Procedures	Documents & Tracking	Deficiency/Rework Log
12f. Completion/Procedure	Documents & Tracking	Completion Insp. Matrix
12g. Staff Responsibilities	Document	Quality Matrix

tions and execution of the twelve basic performance elements summarized in Table 1.

8.4 Generic/Corporate QC Plan

Some contractors have an in-house format for a quality control plan that works well for them and is acceptable to their clients/project owners. These general-purpose plans are sometimes referred to as *Corporate QC Plans*. These plans depict the contractor's strategy to provide effective leadership and management of quality control on their projects, and outline quality policy and procedures. Such plans contain the generic QC processes that are typically employed on the contractor's construction projects, (especially those projects with explicit QC requirements specified in the contract documents). The typical components of the corporate QC plan include the basic QC organizational structure and processes that are listed above and found in Table 1.

8.5 Project-Specific/Site-Specific QC Plan

The QC plan for each project must be developed specifically for the characteristics, needs, and requirements of that project. The specific project organization, number of and qualifications of a proposed staff are appropriate to the project size and scope. The content of the plan includes project-specific quality checks, inspections, and tests that are based on the project specifications, contract drawings, site conditions, and the contractor's experience and expertise.

The corporate QC plan (if employed by the contractor) will be used as a template for development of the Project-specific/Site-specific QC Plan. The corporate QC plan is "tailored" by the contractor to the project-at-hand. The contractor does this by supplementing the generalized format with the organization, personnel, and specific quality control procedures for the specific project. The building project organization description; personnel resumes and appointments; and QC procedures and checklists for the project are simply inserted into the section of the (corporate) QC plan that contains the appropriate generic description of the applicable quality control element. The project-specific QC procedures include quality control checklists for the structure, envelope, and systems inherent in the building to be constructed.

If there is no corporate QC plan as a basis, the project/site-specific QC plan will be developed from scratch (or, more likely, by adapting a previous project plan), including the specific project organization, personnel, and quality processes.

Using ideas from previous plans may be appropriate for some of the planned construction activities, but there can be a sloppy tendency to "crib" too much totally inappropriate information from one old plan to the next new one.

The bottom-line is that the specifics of a project QC plan need to be carefully developed based on the specific components and systems for *that particular project*—and like all things worthwhile, it takes thought, effort, and time to create a plan that is effective.

8.6 Project-Specific Commissioning Plan

"Commissioning" is an over-arching quality management endeavor that, in its purest manifestation, should encompass expert oversight, review, and testing during the entire evolution—*design, construction, operation, and maintenance*—of a building or facility. When a commissioning program and commissioning plan is specified in the contract documents, there needs to be good coordination with the QC Plan. The commissioning process is becoming more well-established in building construction, especially with field commissioning of HVAC systems. However, there is a very limited but growing trend toward "Total Building Commissioning (TBC)," covering all of the major building systems—including architectural systems. The field component of TBC is somewhat *equivalent* to a construction QC program. Sometimes the role, responsibility, and authority of a commissioning authority and a QC manager could overlap or conflict, and this should be clearly sorted out beforehand.

In either the case of commissioning of a particular system (such as the *HVAC system* or the *building envelope*), or the case of total building commissioning, the commissioning approach needs to be integrated with the QC program. *Owners* (in collaboration with their *designer and construction manager*) need to carefully specify quality control and commissioning so they can be either (a) coordinated or (b) fully integrated together. Owners may want to go this route if they have a complex or sensitive building—in such a case, they need to have the budget to do it right and they need to consult a commissioning expert with both the technical credentials and field experience. Contractors need to beware of this issue; read the contract documents carefully, question them accordingly (before bid!), and proceed accordingly with the appropriate commissioning plan, quality plan, and related programs.

An introduction to commissioning and sources for commissioning guidance are found in Paragraphs 3.10 through 3.12 of Section 3, Quality in Building Design and Construction. A building envelope commissioning program and the included processes are described in Section 11, Quality Management and Building Envelope Commissioning.

8.7 Moisture Protection/Control Considerations to Incorporate in a Project/Site-Specific QC Plan

Can We Control Moisture—During Construction—and for the Life of the Building?

Virtually every project exposed to the elements—from roofing a small building to building a multi-million dollar structure—requires a significant degree of moisture protection and control, specified in the design and implemented in the construction. Contractors need to develop a good QC plan and then run the QC program in accordance with its quality control processes and project-specific QC oversight, including plan strategies and checklists that specifically apply to the structure being built.

When developing a QC Plan to cover building systems and components that are affected by moisture during construction, or are intended to keep moisture out during the life of the completed facility, at least three very basic questions must be addressed:

1. *How do you "get a handle" on managing quality on a building project, with all the multiple features, systems, and components and their sometimes complex interfaces?*
2. *How do you ensure that the building goes together in a way that thermal conductivity, moisture, and air infiltration will be effectively controlled?*
3. *How do you control the risk presented by water infiltration during building construction?*

Good Planning and Follow-Through Help Us Control Moisture at the Building Envelope

In answer to the moisture-related problems issues posed in the three questions above—contractors can, with *good planning and follow through*, employ strategies such as the following in their quality control planning:

- *Systematically approach the quality control process to dovetail with the building process*. Break down the building "jigsaw-puzzle" into its *logical features*—the *building systems and components* that go together to comprise the final completed project. This is what the project scheduler does; the QC manager needs to do the same from a quality perspective. The QC program needs to devise and put in place QC processes that can be logically and proactively applied—in accordance with the project schedule. This means *before and while* construction activities occur, as well as *after*. (Sounds simple, sounds obvious—but it often does not happen.)
- *Validate watertight integrity as the components of systems go together*. Contractors and owners (and their architects, as well) can avoid unpleasant and costly surprises that can unfortunately show up during assembly of building systems or at project completion.
- *Provide effective* (vice incomplete or missing) *temporary weather protection during the building process*.

Several examples of quality planning for moisture protection and control are provided in the following paragraphs, including:

(8.8) *QC Planning for the Building Envelope*.
(8.9) *Moisture Protection QC Checklists for Architectural Systems*.
(8.10) *A Plan to Prevent Water Infiltration during Construction*.

Please note that these particular examples of quality control planning would comprise only *"parts"* of a project-specific QC plan—not its entirety. A QC plan outlines and details a comprehensive strategy of processes, procedures, and documentation to encompass quality management of the entire project—from procurement and submittals to final inspection and closeout.

8.8 QC Planning for the Building Envelope

The first step in quality control planning for the building envelope is to determine which systems—usually architectural and structural—comprise the building enclosure. These *building envelope features* are the building materials and systems that are designed to provide water-tightness and air-tightness per the contract documents. The plans and specifications are consulted, and the main building systems are reviewed.

Following (for a hypothetical "typical" project) is a list of some major building systems designed to provide a complete exterior envelope for the building. These architectural components are ultimately intended to provide complete protection against the forces of nature when the project is occupied by the client. The QC plan, consisting of the specified/needed *controls, tests, inspections*, and *documentation*, is developed around each and every building system (also referred to as "*definable features of work*") that go into the building's construction, including the particular systems that provide moisture protection. Some examples of these building features/systems are listed below.

- Waterproofing systems;
- Masonry/precast construction;
- Windows/fenestration systems;
- Curtainwall systems (stone, precast, aluminum, and glass, etc.);
- Metal panel systems, metal parapet caps, etc.;
- Exterior insulation and finish systems (EIFS/Dryvit)/ Stucco systems;
- Preparation/detailing/caulking of all expansion/control interface joints;
- Roofing systems, gravel stops;
- Flashing at interfaces between components or systems;
- Composites of above;
- Other systems.

8.9 QC Checklists for Moisture Control in Building Envelope Architectural Systems

Quality Control Checklists are very important and necessary to a project-specific QC Plan, and essential to the project QC program. QC checklists are developed in the plan, *cross-referenced* to the *specification section* and the *project schedule*, and then expanded on the jobsite as necessary. They are specifically employed as part of the generic *"three phase" control process*. (This process was previously outlined Section 6 in the Responsibility and Authority of the QC Manager, Paragraph 6.6. The subsequent Section 9, Paragraph 9.8, elaborates in detail on the three phases of control.) For each significant feature of work (system or component) built into the project, a preparatory, initial, and follow-up phase of control is conducted by the project QC manager (and QC staff or both). There is a *preparatory phase checklist* developed for use *prior to work* on the construction activity, and an *initial phase checklist* developed for use *as work starts* on the construction activity. These QC checklists are also used during the *follow-up phase* to check and *validate the continuing work* on the particular activity—and to verify workmanship at *completion* of that construction activity.

(*Note:* The following "quality checks" are condensed, culled from typical project QC checklists: they are cursory, partial samples of "quality checks" for only a few of the components that could comprise a particular building envelope. However, they do represent samples of applications where mistakes are commonly made. The quality checks would typically be part of an *initial phase checklist*, and would be used during the *initial and follow-up phases of control* for the applicable construction activity.

1. *Air Retarders and Vapor Barriers*
   Is air barrier installed on correct side of wall?
   Is air barrier sealed at joints and tears?
   Is vapor retarder material and thickness IAW specifications?
   Is vapor retarder installed on correct side of wall?
2. *Moisture Analysis and Materials Properties*
   Has moisture analysis been performed (if required)?
   Do materials meet the properties that were assumed in the moisture analysis?
3. *Sealants and Application*
   Is sealant as specified?
   Joints cleaned and primed as required?
   Sealant application during specified temperatures?
   Sealants applied adequately (with no overspill) in all places where required?
4. *Roofing and Flashing*
   Roofing insulation and sheet material as specified?—
   Are the correct labels on flats/containers/rolls?
   Is the roofing insulation (with vapor barrier and moisture barrier) installed with the correct side up?
   Are roof membrane joints lapped and sealed per specification?
   Flashing material, mil thickness, and color as specified?
   Cants properly installed under roofing and flashing at roof deck-parapet intersection?
5. *Windows*
   Are manufacturer, material, fabrication, jamb, head and sill profile, and thermal break as specified and per approved shop drawings?
   Is there an AAMA Label with the wind load and air infiltration rating as specified?
   Are the fasteners correct, and installed properly into surrounding structural framing?

8.10 A Plan to Prevent Water Infiltration During Construction

This moisture mitigation "plan within" the QC plan—encompassing major production processes—shows both "big-picture" and detail thinking. It is a holistic look at the entire construction process, from estimating the project through building close-in and operation of HVAC systems. It incorporates knowledge and review of weather information, scheduling, and construction, and shows an understanding of how a building goes together. Production techniques are understood and need to be implemented in proper sequence to get a quality result. An "up-front" investment in strategic planning, scheduling, and quality plans should offset the cost of planned temporary protection, and avoid the potentially high expense of water damage and repair. Good production planning can effectively support quality.

- *Estimating—Weather Analysis*–Budgets for temporary weather protection generated from the schedule analysis of NOAA annual weather impacts by examination of the Past 30 years of compiled weather data—temperature and precipitation for the specific location.
- *Preconstruction*–Constructability review of building enclosure system—review envelope details, schedules, phases, sequencing.
- *Schedule-Weather Risk Review*–Review of potential weather impacts to the installation of building exterior enclosure; potential advantages of unitization of skin assemblies (steel framing, EIFS, windows) to minimize exposure to weather.
- *Early buy out of building enclosure subcontracts*–laboratory mock-up testing; trade subcontractors.
- *Coordination of building enclosure access*–Tower crane, man and material hoist, work platforms, lifts, stairtowers and the impact of lateral bracing on the building envelope installation.
- *Site drainage*–On-site grading and control of water flow. Storm Water Plan.
- *Temporary weather protection*–Walls, windows, doors, louvers, curtainwall.
- *Temporary weather protection*–Roof-parapets, skylights, mechanical equipment, shafts-duct, piping, elevators, stairs.
- *Moisture-resistant drywall*–Minimize exposure in all shaft walls-elevators, mechanical ducts and piping.
- *HVAC*–Duct protection for all projects—covered at the point of fabrication.
- *Elevators*–Early operational availability allows removal of cranes, man, and material hoists, allowing the "close up" of the building envelope.
- *Temporary HVAC*–Equipment rental—to control temperature and humidity.
- *HVAC*–Operational availability of the permanent equipment for providing temperature and humidity control for installation of finishes.

<u>What are the benefits of temporary weather protection?</u>

- *Schedule*–Eliminate the adverse impacts from weather and moisture issues.
- *Building finishes*–Drywall installation—eliminate risk of water, mold.
- *Concrete floor moisture*–Eliminate schedule and cost impacts to flooring installation.

8.11 Developing Quality Processes for QC Plans

As previously discussed, the first step in developing the *QC processes* in a construction *quality control plan* is the determination of the particular *building systems* around which to develop the project-specific program for quality control. The second step is to develop a *list of, and quality tracking process* for, these systems—the project "Definable Features of Work (DFOWs)." The *three phases of control* process needs to be incorporated as the proactive, preventive process for checking these building "features." The next steps are to prepare the following information and incorporate them into the QC plan:

- Compile the specified *submittals* into a *submittal log*;
- Compile the *tests and inspections* into a test *plan/log*;
- Develop a *deficiency/rework* tracking system with a *deficiency/rework log*;
- Establish a *completion inspection process* with a *completion tracking matrix*;
- Set up a project *documentation system* with appropriate *forms*.

This chapter, in the following Section 9, explains the pertinent QC strategies to be integrated into a valid QC plan and followed as part of the QC program. Refer to Paragraphs (9.7) *Submittals*; (9.8) *DFOWs/three phases of control*; (9.9) *Testing, inspection and mock-ups*; (9.10) *Monitoring of deficiencies*; and (9.11); *Completion inspections*. *Documentation* is addressed in Section 10.

Section Nine explains in great detail the implementation of the central theme of an effective field QC program, the *three phases of control*, along with the quality processes, *quality checklists* (Paragraph 9.8), and field *test agendas* (Paragraph 9.9) that are used in the control process. Included are some very important quality control processes that can help contractors (and their owner clients) who need to keep wind, water, mildew, and mold out of a building. The structured quality plans and processes described offer a generic, proactive approach that can be applied to any construction activity on the project, including all parts of the building envelope. Watertight integrity can be ensured every step of the way, through preventive measures, quality checks, mock-ups, inspections, and tests.

To validate the construction/installation of the building envelope under the Contractor QC program, tests and inspections may be accomplished (as approved in the QC plan) either by the General contractor, subcontractor, independent third party, or owner's construction manager. In cases of complex structures, *"mock-ups" of building assemblies* (Paragraph 9.9) may be specified to ensure that they will be watertight. When specified, these (costly) endeavors need to be well-planned, coordinated among interfacing subcontractors' schedules and work, and thoroughly tested and inspected in accordance with the contract specifications.

8.12 Submission, Review and "Acceptance" of QC Plans

The *QC Plan* prepared by the contractor typically is submitted to the owner's designated representative for review and acceptance or approval, or in some cases for reference only, depending on how the contract is structured. Typically, the term "*acceptance*" or "*approval*" does not contractually construe the owner's concurrence or agreement with inadvertent or undiscovered flaws in the plan. Changes to the plan must follow the same (specified) contractual submittal process.

—QC plans today are, of course, developed electronically, and may be submitted and reviewed either via hard copy or electronically (or both) depending on the owner's/

contracting officer's requirements and adopted project custom. It is recommended that the *final approved copy and any updates be preserved in the project file and saved in an incorruptible electronic file*.

—However, once the plan is approved, the on-site people running the project really need a bound, hard copy of the project QC manual for easy reference and jobsite use. *Use of a three-ring binder with a table of contents, numbered pages, and tabbed sections/appendices* is strongly recommended, and is specified by some owners/agencies. As a working document supplementing the electronic file, the tried-and-true, "low-tech" three-ring binder format still works well in the field.

Stringent Requirements

The contract documents usually require the contractor to (1) *submit the plan by a date certain after contract award*, (usually on the order of 15–20 days), and (2) start construction only after a plan is considered acceptable. Further, contracts usually state that (3) *revisions to the plan may be required as circumstances dictate*.

The plan must be developed quickly to avoid delaying the construction, yet it must be thorough; this highlights the need for early in-depth involvement in preparation of the plan, and suggests the importance of having a corporate QC plan on hand as a template. (Some contracting officers will allow the preparation of a partial QC plan that completely and adequately covers the first phases of construction (say, 90 days), with a revised date certain for submitting the complete and adequate QC plan in its entirety.) In general, the QC plan is contractually considered a "living document," subject to change when the contractor and owner determine that improvement or supplementation is needed.

9. Developing a Quality Control Plan and Program for a Construction Project

Contractor-Developed Quality Control Programs and Plans (QC Plan)

The concept of a Construction Quality Control Program and a Quality Control (QC) Plan were introduced previously in Sections 5 and 8. *Three operational categories* were identified, as well as *twelve major elements* spread within the operational categories of a quality control program. This section builds on that background. The scope of a QC program is reviewed in detail: (a) Each of *twelve major elements of a QC program is explained in detail*, followed in each case by (b) *a description of how that aspect of the program should be addressed in a thorough QC plan*. The two concepts, a "program and a "plan," are discussed together in this section because it is necessary to understand what a QC program is before one can develop a coherent plan.

On a construction project, the reverse chronological order, of course, occurs: (1) the plan must first be carefully developed in tune with the project requirements, followed by (2) committed, adroit execution of the QC program based on the plan.

(A) Operational Category: Organization, Management and Administration

9.1 (Element #1) Contractor's Project Organizational Structure

Contractors develop an organizational structure for the project that has clear lines of authority, with the following key components and characteristics:

—Home office hierarchy;
—Production management positions on-site;
—Quality management positions on-site;
—Relationships of production and quality management with subcontractors, consultants, and independent testing agencies.

The key contractor positions would typically include the responsible Company Officer; Senior Project Manager, Project Managers Project Engineers, and Project Superintendents, Quality Control Manager, and supporting QC staff.

Although these organizational relationships are usually reasonably clear to the contractor, it is prudent to spell them out on paper, in the QC Plan, for the benefit of all partners in the project, in particular the owner's representatives for contract administration and construction management. Referring to Section 6, Figure 3(*a*) indicates the typical project organization for a *contractor* with a QC program. For reference, Fig. 3(*b*) shows the corresponding project organization for an *owner's* construction management and quality assurance staff.

The Contractor's QC Plan should include an *Organizational Chart* to confirm the management positions and organizational lines of responsibility and authority. The relationships need to be backed up by the contractor's in-house policy and by the language in the subcontracts with supporting organizations.

9.2 (Element #2) Quality Control Positions; Duties, Responsibility, and Authority

The contractor needs to establish staff positions to manage and perform the processes in the project QC program. Each position should have clearly established duties and responsibilities. Most projects require both a qualified QC manager (full-time, on-site) and a qualified alternate QC manager (on-site in absence of the QC manager).

Depending on the size and complexity of the project, other key QC positions typically may include some of the following positions, as considered necessary or as specified: Assistant QC Manager; QC Discipline/Trade Specialists; QC Submittal Reviewers; Clerical/Submittals Assistant, etc.

The Contractor's QC Plan should include Position Descriptions for the *contractor's QC manager and quality control staff*; clearly and explicitly spelling out the *specific duties, responsibility, and authority of each separate position*.

9.3 (Element #3) Individuals Proposed for QC Positions

The contractor needs to find qualified individuals to fill the specified/needed quality control positions, either from in-house staff, outside recruitments, or provided through A-E or consulting firms.

The Contractor's QC Plan should include submission of the names and qualifications of individuals proposed for each of the quality control positions described above.

- *Qualifications:* Resumes are provided to show that the experience, training, and education of each proposed individual matches up with (a) the contractor's assessment of the project needs and (b) the requirements (which may be specified by the owner) for the applicable position.
- *QC Training:* Proposed QC managers (and occasionally other contractor staff) may need to show evidence of certification in a specific training course in construction quality management. Such a course is sponsored by the regional offices of the Associated General Contractors of America (AGC) and the Associated Builders and Contractors (ABC). Some owners will specify this requirement, especially in the Federal Government construction arena.

9.4 (Element #4) Letters of Appointment

Owners consider a project QC manager's role of such significance that they expect the contractor to designate, by specific letter to the nominated individual, the authority and duties delegated by the contracting firm to the individual. The contractor prepares a separate appointment letter to each of the individuals proposed, respectively, for the positions of *QC Manager and Alternate QC Manager* on a specific project. Each letter should be from the officer in the firm responsible for the project, and should clearly state that the individual proposed for the position has the full authority to manage the project QC program, and the responsibility to implement all aspects of the program. Responsibility for key aspects of the program, such as but not limited to the *Three Phases of Control* (discussed in Paragraph 9.8), should be outlined,

Owners typically require that the contractor's QC manager and alternate have the authority to stop work that does not comply with the contract requirements; and their specifications typically mandate that this authority be explicitly stated in the contractor's appointment letter. Such authority effectively gives the QC manager and alternate the clout to prevent the continuation of new construction over work that is not correct.

In addition, owner's specifications require that the project QC manager, in turn, issue appointment letters, outlining duties, and authorities, to key subordinates in the project QC organization such as QC specialists and submittal reviewers. Copies of the letters are included in the QC Plan.

The Contractor's QC Plan should include submission of the *Letters of Appointment, signed by the appropriate authority*, designating the QC person's duties and authority, including *authority of the QC Manager and Alternate to stop noncompliant work*.

9.5 (Element #5) Outside Consultants

Contractors may retain consultants to provide technical evaluation of specialized work required in the contract specification, and to assist them in providing required reports or documentation. Typically, such companies include architectural-engineering firms, engineering consultants, and technical specialty consultants. These companies are retained to help meet the owner's specification requirements, for example: plans and monitoring for lead removal, asbestos removal, and hazardous materials abatement; development of architectural or engineering shop drawings; professional review and P.E. stamp for shoring plans, structural shop drawings, underground heat distribution systems, and cathodic protection systems; testing and balancing of HVAC systems, commissioning, electrical protective coordination studies, etc.

The Contractor's QC Plan should include the *Credentials of outside Consultants*, indicating, for each, the name of the company to be retained and the nature of the consulting services to be provided. Qualifications, experience, and other credentials, such as professional registration or certification, of a company's principal and consultants should be furnished. (*Note:* Independent Testing Laboratories that are retained for construction materials testing are typically addressed in a separate section, described following.)

9.6 (Element #6) Independent Testing Agencies/Laboratories for Construction Materials Testing

An owner's construction contract will usually require the contractor to test critical construction materials used in the work. The contractor is often directed to retain a "third party," an *independent construction materials testing agency/laboratory*, to perform such tests, and will submit the agency credentials under this section of the QC Plan. Certain basic construction materials—the classic cases being soils, concrete, and reinforcing and structural steel—are typically called out for testing by independent agencies.

Independent testing agencies/laboratories are expected to have the capability to perform specific named tests in accordance with accepted national or international standards specified in the owner's contract documents. There are three basic methods that owners employ in their specifications to ensure that the proposed independent testing agency is credible, and they may specify one or more of them in their construction contracts. (1) The owner requires the testing lab to submit their credentials and capabilities to perform the specified tests. (2) The owner has the capability and resources to inspect the independent testing agency's laboratory and assess their capability against the accepted standards. (3) The owner requires that an independent agency/laboratory must have been previously "accredited" by a nationally or internationally sanctioned "fourth party," an independent accreditation agency.

Accreditation of materials testing laboratories by accrediting agencies is also based on accepted national/international standards, and is performed at specified intervals—usually every three years—for those labs that keep their accreditation current. Successful accreditation of a testing organization means that the qualified fourth party has examined the testing laboratory's capabilities, and that the lab is considered acceptable; hence, accredited, in certain specific tests, procedures, and inspection techniques. Accreditation is not a blanket conferring of "acceptance" to do any and all tests, but is granted based on those specific tests, procedures, and inspections for which the lab has earned accreditation.

The Contractor's QC Plan should include the *Credentials of the Independent Testing Laboratories*, identifying the independent laboratories that the contractor will employ to satisfy the contract specification requirements. The information should specifically cite the exact tests that they will perform or specifically show by appropriate credentials that the proposed lab is qualified to perform those tests in accord with the appropriate specification requirements and independent accreditation, or both.

The individuals in charge of testing and those actually performing the sampling and testing must be identified, and their credentials presented to ascertain that the lab's employees are qualified by degree, certification, and experience to provide each testing service that is required in the specification.

(B) Operational Category: Processes and Procedures

9.7 (Element #7) Submittal Procedures

Chapter 22—*Contract Documents and Moisture Control* as well as Section 4 of this chapter address the concept of construction submittals. The contract will require the contractor to submit up-front documentation—known as *submittals*—to the owner. Submittals are intended to validate (*prior to installation*) that the items to be incorporated in the project and the processes planned are in accordance with the contract requirements. "Submittals" typically include *technical information* about materials, equipment, and systems proposed by the contractor to meet the specification requirements. Examples of materials submittals include concrete mix design, manufacturing and strength data for structural steel, fabricated metals such as steel studs and roof joists and roof decking, and data on masonry, doors, windows, roofing, etc. Examples of equipment submittals include performance characteristics of HVAC components such as air handlers, condensers, and cooling towers, or electrical switchgear, generators, etc. System submittals may include detailed shop drawings for concrete foundations, structural steel erection, curtain wall erection, roofing installation layout, HVAC piping and ductwork, and electrical system configuration.

Although the owner typically does not specify the routine means and methods of construction, the specification may require that certain *administrative* processes and critical *construction* processes be preceded by a specific contractor-prepared plan; such plans are also considered "submittals." Examples include QC plans, environmental protection plans, hazardous materials removal plans, demolition plans, sheeting and shoring plans, roofing/staging/scaffolding plans, etc.

The Contractor's QC Plan should include his *Submittal Procedures*, an outline of management of the submittals process. The contractor must clearly (1) identify who in the QC organization is responsible for managing and processing submittals; (2) outline the necessary supplier/subcontractor/contractor procedures for submittal preparation, review and handling of submission to the owner; and ensure that (3) the role of the QC manager or his designated representatives, or both, in reviewing and approving submittals, is clearly established in the QC Plan. Additionally, (4) based on the contract, name and state the roles of the key parties and stakeholders in the submittal review process, such as the Architect-Engineer, Owner's Representative, and Owner.

The role of the QC manager and the role of the owner in reviewing and approving submittals must be clearly delineated, inasmuch as many owners require: (a) the *contractor's QC organization* to carefully review *all* submittals for compliance with the contract specification; (b) approval of routine submittals by the *contractor's QC organization*; (c) final review and approval of complex submittals (typically systems that are an extension of the A-E's design) are reserved to the *owner*.

- Typically, it is very helpful and thus strongly recommended for the contractor to prepare a *Submittals Flow Chart* (in the QC Plan) that shows the entire submission/review/approval process, starting with suppliers and subcontractors and ending with approvals by the appropriate approval authority (QC organization or owner). The chart should show the flow of disapprovals and resubmissions as well as submissions and approvals. The chart should also show the complete distribution pattern to all contract stakeholders. In Section 4, Figure 2(*a*) is a simplified schematic representation of the *submittals process for construction* contracts. Figure 2(*b*) is a simplified submittals flow process for *design-build* contracts.
- *A Submittal Register*, also known as a Submittal Log (see Section 10, Documentation, Paragraph 10.2) is virtually always specified to be included in the plan, and is crucial to managing and tracking the entire submittals process.

9.8 (Element #8) Procedures to Establish and Perform Three Phases of Control

Control Process

Owners will usually specify that contractor QC programs use a proactive control process, consisting of *Three Phases of Control*, to manage quality on a construction project. The three-phase quality process is repeatedly performed by the contractor's QC program staff, each time on a different aspect of a project. The three elements of this essential quality management approach consist of the (1) *Preparatory*, (2) *Initial*, and (3) *Follow-up* phases. Figures 4(*a*)–4(*c*) outline the *concept, procedures and staff for the three-phase process*.

Control Process is Applied to Scheduled Construction Activities/"Definable Features"

These three phases of quality control are applied to each distinctly separate component of work or building system scheduled on a project. Some specifications describe these separate components as *Definable Features of Work* (*DFOW*), a term developed by the Army Corps of Engineers and adopted to a significant degree in the construction community. *A DFOW is always an activity* (*or linked group of activities*) *on the construction schedule, and is easiest to think of and describe in those terms*. Each DFOW or scheduled activity is almost always related to a *specific construction trade*. Each DFOW also will be related to the *specifications*—either to a portion of a contract specification section, a specific specification section, or a grouping of several specification sections. (A now-outdated and ineffective type of practice—a "knee-jerk" response that simply defaults to considering each specification section as a "DFOW" should be avoided—as it obscures the reality of how a project is actually scheduled and built.)

A definition adopted by the Naval Facilities Engineering

Command (*Quality Control Guide Specification, Section 01450*), states, in part, "*A Definable Feature of Work is a task that is separate and distinct from other tasks and has control requirements and work crews unique to that task*."

The three-phase control process is led and managed by the QC manager and performed by both the QC manager and approved QC staff in accordance with an approved QC plan. An introductory example of how the process works on a roofing activity was given earlier under Section 6, Paragraph 6.6, Responsibility and Authority of the QC Manager. The generic aspects of the process itself, including each of the three phases of control, are described below.

- *Phase 1*–The *Preparatory Phase of Control* for a construction activity (DFOW) occurs at the project site *before work starts on that activity*. This phase encompasses submittals review and approval, materials and equipment validation, and a review of the site conditions, safety and contract requirements. The process culminates with a *Preparatory Phase Conference* led by the QC manager (or designated QC discipline specialist, or both), and attended by key staff involved in the activity—*in particular the applicable trade leader* (from the prime or subcontractor). In addition to the trade superintendent/foreman, those attending include the project superintendent, the project safety manager, and (when considered necessary or prudent) the Architect-Engineer. The owner's representative is invited and normally attends.
- *Phase 2*–The *Initial Phase of Control* for a construction activity (DFOW) occurs *as the work starts at the location of the trade activity*. This *Initial Phase Conference* consists of reviewing the material, workmanship, and safety standards in the contract. These are reiterated to the *trade leader*, and he in turn familiarizes the trades-crew with the requirements. The QC manager/specialist will observe and constructively critique the initial work and safety effort as the applicable task is actually performed; establishing a mutual commitment to the contract requirements. The same leader and attendees are involved as in the preparatory phase conference.
- *Phase 3*–The *Follow-up Phase of Control* for a construction activity (DFOW) *occurs continuously for the remainder of the activity*, and consists of QC checks and inspections on a daily/as needed basis, based on the precepts established during the Preparatory and Initial Phases of Control. The follow-up phase is conducted by the QC manager or applicable QC discipline specialist, or both, and culminates in a *Final Follow-up Inspection for that activity*. The *Final Follow-up* should convene the same leader and attendees as in the "preps" and "initials."

How to Make the Three-Phase Process Work for You

Effective QC programs use the three phases of control, a management process that helps guide contractor and subcontractor trades-crews to do the work correctly "the first time." The preparatory and initial phases of control for each DFOW need to be approached with a vision of attaining construction quality through planning and foresight, identifying and avoiding potential problems. This approach minimizes rework, controls costs, preserves schedule time, and enhances the contractor's reputation and ability to secure future business. In summary, this approach includes some of the following fundamental steps:

(1) Establish an appropriate project list of *Definable Features of Work* (*DFOWs*), based on the individual project components/building systems and their associated activities on the project schedule. The project-specific definable features of work form the foundation for the three-phase control process—the heart of the quality control program. The three phases of control are conducted for *each* definable feature of work, establishing a proactive, preventive quality control regimen.

(2) Develop two good standard *conference agendas* to manage and document each *preparatory phase conference* and each *initial phase conference*. The conference agendas should also contain a checklist format to fill in specific quality checks applicable to the particular definable feature of work.

(3) Complete the preparatory phase checklist and initial phase checklist for each DFOW in the QC Plan; update/refine them at the *preparatory* and *initial phase conferences* for that DFOW;

(4) Prior to start of work on each DFOW for the project, start the *Preparatory Phase of Control* to ensure that submittals are approved, materials-on-site are correct, and the work to be built-upon/interfaced with is acceptable. This really needs to happen *before* the preparatory conference occurs. If major submittals are untimely or not yet approved, a preparatory conference would be premature.

(5) The scheduled Preparatory Phase Conference at the project site should follow a thorough agenda, reviewing the contract and submittal requirements. The "prep" needs to be held with the right people, for example—if a trade subcontractor for the particular DFOW is expected to attend, make sure it is the person most familiar with the project who will attend. In some cases, the project manager ("office guy") may be the best individual for this meeting; in other cases the trade superintendent/foreman ("field guy") is probably the right man. Get the right people to show for this important meeting.

(6) As work actually begins on each DFOW for the project, hold a scheduled *Initial Phase Conference* at the actual location of the work being performed on the jobsite. Follow a good, preplanned agenda. Ensure that the crew performing the work gets it right the first time out, setting the standard immediately for the work to follow.

(7) Perform *frequent routine follow-up inspections* (the *Follow-up Phase of Control*) as the work is accomplished on each DFOW. This ensures that the quality benchmarks established in the preparatory and initial phases are effectively maintained.

(8) Maintain a tracking log to validate the conduct of the "*prep*" and "*initial*" *conferences* during the preparatory and initial phases of control for each DFOW; coordinated with item (9) below.

(9) Establish a *quick-reference filing system* for ready access to documentation of the *preparatory* and initial phases of control.

(10) Under some circumstances, reconvene a completed *preparatory or initial phase conference* for a particular

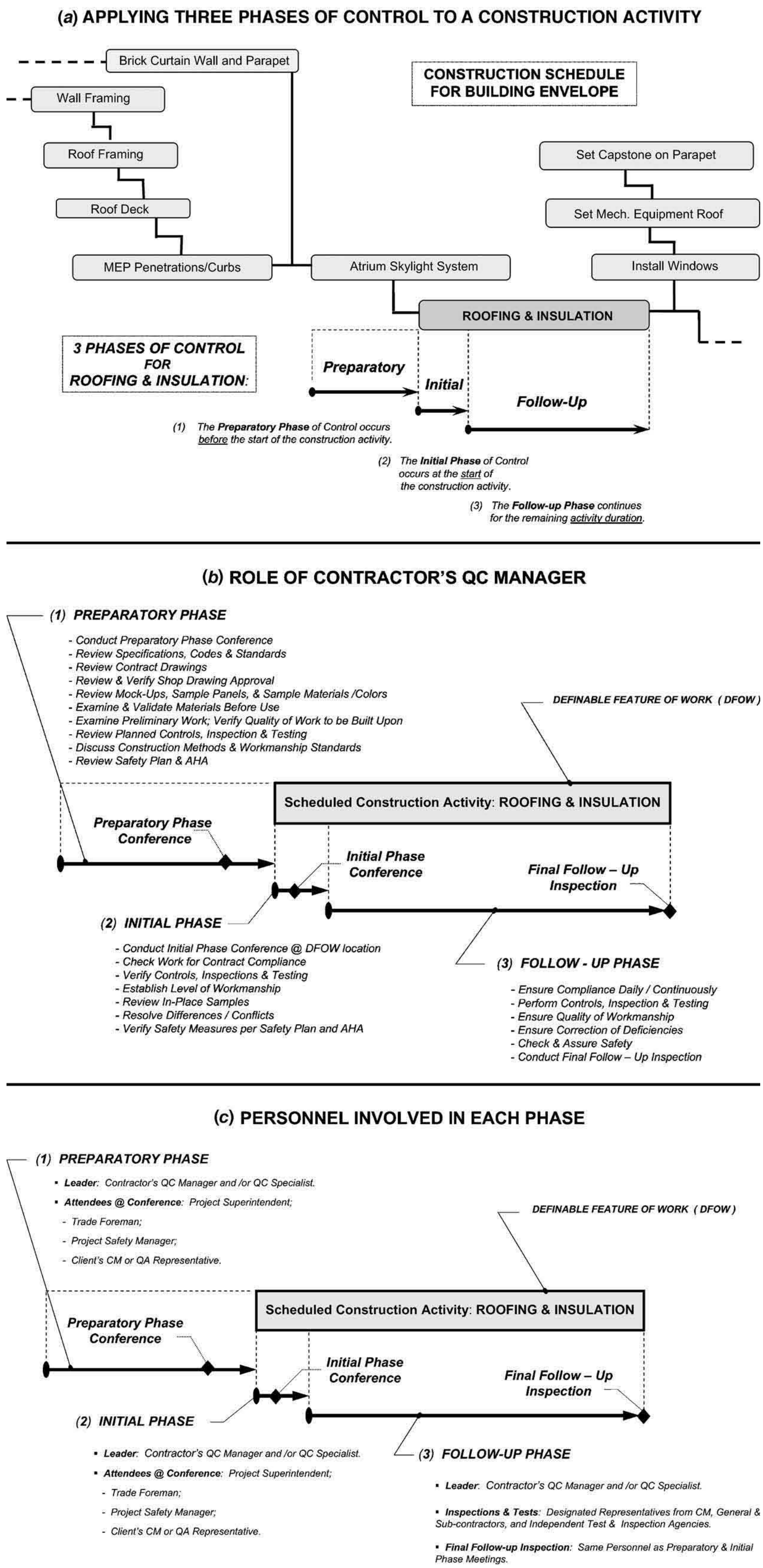


Fig. 4—(a) Applying three phases of control to a construction activity. (b) Role of contractor's QC manager. (c) Personnel involved in each phase.

definable feature of work. Typical issues that would trigger this repeat conference include the following:

- A trend of faltering, slipping/marginal quality; unacceptable work;
- A change in the applicable QC staff;
- A change in the trade superintendent/foreman or crew, or both;
- When work is reactivated after a significant period of inactivity;
- Other production/quality problems.

The contractor's QC Plan, describing three *phases of control*, should emphasize the establishment of a quality jobsite culture based on proactive, preventive processes, including the routine use of *three phases of control* to ensure the attainment of appropriate construction quality on a specific project. Contractor plans should explain the field approach and specific procedures to be implemented to guarantee that the three-phase process will be effectively implemented. The QC Plan should make it clear that the contractor has a management approach, a committed staff, and internal safeguards to prevent undue scheduling pressures from overcoming the proper, timely performance of the three phases of control on a scheduled item of work.

The QC Plan, importantly, should include several *vital* documentation processes, including the development of the following:

- *A project list of Definable Features of Work* (*DFOWs*)*;*
- *Conference Agendas for the Preparatory and Initial Phases of Control;*
- *Preparatory and Initial Phase Checklists* to be used for each DFOW;
- A *tracking log* for preparatory phase conferences and initial phase conferences;
- A *filing/reference system* for easy retrieval of documentation covering the preparatory and initial phases of control.

Section 10, Documentation, Paragraph 10.3, describes these important tools.

9.9 (Element #9) Testing Processes

Field Testing and In-Process Inspections

The contractor develops a field (and off-site) testing program, based on the contract specification requirements for contractors to routinely perform certain specific inspections and tests on their construction. As a matter of self-interest, some contractors may additionally perform their own in-process tests, for example, to prove watertight integrity as the work of interfacing components goes together.

Figure 5(*a*) outlines the typical, generic *field testing process and procedures*; while Fig. 5(*b*) is a comprehensive, specific list of field inspections and tests for assuring *weather-tight integrity* of the *exterior building envelope*.

Testing processes fall into at least three general categories, including those tests, procedures, and inspections typically performed as follows:

(a) At a *factory or plant* with established, repeatable production processes;

(b) *"In situ"*–in a fabrication shop or on the construction site; as well as

(c) Samples taken from the shop or field that are later analyzed and tested in the laboratory.

Examples of (a) *factory tests* include evaluation of a representative sample of a standard air-handling unit to verify that the particular model will meet the specified airflow capacity and other parameters; subjecting a sample of a particular window assembly (frames and glazing) to standard air and water infiltration tests; and testing standard precast concrete members for strength.

Examples of (b) *in situ tests* include approximate bearing capacity of soils; slump of concrete; measuring steel bolt

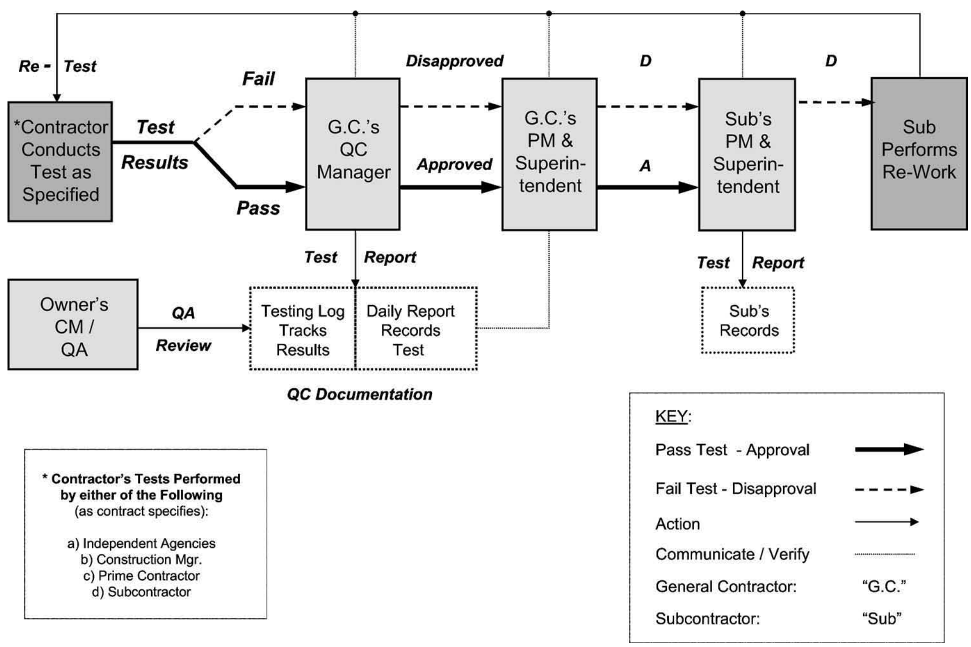


Fig. 5— (a) Contractor's testing process.

LOCATION & SYSTEM	MATERIAL TYPE (as necessary)	FIELD TESTING METHOD
Below Grade		
Below Grade Drainage, Piping, Rock, Geotech Fabric		Hose / Flood
Below Grade Waterproofing	Sheet	Hose / Flood
Below Grade Waterproofing	Liquid Applied	Hose / Flood
Structural Steel		
Foundation / Anchor Bolts		Survey / Tolerances
Columns, Floors, Beams, Stairs		Survey / Tolerances
Structural Framing, Decks, & Sub-Framing	Steel / Concrete	Survey / Location / Dimensions
Slab, Walls, Columns, Beams, Shafts, Stairs, Slab Edge		Survey / Location / Dimensions / Plumb / Tolerances
Floor-Finish		FL, LL, Flatness, Levelness
Exterior Structural Enclosure		
Exterior Sheathing		Sealed / Structural Attachment - Frame
Weather Resistive Barrier	Sheet / Liquid Applied	Inspect / Adhesion
Air Barrier	Sheet / Liquid Applied	Structural Attachment
Air Barrier		Continuity at Penetrations
Concrete Insulation		
Waterproofing / Damp-proofing		Hose
Expansion Joints-Horizontal/Vertical		Location / Hose
Sealants		Survey / dimensions / Adhesion / Hose
Embedments		Survey / Location / Pullout
Masonry - (Brick / Block)		
Structural Framing / Backup		Inspect
Base Flashing/Bld Dams/Inside/Outside Corners		Hose
Shelf Angle Attachment to Frame Steel		Structural Attachment
Lintel Flashing/Sealed/Lapped/End Dams, Term Bars		Hose
Brick Ties/Sealed at WRB/AB		Hose
Expansion Joints-Horizontal Vertical		Location / Hose
Sealants		Survey / Dimensions/ Adhesion / Hose
Windows		
Framing		Survey / Dimensions
Structural Attachment		Survey / Dimensions / Pullout
Flashing / Sill Flashing w/ End Dams		Hose
Head Flashing w/end Dams		Hose
Jamb Flashing		Hose
Internal Gaskets/Seals		hose
Air Infiltration / Exfiltration		Air
Weeps Water		Hose
Sealant Joints		Survey / Dimensions / Adhesion / Hose

Fig. 5— (b) Building envelope field inspection and testing.

Curtainwall		
Framing		Survey / Dimensions
Structural Attachment to Frame		Survey / Dimensions / Pullout
Insulaton Expansion Joints/Insulation		Hose
Base Flashing/End Dams		Hose
Internal Gaskets/Seals		Hose
Weeps		Hose
Perimeter Sealants/ sealants		Survey / Dimensions / Adhesion / Hose
Precast Concrete / GFRC		
Panel-Finish		Inspect - Tolerances, Texture & Color
Dimensions as cast		Survey
Structural Attachment to Frame		Survey / Pull-Out
Insulation		Type, Thickness, Adhesion
Panel to Panel Sealant Joints-Double		Hose
Air Barrier / WRB Continuity		Air
Base Flashing/End Dams		Hose
Sealants		Survey / Dimensions / Adhesion / Hose
Expansion Joints – Horizontal / Vertical		Survey / Dimensions / Hose
Metal Panels		
Panel-as fabricated		Dimensions
Finish		Inspect - Tolerances, Texture & Color
Edge		Tolerances
Structural Attachment to Frame		Survey / Pull-Out
Insulation		Type, Thickness, Adhesion
Insulation Sealant Joints		Survey / Dimensions / Adhesion / Hose
Panel to Panel Sealant Joints		Survey / Dimensions / Adhesion / Hose
Air Barrier / WRB Continuity		Air
Base Flashing / End Dams		Hose
Stone		
Framing		Survey / Dimensions
Structural Attachment of Stone to Frame		Survey/ Dimensions / Pullout
Base Flashing/End Dams		Survey / Hose
Air Barrier/WRB Continuity		Inspect
Expansion Joints-Horizontal Vertical		Survey / Dimensions / Hose
Sealant Joints		Survey / Dimensions / Adhesion / Hose
Stucco		
Framing		Survey, Tolerance
Substrate		Survey
Mesh Attachment to Frame		Survey
Brown Coat		Temperature
Top Coat		Temperature
Expansion Joints Horizontal/Vertical		Survey / Dimensions / Hose
Insulation Sealant Joints		Survey / Dimensions / Adhesion / Hose

Fig. 5— (*Continued*).

EIFS		
Stud Framing		Survey / Dimensions
Exterior Sheathing		Attachment to Frame
Insulation Attachment		Inspect
Base Coat and Mesh		Temperature
Top Coat		Temperature
Back wrapping Windows, Doors, Louvers		Inspect
Drainage-Weeps/Accessories		Inspect
EIFS to EIFS Sealant Joints		Survey / Dimensions / Hose
EIFS to other Materials Sealant Joints		Survey / Dimensions / Hose
Head of Window Flashing/End Dams		Survey / Dimensions / Hose
Sill of Window Flashing/End Dams		Survey / Dimensions / Hose
Expansion Joints-Horizontal-Each Floor Vertical		Survey / Dimensions
Roofing		
Framing		Survey
Substrate		Survey
Cover Sheet		Attachment
Structural Attachment		Survey / Pull Out
Insulation		Location, Type, Thickness, Adhesion
Slope to Drain		Survey
Flashing-Curbs, Pipe Penetrations, Duct Penetrations		Hose
EPDM seams		Flood
Roof Curbs		Hose / Flood
Roof Temp EVT,		Temperature
Parapet-Flashing: Lapped, Sealed		Hose
Sheet Metal-Flashing, Sealed		Hose
Scuppers-Flashing, Sealed		Hose
Sealants-Roof Compatible		Hose
Metal		Hose
Expansion Joints		Survey / Dimensions / Hose
Rock Ballast		Type & Gradation
Pavers		Unit Weight, Durability
Termination Bars		Attachment, Sealed, Hose
Skylights		
Structural Attachment to Frame		Survey,Pull Out
Framing		Survey / Dimensions
Roof / Curb Flashing		Hose

Fig. 5— (*Continued*).

torque; and nondestructive testing of structural steel welds—visual, dye-penetrating, and radiographic.

Examples of (c) *samples taken in the field for later lab analysis or testing* include soil samples analyzed for moisture-density relationships; destructive concrete strength testing after curing of wet-sampled concrete cylinders; and destructive strength testing of a steel bolt sampled from the fabrication shop or construction site. In the case of radiographic weld testing done in shop or field, subsequent expert analysis of the resulting X-ray records will be performed by the lab. The tests performed are based on the contract specifications for a particular project.

Test and Evaluation of Mock-ups

Mock-ups are assemblies constructed of several of the actual specified materials for a project. The purpose of a mock up is to review the installation methods and sequences and to test the interfaces of the various materials. Testing may cover air infiltration, water-tightness, moisture transport, thermal capabilities; or resistance to seismic or blasting loads. Mock-ups are often employed in the *building envelope commissioning* process, as noted in Section 11. Further information on mock-ups can be found in Appendix C.

- *Material and Assembly Interfaces:* The expected performance of a particular building assembly can be tested beforehand to determine the effectiveness of vapor barriers, air barriers, moisture barriers, interfacing materials/configurations, etc. A mock-up assembly could show, for example, how insulation and roofing is installed to the structural roof deck; and flashed to adjacent walls, parapets and structures/curbs/penetrations; or the manner of constructing the curtain wall, showing interfaces with the structure, installation of fenestration, through-wall flashing and caulking; intersection of exterior walls and roof, or a combination thereof, etc. This testing, inspection, and workmanship validation process is, in effect, an *initial phase* of control for a particular building assembly.
- *Locations:* Mock-ups can be constructed at a variety of locations, as considered most practical to accomplish the intended result: (1) a sample assembled on the field site, but not in place; (2) at the field site, incorporated into the construction of the building; (3) offsite at a location nearby the project; (4) at a laboratory to facilitate controlled or sophisticated testing.
- *Early Field Correlation with Design:* The plans and specifications in combination with the shop drawings provide a great deal of information, but cannot substitute for the information provided by an actual field mock-up. Mock-ups permit the construction team—the owner, A/E, CM, GC, subcontractors, and material manufacturers to physically test the wall systems and actually see how these materials interface, connect and function.
- *Performance Validation:* Mock-ups test the performance of the designs and the construction, or provide options for evaluation and selection, or both. They allow the contractor an additional venue to develop the best construction techniques and sequencing. They provide the owner, the architect, the contractor, and the subcontractors an opportunity to develop the most effective means of achieving the project's workmanship goals.
- *Establish Standard of Quality:* Mock-ups provide a method for the contractor to establish the standard of quality that is acceptable for the project. Mock-ups provide a physical example where the construction team can demonstrate and document the required workmanship quality; aesthetics, constructability, and function can be demonstrated to meet that specified within the contract documents. A mock-up is constructed, and then tested; and if the assembly does not perform, it is then disassembled, modified, retested, and finally remedied and approved for construction.
- *Examples:* Field mock-ups of the exterior wall systems provide the opportunity to monitor and test the installation and interfacing of below grade waterproofing, drainage, base flashing, air barriers, masonry, stone, adhered veneer, stucco, GRFC, precast panels, metal panels, EIFS, sealants, terminations, weeps, drip edges, lintels, shelf angles, inside corners, outside corners, end dams, parapets, roofing, wall penetrations, fenestration, louvers, equipment curbs, etc.
- *"Cost versus "Comfort Level:"* The mock-up tests are a cost effective way to assess "up-front"—before the entire structure is completed—the design and the construction techniques that the contractor will use to build a weather-tight structure. The process entails an initial cost investment—with the potential to pay big dividends in elimination of probable issues, and greatly enhancing the possibilities for downstream cost avoidance. Owners and A-E firms should seriously consider specifying the use of a mock-up when the performance of the building envelope is a concern.

The Contractor's QC Plan should describe a field *testing program*—including testing of mock-ups when specified or planned. Testing must be integrated within the context of the three-phase control process, with tests performed at the appropriate time to produce valid and timely results. Tests *must* occur *early* in the installation of building enclosure components such as masonry, metal panels, EIFS, stucco, stone, and flashings.

- The cornerstone of the testing agenda will include a comprehensive *Testing Plan and Log* (see Documentation, Section 10, Paragraph 10.4 following.) The test plan and log outlines the tests, timing and frequencies of testing, and the party responsible for performing and reporting results to the manager of the QC program.

9.10 (Element #10) Procedures to Correct Defects

It is crucial to a prime contractor's reputation to manage the construction quality, including identification, control, and correction of defects. A quality control program—with the three-phase system previously described—is a method of proactively managing construction quality to prevent defects from occurring. In theory, a perfect quality program would build everything right "the first time"—as the work progresses. In practice, well-managed project QC programs do a good job of ensuring that materials and equipment are installed correctly, but they will invariably fall short of "perfection." Reality dictates that some problems with the quality of workmanship and installation will likely arise on any project, no matter how well the project and the QC program is conceived and executed.

Capable contractors, aided by QC staff, are alert to the potential for problems to occur, based on their past experience, knowledge of the project plans and specifications, and familiarity with the skill level of their own tradesmen and subcontractors. Such knowledgeable construction managers will identify a problem before it gets out of hand, and will have standard procedures in place to manage and ensure correction by the appropriate party to the project.

Typically, these procedures center on a *Deficiency Correction System*. (There are several similar terms used in the industry. Correction of noncomplying work is often referred to as "rework," and therefore another term for these procedures is *Rework Tracking System*.) Whatever name you may give it, the thrust of this is a timely and assertive process for contractors to identify, make record of, track, and ensure correction of defects or deficiencies. A conscientious con-

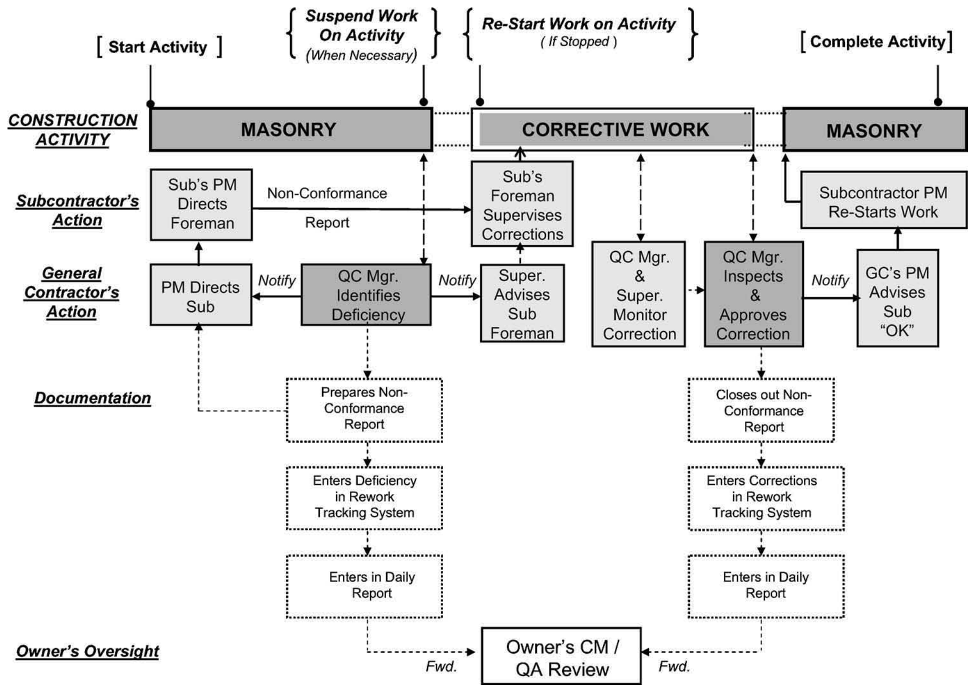


Fig. 6—Process for identifying deficiencies and tracking rework.

tractor will make an entry in the project daily report when a quality problem is first identified, and again when the "out-of-spec" work is eventually corrected.

Most contractors, particularly on larger projects with numerous subcontractors, will also maintain a continuously updated *Deficiency/Rework Log*—a database and spreadsheet that lists all project defects and tracks their correction. A project superintendent will refer to and use this log to help manage the correction through his tradesmen and subcontractors, and a QC manager will use the log to verify that the corrections are occurring. QC managers need to maintain an assertive stance to timely identify a quality problem and ensure its prompt correction, especially when there is the possibility of either the responsible trade crew building over the defect, or concealment of a deficiency within the subsequent work of a different trade. Figure 6 gives the process to *identify, track, and correct deficiencies*. Further details on the contractor's internal deficiency tracking process can be found in *Appendix D*.

The Contractor's QC Plan should outline the contractor's procedures to identify deficiencies, ensure their correction, and track and document their resolution.

- A sample format of the Contractor's *Deficiency/Rework Log* should be provided. See Section 10, Documentation,

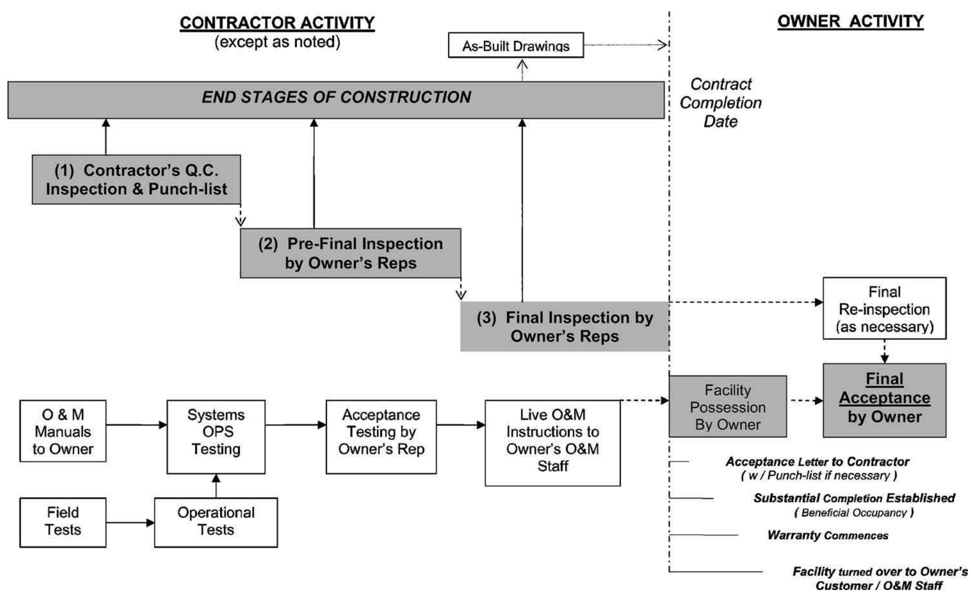


Fig. 7—Final inspection and acceptance process.

Paragraph 10.5 for discussion of the Deficiency/Rework Log.

9.11 (Element #11) Process and Procedures for Completion Inspections

It is crucial for both the owner and the construction contractor to have an orderly, structured way to determine acceptance of an entire project. The contractor needs to make sure that all defects have been remedied, and needs feedback from the owner on the acceptability of the project. Before the owner can accept and use/occupy the facility, the owner representative wants to know that all construction problems have been corrected and that the project complies with the contract requirements (plans and specifications). Based on generations of contracting experience and "lessons learned," a formalized, well-documented completion inspection process has evolved, broken down into three key stages, each a specific, separate inspection: The (1) *"Punch-out" Inspection;* (2) *Pre-Final Inspection;* and (3) *Final Inspection*. The first inspection stage is managed by the contractor; the second and third inspection stages are managed by the owner, but are heavily dependent on the contractor's effectiveness and timing.

The key elements of each stage of the completion inspection process are as follows, and need to be anticipated, scheduled, and coordinated sufficiently in advance of the completion date of the contract:

(1) *Stage One–"Punch-out" Inspection* (Contractor): The contractor's QC manager conducts a complete punch-out inspection of the entire project, preparing a "punch-list" which describes each item of remaining work that does not match up with the contract requirements. Any unresolved items resulting from the QC program's previous performance of the three phases of control and earlier preparation of the deficiency/rework log is, of course, included. *The QC program's punch-list* is presented by the contractor to the owner's representative/contracting officer, and includes a *specific date* (*prior to completion of the contract*) *for the contractor to complete the work delineated on the punch-list*.
   - The contractor then corrects the problems by the punch-list completion date and before the contract completion date. The project superintendent leads this effort, using his tradesmen and subcontractors. This effort is closely monitored and validated by the QC manager through additional follow-up inspections on individual trade items, and is verified by conduct of a second QC punch inspection of the complete project. Once the QC manager is satisfied that the entire project is now in compliance with the contract, the contractor notifies the owner, in writing, that the facility is available for the owner to expeditiously schedule an owner's "Pre-Final" Inspection.

(2) Stage Two—*Pre-Final Inspection* (Owner): After notification (per above) by the contractor that the contract work is "ready," the Pre-Final Inspection is promptly scheduled by the owner's representative to assure that the facility is complete, in contract compliance, and therefore suitable for use and occupancy by the owner. The owner conducts this inspection using his designated representatives on the construction site, often supplemented by various operations, maintenance, security and fire protection personnel, etc.—who will be responsible to operate the facility.
   - Should an owner's punch-list evolve from this inspection, the contractor then notifies the owner, in writing, of the date the owner's punch-list will be completed, along with any other (uncompleted) contract work still scheduled to be finished. The contractor's notification simultaneously requests an owner's Final Inspection, giving reasonable advance notice to the owner to allow scheduling with the appropriate interested parties. It is essential that the remaining contract work be completed and items on the owner's punch-list be corrected at least by the contract completion date.

(3) Stage Three—*Final Inspection* (Owner): The owner will schedule the final inspection based on the notice given (above) by the contractor. The owner may reschedule the final inspection if the contractor fails to meet the completion date of work and punch-list items as scheduled. The owner's final inspection must be timely conducted when the owner is satisfied that all contract work is complete and punch list items have been corrected by the contractor. The contractor should be represented by the Project Manager, Superintendent, QC Manager, and key subcontractors. The owner will typically be represented by the using customer, in addition to the other facility operations personnel that assisted in conduct of the pre-final inspection.
   - Should an owner's punch-list evolve from this inspection, the process reiterates as necessary.

Structure and Communication is Needed to Avoid Potential Confusion

The completion and turnover stage of a contract can be complex and intense, as multiple activities and differing priorities converge. On large or complex projects, or both, the above three completion inspection steps need to be fairly strictly formalized (and shown on the project schedule) to avoid the potential for chaos during the inspection and acceptance phase of a project. Even on smaller or less complex projects, these steps of the completion inspection process—while not as formalized—should really be followed to maintain control and timeliness. Coordination and communication between the contractor and owner's representative are very important in all phases of the project, especially during inspection and acceptance. It may be possible on some projects to combine some of these steps, but contractors should be cautioned not to count on this—and owner's need be wary of short-cuts that may damage the integrity of the acceptance process. It is incumbent on contractors to meet their obligation to finish the project correctly and on time; and it is incumbent on owners to always provide a fair and timely assessment of the contractor's completed work.

Engage Early

As outlined above, it is important to start the completion inspection process before the project work is entirely complete, in order to maintain an inspection timeline (encompassing the three major iterations) in parallel with completion of work of all of the trades. This will reduce the potential for project delays due to "punch-list work," and enable corrections while the trade is readily available. "Dragging out" of this process by either or both parties will lead to an unsatisfactory outcome for both—the owner's use and occupancy could be delayed, rework call-backs may be costly for the contractor, and the contractor's reputation (vital to secure new work) can be damaged.

Completion Issues

Issues such as (1) the owner's need to timely occupy and use the facility, and (2) assessment of the actual acceptable completion date for contractual purposes—will likely arise in the event of uncompleted work or an uncompleted punch-list upon the contractually-specified completion date. (See the chapter in this manual on Disputes.) Such issues can get contentious and even nasty, and are best avoided by proactive, timely, fair, and up-front relationships between the owner, designer, and contractor.

The Contractor's QC Plan should include the quality control procedures for implementing the *completion inspection process*, ensuring that the process is structured and well-documented by the contractor. The plan needs to name the QC staff responsible for the punch-out inspection, monitoring and follow-up inspections of corrective work, and any subsequent necessary reinspections. The contractor/subcontractor participants and attendees in each stage of the three-stage completion inspection process should be identified.

- *A Completion and Turnover Matrix* is a desirable document used to plan, track and document efforts during the completion phase of a project. This document is described in Section 10, Documentation, Paragraph 10.6.

10 Documentation Management for Construction Projects

Accurate and complete documentation of construction activities on and off the project site will enable effective checks of project status (progress, production, and quality) as the work progresses. Documentation also provides a historical record that will validate the construction/quality process and protect the interests of both the contractor and the owner/client. The *designer, contractor*, and *owner's representative* each prepare and process documentation and maintain files for the project. Each entity uses documents that are germane to its specific role and, in addition, each entity uses documents that have been prepared by or will pass through the hands of one or more of the other entities. Routine construction and quality activities are documented and specified reviews and approvals are conferred through the intense document flow characteristic of a construction project.

This section specifically focuses on the *construction contractor's* role in documentation. The section discusses the information to be recorded to document the typical construction management and quality control processes performed in the field. This section also shows how to develop documentation procedures within the contractor QC plan.

Operational Category (C), Process Tracking and Documentation

The construction tracking and documentation processes have been previously described (Section 5, Figure 3(*c*), and Section 8) as the third ("Part C") of three major operational categories that constitute a QC program. Documentation of the quality control program is considered indispensable to the successful management of a building construction project. It is also important that the contractor's plan for process tracking and documentation be adequately thought out and presented in the contractor's quality control plan. The Appendices E through K to this chapter include several examples of sample documentation forms that would be included in a typical QC plan to show the contractor's intended approach to recording important project information

(Element #12) Construction Documentation Processes

During construction, the greatest contractual documentation burden is usually borne by the construction contractor, who necessarily is responsible for building and delivering the project in accordance with the owner's specified terms. Following is the construction and quality documentation normally desired and typically required of *construction contractors*. The format following addresses planning for and documenting actions performed under the *twelve elements* of a construction quality control program. Such documentation is an essential part of the contractor's project management effort and well-managed documentation is one of the cornerstones underlying project success. The typical project documentation processes for construction and quality are outlined below.

The Contractor's QC Plan should include *procedures* for documenting the project that will meet the contractor's management needs while satisfying the owner's requirements for construction and quality documentation, including various critical submissions and approvals. In addition, the plan should include a *sample* of the format of each document or form planned for use to document and track construction and quality processes. These will be reviewed for suitability by the owner's representative.

10.1 (Element 12a) General Documentation

The following documents are typically used on a daily basis in the management of the on-site construction.

- *Construction Schedule* developed by the prime contractor, typically "accepted" (not necessarily "approved") by the owner. The schedule is consulted daily/frequently, is reviewed by all parties at regular project meetings, and is typically formally updated monthly *and as necessary* by the contractor.
- *Project Status* (*Progress/Production/QC*) *Meeting Agenda*, with regular (typically weekly or bi-weekly) minutes prepared by the prime contractor, reviewed by all parties, and regularly updated by the prime. A typical meeting agenda is summarized in Section 7, Paragraph 7.5.
- *Daily Production Reports* prepared by the project superintendent working for the prime contractor. These record information such as the day's weather; work performed, by whom, and exact location; man-hours worked by each trade; schedule activity numbers of work performed; materials received; equipment on the job—working or idle; pertinent other information; instructions received and given; and remarks as necessary on the day's work. The *project superintendent* signs the report. On large projects, daily reports will also include appended subcontractor daily reports prepared by the applicable trade superintendents/foremen. A sample

daily production report is in Appendix E.

- *Daily Quality Control (QC) Reports* prepared by the QC manager record the quality control activities performed by the QC manager and QC staff on that day. This includes information such as submittals reviewed; validation of delivered materials; control activities, inspections, and tests; schedule activity numbers of work reviewed; etc. The *QC manager* signs the report and certifies its validity. Appended to the daily QC report are other routine reports of quality control observations on that day. These supplemental sheets include the completed *conference agendas/QC checklists* which are used to document the preparatory phase conference and the initial phase conference for each activity or related group of activities on the schedule. Sampling, testing, inspections, and other pertinent quality activities that occurred on the day of the report may be documented with necessary additional reports included and attached to the daily report. A sample *daily QC report* is in Appendix F.
- *The Preparatory Phase Conference Agenda/Checklist* is a format/form used in conducting a preparatory phase meeting for each separate construction activity or group of activities ("definable feature of work") on the schedule. The form documents those in attendance; the review of the applicable drawings and specifications; the validation of submittals and materials on site; review of work to be built upon; plans for executing the work, and plans for safety. The conference agenda incorporates the *preparatory phase checklist* (discussed under Element #12c in Paragraph 10.3). A sample *preparatory phase checklist* is in Appendix G.
- *The Initial Phase Conference Agenda/Checklist* is a format/form used in conducting an initial phase meeting for each major item ("definable feature of work") on the schedule. The form documents those in attendance, pertinent agreements, the start of the particular major item of work, methodology and workmanship, and safety processes employed. The conference agenda incorporates the *initial phase checklist* (discussed under Element #12c in Paragraph 10.3). A sample *initial phase checklist* is in Appendix H.
- *Other QC Documentation Forms:* Contractors find that it is effective to have preprinted forms to document certain repetitive quality control actions involving inspections, sampling and testing. Examples of some applicable repetitive work/QC activities include concrete placement or waterproofing samples, structural steel bolt tightening procedures, moisture sampling, water infiltration testing, etc.
- *Routine Transmittal Forms*, which are used to document the routine but important forwarding of important information between the parties to the design and construction, such as samples, technical submittals, test results, etc.

The Contractor's QC Plan—General Documentation: The *QC Plan* should be coordinated with the *construction schedule*, which is a separate submission. The contractor should include in the plan the proposed sample forms for the following:

—*Project status (progress/production/QC) meeting agenda*;
—*Daily production and Quality Control reports*;
—*Preparatory and initial phase conference*;
—*Routine inspection forms for materials sampling and testing*; and
—*Routine transmittal formats*.

10.2 (Element 12b) Submittal Register/Log

The *submittals process* was previously discussed in Section 9, Paragraph 9.7. The submittals process includes design submissions (for design-build projects) and construction submissions. The *submittal register/log* is a critical reference tool for planning, executing and validating the submittals process during the contractor design phase (design-build contracts), and during construction. *This discussion primarily addresses construction submittals.* The owner's contract requires the contractor to furnish samples and submittals that will show compliance with the project specifications. The contractor's preparation and furnishing of each submittal to the reviewing authority, and the reviewing authority's acceptance or approval, must be effectively coordinated with the construction schedule so as to avoid delay to the project. Any needed submission, review, acceptance or approval of a submittal must occur before the material or equipment depicted in the submittal is procured (highly preferable) or installed (mandatory). This common-sense approach protects all players in the process, and maintains the integrity of the contract.

The Contractor's QC Plan—Submittals Documentation: The contractor prepares and includes in the QC Plan a complete, comprehensive *submittal register*, a list of the contractually required submittals in a spreadsheet format, showing each submittal and sample specified in the contract, exactly where it is specified (section and paragraph), the category of submittal (design phase, administrative plan, catalog information, shop drawings; etc.). The register includes columns that will be used by the contractor to manage and track future actions taken on each submittal by the pertinent contractual parties. (For example, the date submitted to various parties and dates of approvals, rejections and resubmittals, etc.) A crucial contractor entry to the register is a valid date that the submittal is needed "back"—accepted or approved—in order to meet the schedule for design (if design-build contract), and for procurement, delivery, and installation of material or equipment in the construction contract. The register will also be referred to by the A-E and owner to track and validate the contractual actions taken. Once accepted, typically by the owner's representative, the submittal register—commonly referred to as the *submittal log*—becomes a tracking tool that is updated every time any action is taken on a submittal, be it an initial submission, approval, rejection, or resubmittal. A sample *submittal register/log* is in Appendix I.

10.3 (Element 12c) Documents and Tracking Systems for the Three-Phase Control Process

As previously elaborated (in Section 9, Paragraph 9.8), the quality control process of *three phases of control—preparatory, initial, and follow-up* is integral to the quality control program established by the contractor. These three control phases are applied to each separate category of construction activity or building system (known also as a "definable feature of work" or "DFOW") on the project schedule. Although numerous construction projects may have some similar construction systems and building trades, typically each individual construction project will have a unique assemblage of building materials, installed equipment, building systems and associated trades as well as a unique project schedule that enables integration of the disparate components into a completed facility.

Each individual project, then, has its own unique variety and combination of major construction activities. In order for the quality control process to be effective, the QC organization applies the three-phase control process to each significant activity (DFOW) in the particular construction project.

The Contractor's QC Plan—Definable Features of Work (*DFOW*)*:* An elemental part of the contractor's QC planning is to identify the major schedule activities or grouping of schedule activities which will be the logical *definable features of work*, and to propose the appropriate *DFOWs* in the QC Plan. As the heart of the QC effort, the three-phase control process needs to be well documented, effectively tracked and validated; and the documents easily accessed. Four related documentation efforts establish and support the three-phase control processes:

- *A project-specific list of Definable Features of Work* (*DFOWs*)*:* Based on the structures, equipment, systems, and finishes specified and scheduled, the construction activities to be monitored through the three-phase control process are identified and listed in the plan. It is important that each DFOW on this list be cross-referenced to the appropriate schedule activity or cluster of schedule activities by the relevant schedule identification number (or other relevant nomenclature) from the project schedule.
- *Preparatory and Initial Phases—Conference Agendas with Checklists* for each DFOW: As part of the QC Plan, the contractor develops *conference agendas* and associated *checklists* for use at the preparatory and initial phase conferences for each DFOW.

  The *checklists* for *preparatory* and *initial phase conferences* are each in a generic, "fill-in-the-blanks" format submitted in the QC Plan. The conference checklists are used, respectively; at all preparatory and initial phase meetings (refer to General Documentation, Element 12a, Paragraph 10.1 above.

  System-specific quality checklists for the *preparatory phase* and the *initial phase* are unique for each separate DFOW; are submitted in the plan; and are cross-referenced to the relevant specification section(s), as appropriate. The checklists contain quality "checks" that the QC manager and staff, or both, will employ to verify the quality of the specific construction activities that comprise the DFOW. The quality checks typically are based on (1) the requirements of the contract drawings and specifications, (2) referenced specifications and standards, (3) accepted industry workmanship standards, and (4) the knowledge and experience of the construction contractor's production and QC staff. Samples of the *quality checklist format* for the *Preparatory Phase* and the *Initial Phase* are found, respectively, in Appendices G and H.

  There have been two basic schools of thought on the timing associated with the development of the preparatory and initial phase checklists: (1) The first view is that the quality checklists should be *fully developed in the submitted QC Plan*, allowing the contractor to "hit the ground running" proactively as opposed to reacting with late-emerging quality checks as construction starts. This approach also permits the owner's representative an early assessment of the contractor's methodology. (2) The second view is that the (essentially "blank") standard-issue quality checklist format be available in the QC Plan for development "later." Each "blank" checklist in the QC Plan would list the appropriate *definable feature of work*, cross-referenced to the appropriate specification section—with no checklist items yet entered on the form. The actual quality "checks" would be developed later and inserted by filling in the blanks *prior to and during the preparatory or initial phase meetings*. Supporters of the second approach consider it more realistic, allowing earlier submission of the QC Plan and taking advantage of the synergy accruing with more trade/discipline expertise available on the jobsite during construction.

  The most feasible and advantageous approach is probably found in a third, less-articulated view—a basic list of checks is submitted by the contractor with the QC Plan, to be enhanced and refined on the job well before the work starts on the DFOW and to be completed during the preparatory and initial phase meetings. An approach that includes more rather than less in the initial QC Plan submission is really most appropriate. This is supported by the electronic availability of this type of information. Many contractors have their own previously-developed corporate knowledge in the form of quality checklists. Also, there is an emerging availability of vast electronic databases with QC checklists developed by industry authorities or large government entities such as the U.S. Army Corps of Engineers. In any case, further enhancement of a quality checklist can also occur as a result of the owner's review, incorporating the owner's "lessons learned." The checklist, however, remains the contractor's responsibility.

  Tracking Log for Preparatory Phases and Initial Phases: The log serves as a quick reference tool to help manage the quality effort and to assess the status and timeliness of the proactive QC approach. The tracking log document is simply an extension of the *list of definable features of work*—a spreadsheet listing the DFOW—with columns showing: (i) the applicable specification section(s) for each DFOW; (ii) the applicable schedule activity numbers for each DFOW; (iii) the scheduled dates for each preparatory and initial phase meeting; and (iv) the actual dates of occurrences of each preparatory phase meeting and initial phase meeting. As the planned construction schedule is periodically revised, the quality control manager must be conversant daily with the project schedule. The QC manager needs to consider whether or not the planned dates for the preparatory and initial phases should be changed and accordingly updated in the log. (*Note:* If the construction schedule is structured to show the dates of the preparatory and initial phases of control; a regularly updated schedule "sort" of quality control activities could serve as the tracking log for "preps" and "initials." This would also have the sophistication of indicating "early" and "late" start and finish dates.)

Reference System for Documentation of the Preparatory and Initial Phases of Control: In the field, after the contractor conducts the preparatory or initial phase conference for a DFOW, the contractor's conference record/checklist is attached to the daily report, submitted to the owner's representative, and a copy filed by the contractor with all the daily reports. The conference is documented on the preparatory and initial phase checklist forms. The preparatory phase and initial phase meeting records are important documents for the prime contractor, subcontractor and the owner's representative. These conference records help to confirm approaches to and agreements on workmanship, and often they need to be consulted "down the road" when a quality matter or issue subsequently arises. On a large project, daily reports are (hopefully chronologically) immersed in extensive files covering a long period of time, and the attached preparatory and initial phase records are scattered and possibly "buried" within this milieu. Efficiency concerns have prompted the field use of a simple reference system for easy retrieval of documentation covering each preparatory and each initial phases of control. The first part of the reference system is the preparatory and initial phase log described above; and the second is a simple three-ring binder containing the record (conference minutes and checklist) of each preparatory and initial phase conference. The log is in the front of the binder, and the binder can be organized by order of date, schedule activity number, or specification section. This information can also be readily accessed.

Notes on Documentation for the Preparatory and Initial Phases:

(1) The (generic) *conference agendas for the preparatory or initial phase* and (project-specific) *checklists for the preparatory or initial phase* (see Element 12a and 12c) are usually combined into one document.

(2) If the project is electronically documented throughout, access to the preparatory and initial phase records is usually much less of a problem.

(3) If the construction schedule is loaded with and contains the planned and actual dates for each preparatory and initial phase meeting—and is updated regularly, communication between the production and quality teams will be enhanced, leading to better management of both production and quality. Some owners require this approach to scheduling.

(4) Project teams that have implemented electronic documentation, and have incorporated the preparatory and initial phases into the construction schedule document, are ahead of the game in efficiency and effectiveness. This does not suggest that teams should do away with the "hard-copy" version of the log and reference system for preparatory and initial phases. The three-ring binder usually works well in the field to obtain ready access to details of the preparatory and initial phases of control.

10.4 (Element 12d) Testing Plan and Log

The *testing process* was previously discussed in Section 9, Paragraph 9.9. The *Testing Plan and Log* is used to list, schedule, and track all of the specified testing for a construction project; including sampling and testing by the prime and subcontractors, manufacturer's representatives, third-party testing firms, and consultants on site. It should also cover specified sampling and testing to be done off-site for custom fabrications, such as precast concrete, structural steel, and curtainwall systems. The "plan" portion covers the test requirements and responsible entity, while the "log" portion documents who did what and when. A sample *Testing Plan and Log* format is found in Appendix J.

The Contractor's QC Plan—Testing Plan and Log: The *testing plan and log* is a spreadsheet which lists each specified requirement for sampling or testing, in order of specification section and paragraph number. The type of test is named in accordance with the specified industry nomenclature; the required frequency is clearly indicated; and the responsible organization or person, or both, have been specifically identified. Columns are available for the QC staff to record and track the actions taken during construction, including when performed, location of test, by whom, whether the test is satisfactory or not, and any retesting effort/results when necessary.

10.5 (Element 12e) Deficiency/Rework Log

As noted in Section 9, Paragraph 9.10, Procedures to Correct Defects, the contractor's QC staff proactively identifies and tracks the correction of deficiencies, using the daily QC report to document problems and actions taken. In addition, the QC staff uses a *deficiency/rework tracking log* to record and track construction work activities that are deficient, and require remediation or replacement in order to meet the contract requirements.

The Contractor's QC Plan—Deficiencies and Rework: The QC Plan should include the *Deficiency/Rework Tracking Log*, a spreadsheet that identifies the nature of the defect (requiring either rework or replacement); the schedule activity number of the work under scrutiny; the location of the defect in relation to the building configuration and the project drawings; the applicable drawing number and detail or section that depicts the work in question; and the applicable specification section and paragraph that specifies the nature of the work. Columns will be included to fill in pertinent information such as the date the defect was discovered; the party responsible for correction and how the responsible entity was notified; any interim actions taken; and the date the defect was corrected. A sample of the *deficiency/rework tracking log* is found in Appendix K.

Internal Notification: Experienced contractors will often also employ a standard internal form to notify the responsible subcontractor foremen (in the field) and the responsible subcontractor project managers (in their home office) of their responsibility to fix a defect. The form may have a space for the recipient to respond when the defect is corrected.

10.6 (Element 12f) Completion Inspection Matrix

The *completion inspection process* was previously discussed in Section 9, Paragraph 9.11. The contractor/subcontractor participants and attendees in each stage of the three-stage completion inspection process should be identified in the QC Plan. The dates of the inspections should be planned in the project schedule based on the specified timelines therein and the contractual completion date. However, the actual scheduling of each of these will ultimately be based, in large part, on the efficacy of the contractor, the weather; actions of the owner; and the relationship (or lack thereof) between the contractor and the owner. It is also likely that some of the names of those responsible for the prime's effort and the subcontractors, efforts during the final inspection stages will change as the project evolves and winds toward completion

The Contractor's QC Plan should include a *completion and turnover matrix*, including:

A list of the completion activities and turnover items, such as:

- System acceptance inspections for each system;
- System O&M manuals for each system;
- System training for each system;
- "As-Built" drawings and other documents to turn over to the owner;
- Keys, spare parts, and any material or equipment to turn over to the owner;
- (Stage 1), "Punch-out" inspection;
- (Stage 2), Pre-final inspection;
- And (Stage 3), Final inspection.
- (Each of the subcontractors/trades is listed as a subcategory under each inspection stage.)

Columns are included on a spreadsheet to enter the following:

- Schedule identification number of each activity;
- Planned dates (based on the construction schedule) of each action or activity;
- Actual dates when each listed action or activity was performed.
- Primary individuals responsible for each of the listed activities, items and documents, including those responsible for conducting systems training, and each person responsible for a trade during the completion inspection process.

As the project nears completion, the matrix should be maintained current by updating to reflect any planned schedule revisions and any personnel changes. It is possible that the completion inspection matrix can be *combined* with the personnel responsibility matrix described following.

10.7 (Element 12g) Quality Matrix

This planning and tracking tool is also sometimes called a *Personnel Responsibility Matrix*. One of the logical first steps in the contractor's quality planning is to figure out who will be doing what regarding the three major quality processes: (1) *submittals;* (2) *three phases of control;* (3) *inspections and testing*. The development and operation of a project-specific quality program centers around these processes, which in turn depend on qualified people with the right expertise. On larger projects, the quality team typically includes a QC manager, QC discipline/trade specialists; submittal reviewers for each discipline (architectural, civil, structural, plumbing, mechanical, electrical, etc.); and testing personnel by specialty or discipline. These skilled personnel may be furnished from the prime contractor, subcontractors, A-E firms, consulting firms, and independent third-party inspection/testing agencies.

The *personnel responsibility matrix* is prepared by the prime contractor. Initially, the matrix can serve as a project-planning tool, outlining the key quality processes and the intended entities/individuals responsible for those processes. It is the foundation from which the project-specific QC Plan can be developed. Once the plan is fully developed, submitted, and approved, the refined and completed matrix becomes a valuable reference to the many quality processes for all players in the project—contractor, A-E, and owner. Although the completed QC Plan can be consulted and any particular "slice" of the needed information likely found in the appropriate section, the personnel matrix provides ready access—in one simple table—to determine who is responsible for each quality process on the project.

The Contractor's QC Plan: The contractor develops a *personnel matrix* in spreadsheet format; showing—*for each section of the specification:*

- The various personnel who will review and approve submittals;
- The various personnel who will perform and document the three phases of control; and
- The various personnel who will perform and document the inspections and testing.

Typically, the specification sections are listed, and columns are provided for the three (or more) categories of quality processes—(1) *submittals;* (2) *three phases of control;* (3) *inspections and testing*. (The last category could be broken into two categories on larger projects. This may make sense when there are a large number of specific inspections of different systems; or when there are several iterative quality inspections of a major system, typically by a third-party expert.)

11 Quality Management and Building Envelope Commissioning

The Relationship Between Quality Management and Commissioning

In order to describe the concept of *Building Envelope Commissioning*, it is useful to first briefly revisit the basics of quality control and quality assurance that have been previously discussed. These precepts are the basic building blocks upon which an effective commissioning process can proceed. Commissioning is a systematic, comprehensive, detailed quality management process that represents an enhancement of—or "quantum-level-leap"—over normal QA/QC processes, but incorporates and depends upon some or all of the quality processes already addressed herein.

This chapter on the quality management of building design and construction is based upon a simple premise—preventing problems is better (and less costly) than fixing problems after they occur. The thesis is—that by planning and implementing proactive processes within a quality control and assurance framework, the potential for consequent tear-out, rework, and wasted cost will be minimized. All parties to the building design and construction process—owner, designer, and builder—benefit in the long run by planning and executing a pro-active quality management approach to the design and construction of facilities.

11.1 Summary of Chapter Tenets

The three major players in the planning, design, and construction of a building are (1) the owner, (2) the designer, and (3) the builder.

Previous sections of the chapter have focused on the following ideas:

(1) Each building project is unique in nature of site, weather, size, scope, and complexity. The building industry is complex, somewhat fragmented, and some players in the construction business are skeptical or resistant to quality measurement measures. All contractors believe that they do quality work and know what it takes to do an adequate job. Most builders genuinely are committed to providing the right materials and good workmanship.

However, some builders feel that too much attention to quality tends to compromise progress—and costs them more. They would rather build it fast and fix things as they go along, letting the subcontractors absorb the rework costs, or hoping the owners won't discern the problem. This attitude, unfortunately, has an impact on the approach of all contractors toward building projects, because the more conscientious firms sometimes have to compete—cost-wise—with less committed firms that often submit low bid prices. Most construction tradesmen are competent and take pride in their work, but the pressure of cost and time for each contractor and subcontractor can lead to compromises in the quality of the tradesmen's work.

(2) *The designer and contractor selected by the owner constitute the most basic steps in determining the quality of the project*. Competitive selection (where competence and experience are evaluated as well as price) for facility design and construction contracts levels the playing field between competing firms of differing capabilities.

- For *design contracts*, facility owners usually employ *competitive selection* of design firms (architect-engineer or A-E), as the industry norm.
- For *construction contracts*, *competitive selection* of construction contractors (in lieu of low-bid contracting) is a preferable approach when building facilities with some degree of complexity.
- Under a *design-build contract*, facility owners usually employ *competitive selection* of a design-build entity (often a general contractor in joint venture with an A-E firm) to manage both design and construction.

(3) Each party to a facility project—the (1) *owner*, (2) *designer*, and (3) *builder* (general contractor)—need to effectively plan and coordinate the procurement, design and construction of a building. *Construction management* (*CM*) firms can provide the expertise to help the facility owner manage the design and construction of a building project.

The relative "levelness" of the playing field is further enhanced by requiring competing firms to provide an *internal quality control program* if awarded a project: (a) For the facility design phase, this means that quality reviews and revisions of design stages—including third-party expertise—must be considered in the cost structure of each competing architect-engineer's fee proposal. (b) For the facility construction phase, this means that management to ensure quality of materials and workmanship needs to be factored into each competing contracting firm's proposed contract costs.

(4) The building design process involves development of the project scope to meet the owner's needs, followed by an evolving design that is checked at predetermined progress intervals by knowledgeable design and construction representatives for the owner, as well as by third parties retained by the A-E.

(5) Ideally, the owner requires and explicitly specifies that the construction contractor employ a project quality control program to verify both off-site fabrication and on-site construction. Typical QC processes include quality meetings and conferences, review and approval of technical submittals; agendas for performing quality controls, tests and inspections while timely coordinating with the construction sequence of work; acceptance and rejection of materials, equipment, and workmanship; tracking of corrective work; and completion inspections.

(6) During construction, the owner typically provides quality assurance oversight (either using his own forces, his designer, or a construction management firm). The construction contractor should provide day-to-day quality control of construction. The construction contractor's project team consists of production and schedule management personnel cooperating with quality control management staff. Mutual cooperation, scheduling and integration of quality processes with the construction sequence ensure that quality gets "built in" without delays or rework. This integrated approach ensures building to the owner's specified needs; helps the contractor earn a reasonable profit, and enhances his reputation in the industry, generating more business for the construction firm.

(7) Honest, open, prompt communication and coordination between the key players—owner, designer, and constructor—is the only good policy, even if there is disagreement.

(8) Owners should specify a construction contractor-prepared quality control plan for a construction project. Effective contractors—as part of their internal management policy—need to have a systematic framework of QC processes, within which a detailed project-specific plan is developed for each construction contract.

(9) Effective project-specific QC plans need to address the specific characteristics of a building, such as the technical details of the *building envelope/enclosure*. The building enclosure is the facility's line of defense against the elements of site conditions, weather, cold, heat loss and gain, vapor transmission, air infiltration, and of course, water infiltration/leaks. The building envelope also needs to work properly to ensure the proper function of the interior space conditioning system.

- One approach for more complex building enclosures is for owners to specify that the contractor assemble and test a *mock-up* on the building site—before constructing the envelope of the structure—to demonstrate the effective integration of the various components into seamless foundation, wall, fenestration and roof systems that will meet the owner's specified needs.

- Another approach—one which relies upon and coordinates with the quality management processes here discussed (and which often can include mock-ups)—is for owners to specify *building envelope commissioning*. This is discussed below under the paragraph *An Approach to Building Envelope Commissioning*.

(10) Effective, complete documentation of progress, quality and test results is essential for all participants in the building project—owner/owner's CM / third-party consultants; designer (architect-engineer); and building contractor.

11.2 An Approach to Building Envelope Commissioning

The advantage of independent third-party expertise in building envelope design and construction; and the use of commissioning of building systems was previously addressed in cursory fashion in Paragraphs 3.10 and 3.11, Section 3; and Paragraph 8.6, Section 8 of this chapter.

A *Building Envelope Commissioning* process has been developed within the facility design and construction field in response to the following conditions and needs:

Why Perform Building Envelope Commissioning?

As with quality control and quality assurance programs, commissioning of building systems was developed in response to building to envelope failures that can wreak havoc on user comfort, productivity, and costs. Building envelope shortcomings have plagued the construction industry for years, and such construction quality issues can arise on simple as well as complex projects. Of course, large and complex projects that encounter these kinds of failures experience significant adverse impact.

Building envelope commissioning can help the owner achieve his ultimate specified end needs, including user comfort, functionality, lower life cycle maintenance cost, and expected building life span. Buildings with a complex end-use for the customer are more susceptible to a need for a commissioning, because the effect of poor building performance on the mission of the organization and facility is so critical.

Both traditional and evolving technology of building structures and skins entail interfaces between different components, assemblies, and systems. As materials and designs become more sophisticated, the appropriate integration of these disparate building parts becomes even more imperative.

Building materials or components are either prefabricated or built on-site into building assemblies. Assemblies, when put together as a structure or building skin, become a viable building system.

As previously discussed, a construction project is a complex montage of systems installed both in sequence and in overlapping time frames by a number of disparate trades employed both by traditional and specialty subcontractors. The composition of the typical construction contract specification means that each discipline or trade has its own technical specification, sometimes without adequate reference to the separately-specified adjacent systems installed by another trade.

The subcontractors and their tradesmen installing one system or assembly, for example, the building skin, may not be aware of all the subtleties of workmanship that are necessary to properly interface with adjoining assemblies of the wall systems such as doors, windows, curtainwall, masonry facade, etc. Critical features and materials that bridge the gap between adjacent components, assemblies or systems include caulking and sealants, waterproofing, expansion joints and flashing. Construction drawings—as well as the aforementioned specifications—sometimes do not clearly delineate interfaces between adjacent assemblies and systems installed by different trades.

These "facts on the ground" give rise to the need for an overall integrating quality assurance strategy that will go beyond the traditional management and coordination responsibility of the general contractor and his project quality control efforts.

What Projects are Appropriate for Building Envelope Commissioning?

Building Envelope Commissioning can be developed for any construction project. Initial quality assurance cost for commissioning varies greatly, depending on commissioning scope. Typically, the additional cost varies in a range under 1 % of total project cost. Because of the potential long-term positive payoff to owners, the most cost effective application of building envelope commissioning may be on large projects, complex projects, as well as more moderate-sized projects of complexity. Examples of projects that would likely benefit from this process would be manufacturing facilities; high-technology facilities and laboratories; hospitals; projects requiring sustainable design, green building precepts, LEED requirements, etc; and any large structure where there is a considerable workforce that would be adversely affected by failures in the building envelope.

However, with the increasing cost of energy, and political and consumer awareness of the need to protect the environment—as well as this country's necessary vision to become less dependent on imported oil, building commissioning may eventually be seen as a cost-effective quality process for even small and routine projects. The scope and cost of commissioning for smaller, less complex projects is proportionally less than the cost for larger, complex projects. Time is money. Consequently, an owner's prudent investment up-front in a quality assurance program incorporating building envelope commissioning can provide the owner with tremendous downstream leverage in potential cost and time savings.

This chapter previously addressed contractual methods under Section 2. It is worth repeating that *hiring the right designer with the right expertise and the right contractor with the necessary experience and skills to build the desired project is paramount as the baseline foundation of a quality project*. Although not addressed in any significant fashion in Section 2, owners with special needs may want to consider contractual methods that include limited cost-plus provisions for certain sophisticated or new technologies incorporated in the building envelope, for building envelope mock-ups, or for testing representative sections of the building enclosure.

Owners who intend to follow this course need to have the appropriate budget to support their specific needs, and contracts may need to incorporate some flexibility in the cost of building envelope commissioning, since there are sometimes design options for different materials, components, and assemblies to be selected by the contractor. Therefore, the cost of building envelope commissioning depends not only on the scope of the commissioning effort, but to some degree on the possible uncertainty during design/development of the exact building configuration that will be selected during the construction phase.

Who Performs Building Envelope Commissioning?

Building Envelope Commissioning is performed by construction production staff, construction quality control staff, and owners' quality assurance entities. All parties to the building process are involved. This includes the contractor and the applicable subcontractors, the designer, and—importantly—the owner and owner's construction manager.

Finally, a commissioning "czar"—if you will—an *independent, third-party commissioning authority* provides the necessary leadership and management of the building envelope commissioning process, providing enhanced quality assurance. This authority is retained by the owner and is called the *Building Envelope Commissioning Agency or Agent* (*BECA*). In some cases, facility owners may specify that the BECA be provided in the construction contract as part of the contractor's overall QC/QA responsibility.

The BECA needs to be a qualified, independent agency or consultant, with the appropriate technical credentials and documented experience in managing building enclosure commissioning on similar previous projects. The BECA (Agency) provides a BECA (Agent) manager for the project. As is the case with the contractor's quality control manager, the owner's (or contractor's, as appropriate) BECA manager for quality assurance on-site really has to be a technical expert (in this case as regards building envelopes). The BECA manager must be given sufficient authority to positively influence the outcome of project quality.

In summary, the Commissioning Team assembled under the BECA, typically consists of the following players:

- Owner and owner's design and CM consultants;
- Building Envelope Commissioning Agency and BECA Manager;
- Architect/Engineer of record;
- General contractor;
- Building envelope trade subcontractors, specialty subcontractors;
- Building envelope suppliers and authorized system manufacturers representatives;
- Test personnel provided by the independent BECA agency, independent testing laboratories, or contractor trades, as appropriate and specified by the owner.

How Does the Owner Specify Commissioning?

A few jurisdictions have recently developed standard guide specifications for building envelope commissioning during construction. See Section 3, Paragraph 3.11 for a relevant standard by the National Institute of Building Science (NIBS). The owner, using the expertise of his designer and construction manager, as well as the BECA, as appropriate, will tailor the building commissioning specifications to the project-specific needs.

Commissioning of the building envelope on a construction project will affect the time and cost of contractor effort, including production and specialty trades labor, contractor quality control, and associated testing. During the contractor selection/cost proposal process, general contractors need to bid a legitimate contract price based on an owner's construction documents that are complete, including a comprehensive owner commissioning specification. The construction contractors who will compete for the project must be able to accurately discern the scope of the commissioning effort, and clearly be informed of who will do what.

In the case when the *owner* furnishes the BECA during the construction phase of a construction or design-build project, the owner's specification for construction must advise the general contractor of the commissioning requirements that will be required. The implementation of commissioning by the owner's BECA will include the general contactor and his subcontractors as key players on the commissioning team.

If, alternatively, the *general contractor* is to provide the BECA under the owner's construction or design-build contract, the construction specifications should naturally explicitly specify the role of the general contractor in managing and implementing his *own* commissioning program—by using an independent, third-party BECA (approved by the owner) to validate conformance with the owner's quality requirements.

Building Envelope Commissioning Starts with a Good Design

As noted above, the expertise of the designer in developing an appropriate and complete design of the building envelope is paramount. The project architect-engineer of record [either: (a) responsible to support the owner during the owner's separate construction-contract, or (b) responsible to support the general-contractor under the owner's design-build contract] must be open and amenable to collaboration with—and design reviews by—the construction team of owner, owner's construction manager, and the BECA. The knowledge and expertise of the CM (when applicable) and BECA in building envelope configurations, interfacing system details, and test procedures should be tapped and incorporated into the A-E's design evolution. The design should consider long-term life-cycle costs and operation and maintenance costs, as well. Two typical contractual situations are noted below:

- If the owner will provide the BECA during a construction project, it is advisable and highly advantageous for the owner to retain the BECA during the owner's design stage of the project to (1) critique the building envelope design as it evolves, as well as (2) contribute to the commissioning specification development.
- In the case of a design-build contract with a contractor-furnished BECA, the contractor's BECA should, similarly, be actively involved during the contractor's and owner's design reviews of the design-build contractor's construction documents (plans and specifications) for the building envelope.

Quality Assurance and Quality Control

The *quality assurance* effort provided by the BECA during construction under *building envelope* commissioning is intended to validate and provide supplemental oversight to the *quality verification* processes inherent in the contractor's *project quality control program*. Commissioning Q.A. is intended to complement—rather than replace—contractor QC efforts.

What are the Responsibilities of the Building Envelope Commissioning Team During Construction?

- If the BECA is retained during the design process, the BECA should be employed as a key partner in design concept critiques and design reviews of the construction plans and specifications for the building envelope developed by the A-E of Record.
- The BECA will lead, manage, and coordinate the process of building envelope commissioning during construction.
- The general contractor and his quality control manager will ensure that the BECA receives all technical submittals and shop drawings prepared by the contractor (including subcontractors and suppliers/manufacturers). The BECA will monitor A-E reviews and approvals.
- The Architect-Engineer of Record (the designer) will review and approve all technical submittals for the building envelope.
- The BECA conducts system coordination reviews of all submittals entailing the building envelope.
- The BECA will conduct all commissioning meetings, including a kick-off/scope meeting and regular commissioning meetings to drive and coordinate the activities of the commissioning team.
- The General Contractor, contractor quality control staff, and building envelope subcontractors will attend commissioning meetings.
- Subcontractors in particular will each contribute information about their specific "piece of the pie." Concurrently, each subcontractor will gain an understanding of how their work interfaces with the overall project and other subcontractor trades.
- The contractor's QC manager and staff must coordinate his contractual responsibilities with the BECA QA effort, and vice versa.
- Testing will be provided (as specified in the owner-prepared contract documents) by the BECA, independent testing labs, or trade, as appropriate.
- The BECA will oversee the conduct of field testing and functional performance testing, including air, vapor, water, and thermal testing, etc.
- The BECA will monitor and track all testing activities, and will follow up to ensure that unsatisfactory or failed tests result in corrective action by the contractor and retesting by the appropriate party.
- The BECA will document all commissioning activities, field testing, and functional performance testing.

What are the Processes Involved in Building Envelope Commissioning?

- Careful review and critique of the design details—especially at the interfaces between material components, assemblies and systems.
- Consideration during design and construction of life-cycle costs and O&M costs.
- Monitoring and coordination of technical submittals and system shop drawings.
- Verification of manufacturer's testing of building envelope components.
- Monitor installation of assemblies, systems and mock-ups (as required by owner's specification).
- Integration of field production and quality effort through regular communications and commissioning meetings.
- Development of field testing protocols.
- Development of field sampling techniques to evaluate building components, assemblies and systems.
- Development of field mock-ups where appropriate.
- Field Verification: Incremental in-process inspection and testing as building envelope is assembled.
- Functional performance testing under simulated or actual conditions.

In-Process Inspection and Testing

The periodic, incremental, repetitive nature of the in-process tests and inspections is intended to ensure that rework is minimized. Frequent inspections and tests of mock-ups(as necessary); and of either sample areas or the entire envelope are conducted in order to assure that components are being assembled with the required integrity to withstand specified levels of resistance to air and water infiltration as well as vapor permeability and heat transfer. Inspections and tests assure continuity, strength and durability of vapor barriers, air barriers, thermal insulation, and water barriers.

Plans for the quality evaluation and testing of building envelope assemblies are addressed in Paragraphs 8.7 through 8.11 of Section 8 as regards the contractor quality control program. QC plans for testing and inspection are further outlined in Paragraph 9.9. A representative list of potential building envelope tests is provided in Fig. 5(*b*), Section 9. The quality evaluation concepts addressed in the previous sections focused on quality control are easily transferable to the structured quality assurance regimen of building envelope commissioning.

Assemblies and Mockups: The BECA's testing protocol cannot be fully developed without understanding the construction sequence. Conversely, inspection and testing may lead to an improved construction sequence and coordination between trades. Rework or fine-tuning of the construction sequence can occur in small bits and pieces before the entire building is put together. In this vein, the use of either (1) "sample" free-standing *mock-up* assemblies, or (2) sample areas built into the finished envelope can prove effective, but must be considered as appropriate contract costs by the owner and contractor. See the discussion under Paragraph 9.11, which contains an explanation of the process of evaluating and testing mockups of building systems. Appendix C of this chapter includes further tips on the mock-up process.

Functional Performance Testing

The "bottom-line" for the commissioning process is the functional performance testing of the building envelope after it has been built. However, if the contractor or owner waits until the end of the project to do any significant testing, difficult problems may emerge that are costly, time-consuming, and perhaps virtually impossible to effectively correct. Therefore, functional performance testing of weather-tightness, thermal and vapor transmission properties of the finished building envelope necessarily occurs as the culminating event following previous field tests. Functional performance tests will likely be successful if they follow the series of in-process tests that were incrementally conducted while components were built into assemblies, and assemblies constructed into building systems. This iterative process enhances the probability that each building system is properly interfaced and integrated into the entire building envelope as a whole entity.

Ideally, functional performance tests could be performed under actual conditions of building seasonal variations, weather and use, but practically a test protocol of simulated conditions will often be most practical and ultimately appropriate. In order to create the appropriate simulated conditions, however, temporary environmental chambers may have to be built on the outside of the building, or representative portions of the building envelope that have been randomly selected as appropriate sample areas. Such protocols need to be built into the project cost, either by the owner specifying such an approach "up-front," or by a mutually agreed contract change.

Depending on the nature of the building envelope and the owner's requirements, some of the parameters to be tested could include those listed below. The needed tests must be based on established ASTM (see Appendix B) or other standards (as addressed in other chapters of this manual).

- Building ventilation for sufficient air exchange and indoor air quality;
- Vapor transmission/permeability characteristics of materials intended as vapor barriers;
- Heat transfer rates for thermal insulation;
- Air infiltration resistance of air barriers;
- Seasonal air leak detection ("hot-spots" in winter; "cold spots" in summer) using infrared scanning of the envelope when the interior is pressurized;
- Leak testing protocols for building envelope assemblies;
- Water conveying capacity and infiltration resistance of roof and other drainage planes;
- Wind and water infiltration resistance of fenestration assemblies;
- Adhesion characteristics of thermal insulation, vapor barrier or air barrier to substrate;
- Wet and dry film-thickness measurements of liquid-applied membranes.

  If the tests show deficiencies, rework and re-testing may be required.

Final performance evaluation and testing for building envelope function under building envelope commissioning assures that the project not only appears to be substantially complete, but has actually met the standards required by the owner's construction specification.

Appendix A: Organizations for Building Code Standards

ICC

International Code Council
5203 Leesburg Pike
Suite 600
Falls Church, Virginia 22041-3401
703-931-4533

BOCA

Building Officials and Code Administrators International, Inc.
4051 West Flossmoor Road
Country Club Hills, Illinois 60478-5795
800-214-4321 www.BOCAI.org

ICBO

International Conference of Building Officials
5360 Workman Mill Road
Whittier, California 90601-2298
800-284-4406 www.ICBO.org

SBCC

Southern Building Code Congress International, Inc.
900 Montclair Road
Birmingham, Alabama 35213-1206
877-442-6337 www.sbcci.org

Appendix B: Organizations for Workmanship Standards

ASTM	ASTM International 100 Barr Harbor Drive, PO Box C700 West Conshohocken, Pennsylvania 19428-2959 www.astm.org 610-832-9585
ANSI	American National Standards Institute 1819 L. Street, NW Suite 600 Washington, DC 20036 202-293-8020 www.ansi.org
ACI	American Concrete Institute P.O. Box 9094 Farmington Hills, Michigan 48333-9094 248-848-3700 www.aci-int.org
ASCE	American Society of Civil Engineers 1801 Alexander Bell Drive Reston, Virginia 20191-4400 703-295-6000 www.asce.org

ASHRAE
American Society of Heating, Refrigerating and Air-Conditioning Engineers, Inc.
1791 Tullie Circle, N.E.
Atlanta, Georgia 30329
404-636-8400 www.ashrae.org

AAMA
American Architectural Manufacturers Association
1827 Walden Office Square
Suite 550
Schaumburg, Illinois 60173
847-303-5664 www.aamanet.org

AISC
American Institute of Steel Construction
One East Wacker Drive, Suite 3100
Chicago, Illinois 60601-2001
312-670-2400 www.aisc.org

AITC
American Institute of Timber Construction
7012 Revere Parkway, Suite 140
Englewood, Colorado
303-792-9559 www.aitc-glulam.org

BIA
Brick Industry Association
11490 Commerce Park Drive
Reston, Virginia 20191-1525
703-620-0010 www.bia.org

EWA
APA The Engineered Wood Association
7011 South 19th
Tacoma, Washington 98466
253-565-6600 www.apawood.org

FHA
Federal Highway Administration–National Highway Specification
400 Seventh Street, SW
Washington, DC 20590
www.fhwa.dot.gov

GA
Gypsum Association
810 First Street NE, #510
Washington, DC 2002
202-289-5440 www.gypsum.org

NFPA
National Fire Protection Association, Inc.
One Battery March Park
Quincy, Massachusetts 02269
617-770-3000 www.nfpa.org

UL
Underwriters Laboratories, Inc.
333 Pfingsten Road
Northbrook, Illinois 60062-2096
847-272-8800 www.ul.com

NCMA
National Concrete Masonry Association
13750 Sunrise Valley Drive
Herndon, Virginia 20171-4662
703-713-1900 www.hcma.org

PCA
Portland Cement Association
5420 Old Orchard Road
Skokie, Illinois 60077
847-966-6200 www.cement.org

PTI
Post Tensioning Institute
8601 N. Black Canyon, Suite 103
Phoenix, Arizona 85021
602-870-7540 www.post-tension.org

PCI
Precast/Prestressed Concrete Institute
209 W. Jackson Boulevard, #500
Chicago, Illinois 60606-6938
312-786-0300, www.pci.org

NECA
National Electrical Contractors Association
3 Bethesda Metro Center, Suite 1100
Bethesda, Maryland
301-657-3110 www.neca-neis.org

SMACNA
Sheet Metal and Air Conditioning Contractor's National Association
4201 Lafayette Center Drive
Chantilly, Virginia 20151-1209
703-803-2980 www.smacna.org

EDI
Exterior Design Institute–(EIFS)
1531 Barley Street
Norfolk, Virginia 23502-1603
800-742-5576
www.exterior-design-inst.com
www.eifshotline.org

MBMA
Metal Building Manufacturers Association
1300 Sumner Avenue
Cleveland, Ohio 44115-2851
216-241-7333 www.mbma.org

AWI
Architectural Woodwork Institute
46179 Westlake Dr., Ste 120
Potomac Falls, Va 20165
571-323-3636 www.awinet.org

AWS
American Welding Society
550 N.W. LeJenne Road
Miami, Florida 33126
305-443-9353 www.aws.org

WWPA
Western Wood Products Association
522 SW Fifth Avenue

	Portland, Oregon 97204-2122 503-224-3930 www.wwpa.org
AFPA	American Forest and Paper Association
AWC	American Wood Council/AFPA 1111 19th Street, NW, Suite 800 Washington, DC 20036 202-463-4713 www.awc.org
SSPC	Society for Protective Coatings 40 24th Street, 6th Floor Pittsburgh, Pennsylvania 15222-4656 412-281-2331 www.sspc.org

Appendix C: Mock-up Guidance

Tips for Success

- When the building enclosure is complex and otherwise crucial to the success of the project, or both, owners are well advised to include the provision of a mock-up in the project budget; and to adequately specify a building enclosure mock-up in the project contract documents.
- Mock-ups provide the ability to view building enclosure component wall systems, and to witness incrementally conducted water tests at critical stages of assembly, as the various components of the mock-up are sequentially put together.
- The building enclosure mock-up must be completed in adequate time to allow the debugging of the building enclosure system prior to fabrication of the system components.
- Mock-ups are time-critical, and must be included on the project schedule.
- It is extremely important that the Architect/Engineer, Owner, and Independent Third-Party Design/Testing Professional all participate in the mock-up review. All details should be reviewed in the sequence of proposed installation, for example: connection to the structure, framing, miscellaneous anchorage, flashing, weep system, coping, joints, and adjacent material relationships, etc.
- Contractors are advised not to build a mock-up that cannot be repetitively duplicated when constructing the building enclosure under the realistic condition of continuous field production on the project site.
- Do not build a mock-up that you don't have the budget to provide.
- The mock-up should represent the requirements of the building enclosure shown in the contract documents.
- For all mock-ups, provide field documentation and a quality control inspection report for each incremental step of the mock-up that is installed. Fully document the mock-up (photos, video, etc.).
- Procedures for incremental water testing of the mock-up and the installed building envelope should be generated within a project quality control plan.

  Should project documents require an off-site mock-up/test, owners should (1) require a formal submittal of mock-up shop drawings from the manufacturer/subcontractor; (2) specify that a qualified independent testing laboratory witness the assembly of mock-up components and oversee/conduct the incremental testing; and (3) verify that the laboratory testing facility will document all test data as well as the actual construction of the mock-up.

Appendix D: Deficiency/Rework Tracking Guidelines

Inspection Discrepancy Procedure

Intended as an inspection system whereby all discrepancies in quality, workmanship, materials, equipment, supplies, and unauthorized deviations, or a combination thereof, from engineering requirements on specifications can be called to the attention of responsible supervision personnel.

1. Discrepancies will be recorded on the Quality Control Daily report form. Each discrepancy will be assigned a number by the recording Quality Control Manager. A concise statement locating the discrepancy and description of the discrepancy will be filled in by the Quality Control Manager.
2. When material, equipment, supplies, or workmanship that does not conform to the contract drawings or specifications are rejected, the rejecting Quality Control Manager will initiate a discrepancy report and immediately furnish copies to the contractor's Project Manager and Superintendent or Subcontractor's Job Representative.
3. Upon reviewing the discrepancy report, the Quality Control Manager will examine the rejected items. If in his opinion any of the rejected items can be reworked to a usable condition, the discrepancy report will be so noted. However, if in his opinion the item cannot be reworked, either from a practical and economical standpoint, the item shall be scrapped and an entry made on the discrepancy report concluded to that effect.
4. Upon completion of rework on items specified for rework, the Quality Control Manager will be notified and he will reinspect the item(s) to the original requirement plus the rework information on the discrepancy report. If it is found acceptable, the discrepancy report will be so noted. From this point on, the item(s) will be handled in the normal manner. If however, the item(s) is still not acceptable to the Quality Control Manager due to poor workmanship, etc., arising from the rework, we will treat this item as a first time rejection and this will be resubmitted for inspection only after further rework.
5. The discrepancy report log will be periodically reviewed by the Project Manager with the Quality Control Manager to formulate a disposition of each listed uncorrected discrepancy. They will establish timetables for final resolution of all discrepancies.

APPENDIX E - CONTRACTOR PRODUCTION REPORT

(ATTACH ADDITIONAL SHEETS IF NECESSARY)

CONTRACT NO	TITLE AND LOCATION		DATE REPORT NO	
CONTRACTOR		SUPERINTENDENT		
AM WEATHER	PM WEATHER		MAX TEMP (F)	MIN TEMP (F)

WORK PERFORMED TODAY

Schedule Activity No.	WORK LOCATION AND DESCRIPTION	EMPLOYER	NUMBER	TRADE	HRS

JOB SAFETY	WAS A JOB SAFETY MEETING HELD THIS DATE? (If YES attach copy of the meeting minutes)	☐ YES	☐ NO	TOTAL WORK HOURS ON JOB SITE, THIS DATE, INCL CON'T SHEETS	
	WERE THERE ANY LOST TIME ACCIDENTS THIS DATE? (If YES attach copy of completed OSHA report)	☐ YES	☐ NO	CUMULATIVE TOTAL OF WORK HOURS FROM PREVIOUS REPORT	
WAS CRANE/MANLIFT/TRENCHING/SCAFFOLD/HV ELEC/HIGH WORK/ HAZMAT WORK DONE? (If YES attach statement or checklist showing inspection performed.)		☐ YES	☐ NO	TOTAL WORK HOURS FROM START OF CONSTRUCTION	
WAS HAZARDOUS MATERIAL/WASTE RELEASED INTO THE ENVIRONMENT? (If YES attach description of incident and proposed action.)		☐ YES	☐ NO		

Schedule Activity No.	LIST SAFETY ACTIONS TAKEN TODAY/SAFETY INSPECTIONS CONDUCTED	☐ SAFETY REQUIREMENTS HAVE BEEN MET.

EQUIPMENT/MATERIAL RECEIVED TODAY TO BE INCORPORATED IN JOB (INDICATE SCHEDULE ACTIVITY NUMBER)

Schedule Activity No.	Submittal #	Description of Equipment/Material Received

CONSTRUCTION AND PLANT EQUIPMENT ON JOB SITE TODAY. INDICATE HOURS USED AND SCHEDULE ACTIVITY NUMBER.

Schedule Activity No.	Owner	Description of Construction Equipment Used Today (incl Make and Model)	Hours Used

Schedule Activity No.	REMARKS

CONTRACTOR/SUPERINTENDENT DATE

APPENDIX F - CONTRACTOR QUALITY CONTROL REPORT

(ATTACH ADDITIONAL SHEETS IF NECESSARY)

DATE

REPORT NO

PHASE	CONTRACT NO	CONTRACT TITLE

PREPARATORY

WAS PREPARATORY PHASE WORK PREFORMED TODAY? YES ☐ NO ☐

IF YES, FILL OUT AND ATTACH SUPPLEMENTAL ***PREPARATORY PHASE CHECKLIST.***

Schedule Activity No.	Definable Feature of Work	Index #

INITIAL

WAS INITIAL PHASE WORK PREFORMED TODAY? YES ☐ NO ☐

IF YES, FILL OUT AND ATTACH SUPPLEMENTAL ***INITIAL PHASE CHECKLIST.***

Schedule Activity No.	Definable Feature of Work	Index #

FOLLOW-UP

WORK COMPLIES WITH CONTRACT AS APPROVED DURING INITIAL PHASE? YES ☐ NO ☐

WORK COMPLIES WITH SAFETY REQUIREMENTS? YES ☐ NO ☐

Schedule Activity No.	Description of Work, Testing Performed & By Whom, Definable Feature of Work, Specification Section, Location and List of Personnel Present

REWORK ITEMS IDENTIFIED TODAY (NOT CORRECTED BY CLOSE OF BUSINESS)		REWORK ITEMS CORRECTED TODAY (FROM REWORK ITEMS LIST)	
Schedule Activity No.	Description	Schedule Activity No.	Description

REMARKS (Also Explain Any Follow-Up Phase Checklist Item From Above That Was Answered "NO"), Manufacturer's Representative On-Site, etc.

Schedule Activity No.	Description

On behalf of the contractor, I certify that this report is complete and correct and equipment and material used and work performed during this reporting period is in compliance with the contract drawings and specifications to the best of my knowledge, except as otherwise noted in this report.

AUTHORIZED QC MANAGER AT SITE DATE

OWNER'S QUALITY ASSURANCE REPORT

DATE

QUALITY ASSURANCE REPRESENTATIVE'S REMARKS AND/OR EXCEPTIONS TO THE REPORT

Schedule Activity No.	Description

OWNER'S QUALITY ASSURANCE MANAGER DATE

APPENDIX G - PREPARATORY PHASE CHECKLIST

(PAGE ONE - CONTINUED ON SECOND PAGE)

CONTRACT NO	DEFINABLE FEATURE OF WORK	SPEC SECTION / SCHEDULE ACT NO.	DATE / INDEX #

PERSONNEL PRESENT

GOVERNMENT REP NOTIFIED ____ HOURS IN ADVANCE: YES ☐ NO ☐

NAME	POSITION	COMPANY/GOVERNMENT

SUBMITTALS

REVIEW SUBMITTALS AND/OR SUBMITTAL REGISTER. HAVE ALL SUBMITTALS BEEN APPROVED? YES ☐ NO ☐

IF NO, WHAT ITEMS HAVE NOT BEEN SUBMITTED? ____________

ARE ALL MATERIALS ON HAND? YES ☐ NO ☐

IF NO, WHAT ITEMS ARE MISSING? ____________

CHECK APPROVED SUBMITTALS AGAINST DELIVERED MATERIAL. (THIS SHOULD BE DONE AS MATERIAL ARRIVES.)

COMMENTS: ____________

MATERIAL STORAGE

ARE MATERIALS STORED PROPERLY? YES ☐ NO ☐

IF NO, WHAT ACTION IS TAKEN? ____________

SPECIFICATIONS

REVIEW EACH PARAGRAPH OF SPECIFICATIONS. ____________

DISCUSS PROCEDURE FOR ACCOMPLISHING THE WORK. ____________

CLARIFY ANY DIFFERENCES. ____________

PRELIMINARY WORK & PERMITS

ENSURE PRELIMINARY WORK IS CORRECT AND PERMITS ARE ON FILE.

IF NOT, WHAT ACTION IS TAKEN? ____________

APPENDIX G - PREPARATORY PHASE CHECKLIST

(PAGE TWO - CONTINUED FROM FIRST PAGE**)**

CONTRACT NO	DEFINABLE FEATURE OF WORK	SPEC SECTION	DATE
		SCHEDULE ACT NO.	INDEX #

TESTING	IDENTIFY TEST TO BE PERFORMED, FREQUENCY, AND BY WHOM.
	WHEN REQUIRED?
	WHERE REQUIRED?
	REVIEW TESTING PLAN.
	HAS TEST FACILITIES BEEN APPROVED?
SAFETY	ACTIVITY HAZARD ANALYSIS APPROVED? YES ☐ NO ☐
	REVIEW APPLICABLE PORTION OF EM 385-1-1.
MEETING COMMENTS	NAVY/ROICC COMMENTS DURING MEETING.
OTHER ITEMS OR REMARKS	OTHER ITEMS OR REMARKS:

QC MANAGER DATE

APPENDIX H - INITIAL PHASE CHECKLIST

	APPENDIX H - INITIAL PHASE CHECKLIST	SPEC SECTION	DATE
CONTRACT NO	DEFINABLE FEATURE OF WORK	SCHEDULE ACT NO.	INDEX #

PERSONNEL PRESENT

GOVERNMENT REP NOTIFIED _____ HOURS IN ADVANCE: YES ☐ NO ☐

NAME	POSITION	COMPANY/GOVERNMENT

PROCEDURE COMPLIANCE

IDENTIFIY FULL COMPLIANCE WITH PROCEDURES IDENTIFIED AT PREPARATORY. COORDINATE PLANS, SPECIFICATIONS, AND SUBMITTALS.

COMMENTS: ______________________________

PRELIMINARY WORK

ENSURE PRELIMINARY WORK IS COMPLETE AND CORRECT. IF NOT, WHAT ACTION IS TAKEN?

WORKMANSHIP

ESTABLISH LEVEL OF WORKMANSHIP.

WHERE IS WORK LOCATED? ______________________________

IS SAMPLE PANEL OR MOCK-UP REQUIRED? YES ☐ NO ☐

WILL THE INIITAL WORK BE CONSIDERED AS A SAMPLE? YES ☐ NO ☐

(IF YES, MAINTAIN IN PRESENT CONDITION AS LONG AS POSSIBLE AND DESCRIBE LOCATION OF SAMPLE) ______________________________

RESOLUTION

RESOLVE ANY DIFFERENCES.

COMMENTS: ______________________________

CHECK SAFETY

REVIEW JOB CONDITIONS USING EM 385-1-1 AND JOB HAZARD ANALYSIS

COMMENTS: ______________________________

OTHER

OTHER ITEMS OR REMARKS

____

QC MANAGER DATE

APPENDIX I - SUBMITTAL REGISTER

CONTRACT NO.

TITLE AND LOCATION

CONTRACTOR

ACTIVITY NO	TRANSMITTAL NO.	SPEC SECTION NO.	DESCRIPTION OF ITEM SUBMITTED	PARAGRAPH NO.	CLASSIFICATION - GOVT. OR A/E REVWR	CONTRACTOR: SCHEDULE DATES			CONTRACTOR ACTION			APPROVING AUTHORITY				MAILED TO CONTR/ DATE RECEIVED FROM APPR AUTH	REMARKS
						SUBMIT	APPROVAL NEEDED BY	MATERIAL NEEDED BY	ACTION CODE	DATE OF ACTION	DATE FWD TO APPR AUTH/ DATE RECEIVED FROM CONTR	DATE FORWARD TO OTHER REVIEWER	DATE RECEIVED FROM OTHER REVIEWER	ACTION CODE	DATE OF ACTION		
(a)	(b)	(c)	(d)	(e)	(f)	(g)	(h)	(I)	(j)	(k)	(l)	(m)	(n)	(o)	(p)	(q)	(r)

APPENDIX J - TESTING PLAN AND LOG											
CONTRACT NUMBER			CONTRACT NUMBER							CONTRACT NUMBER	
SPECIFICATION SECTION AND PARAGRAPH NUMBER	SPECIFICATI ON SECTION AND PARAGRAP H NUMBER	SPECIFICATION SECTION AND PARAGRAPH NUMBER	SPECIFICATI ON SECTION AND		SPECIFICATION SECTION AND PARAGRAPH NUMBER	SPECIFICATION SECTION AND PARAGRAPH NUMBER	SPECIFICA TION SECTION AND		SPECIFICATI ON SECTION AND PARAGRAPH NUMBER	SPECIFICATI ON SECTION AND PARAGRAPH NUMBER	SPECIFICATION SECTION AND PARAGRAPH NUMBER
			PARA GRAP H NUMB ER	PARA GRAP H NUMB ER			PAR AGR APH NUM BER	PAR AGR APH NUM BER			

APPENDIX K – DEFICIENCY / REWORK TRACKING LOG

Contract No. and Title:

Contractor:

NUMBER	DATE IDENTIFIED	DESCRIPTION	CONTRACT REQUIREMENT (Spec. Section and Par. No., Drawing No. and Detail No., etc.)	ACTION TAKEN BY QC MANAGER	RESOLUTION

MNL18-EB/Oct. 2009

26

Legal Considerations and Dispute Resolution: The Water-Related Construction Defect

Bruce W. Ficken[1]

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 legal 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.

As a preliminary matter, the liability that a party, be it a contractor, design professional, or owner, may face, may be affected by the applicable statute of limitation or statute of repose. A statute of limitation is a statute that establishes a time limit for suing, based on the date when the claim accrued (as when the injury occurred or was discovered) [1]. See, e.g., Cal. Civ. Proc. Code § 339 (2007) (action upon a contract must be brought within two years of the discovery of the loss or damage suffered). By contrast, a statute of repose bars any suit that is brought after a specified period of time since substantial completion of the structure, even if this period ends before a party has discovered an injury [1]. For example, California's statute of repose bars actions to recover damages for latent construction defects more than ten years after substantial completion of the work of improvement, regardless of when the injury is discovered. Cal. Civ. Proc. Code § 337.15 (2007). Both statutes of limitation and statutes of repose are designed to protect litigants from stale claims. However, neither are immutable and courts sometime find excuses to permit litigation even after the running of the statutes [2].

The following discussion sets forth the 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 [3]. Thus, if a contractor fails to construct in accordance with applicable contract documents, he is responsible for resulting damages [4]. 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.[5]" 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.[6]"

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

[1] *Pepper Hamilton LLP, Philadelphia, PA.*

specifications if his work fails to meet specified performance requirements [7].

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 [8].

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 foreseeable obligation that this work will be done by competent workmen in a workmanlike manner [9].

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 over a century ago in *Filbert v. City of Philadelphia* [10]. 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 [11].

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 deck collapses because the slab thickening caused the 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 [12].

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 the 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* [13], 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 [14]. 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 [15].

The Failure to Warn of Known Defects

The contractor who knows 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 [16]. 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 [17]. 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 [18].

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 [19]. 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.

Furthermore, many organizations have enacted specific standards that must be followed by the architect (and contractor). For example, American Concrete Institute ("ACI") has developed a recognized building code for design of concrete structures. ASTM International ("ASTM") publishes standards, testing methods, recommended practices, definitions, and other materials that an architect must follow in designing a project (and a contractor must follow in constructing a project). Other relevant organizations that establish similar standards include the American Architectural Manufacturers Association ("AAMA") and the American Society of Heating, Refrigerating, and Air Conditioning Engineers ("ASHRAE"). The architect often incorporates these standards into the project specifications.

A leading case on architect liability is *Bloomsburg Mills, Inc. v. Sordoni Construction Co*. [20], 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... [21].

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. Furthermore, when a design professional reviews a contractor's shop drawings, depending upon the language in the contract, the architect may also become liable for any errors contained in the shop drawings. Thus, some jurisdictions have 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 [22]. According to this standard, the design professional promises that if the contractor constructs according to plans and specifications, the resulting construction will not fail [23]. Other jurisdictions, however, take the position that an architect provides no implied warranty and cannot be held liable absent a failure to use ordinary care [24].

Depending on the jurisdiction, then, *Bloomsburg Mills* may provide 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 into 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.

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 [25].

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 [26]." 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 standard 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* [27], 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 [28]." 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 [29]." Based on, *inter alia*, the nature of the 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 [30]."

As *Cann* demonstrates, the duty of the design professional to discover defects through inspection or observation, even with the use of 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 Alabama Supreme Court case of *Watson, Watson, Rutland/Architects, Inc. v. Montgomery County Board of Education* [31], 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 Work… to determine in general if the Work is proceeding in accordance with the Contract Documents [32]." 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 [33]." 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 [34]." 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 [35]. 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 [36]. 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 or observe, or both, 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 architect 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 or observe, or both, a construction defect, while a source of architect 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.* [37], 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 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 [38]. 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 jury verdict was, in fact, a judgment against the three defendants jointly and severely [39].

Architect's Certificates

Contractors doing substantial projects are paid periodically according to the percentage of work completed. 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.* [40], 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 [41]."

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 architect'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 [42]." 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 [43]."

Thus, while an architect may be liable for "overcertification" in terms of the percentage of the work completed [44], 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 [45]. 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 [46]. 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 is 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 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 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 some 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 the 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 [47].

The Case Study: Mold and Mildew Contamination

In 1984, Our Way Development ("owner") purchased an oceanfront site in Turtle Beach, South Carolina. Shortly thereafter, the owner hired Martian Design ("architect") to design a 16-story, oceanfront 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 substitution 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 weatherproofed prior to installation of interior drywall partitions. The owner, however, anxious to see its hotel open, refused an extension, and the contractor went ahead with drywall erection before the building was weather tight.

In March and again in April the building was inundated with heavy rains. Much of the interior drywall 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 drywall.

At that point the architect recommended that all drywall be demolished and replaced. However, both the contractor, insured for this damage, and the owner (still anxious to get its hotel open), 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 "waterproof" 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 opened for business.

Almost immediately, mold and mildew began to appear on lampshades, bed linens, and other similar items. However, by early Summer 1987, mold and mildew spotting began 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, the owner's consultant issued its "preliminary" report. It documented extensive water leaking in the building, but specifically declined to assess responsibility between the contractor and the architect.

During the winter of 1987–1988, the owner replaced the entire exterior skin of the building, presumably to correct the leak problem. However, the owner did not conduct extensive leak testing of the new building skin.

Also during the winter of 1987–1988, 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 on 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 developed more fully 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 (for example, a buckled beam or imploded glass)?
   c. Has the 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 to 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 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 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 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 phenomena 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 damage 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 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 bath-

room fan exhausted, in reality, the two systems 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 to 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 walls. Water leaking into those walls from outside was the only logical explanation.
3. Areas where 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 the dispute. Each side must find an explanation for every observed phenomenon which is consistent with his theory of 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 for not only 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 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 requested only 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 its 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 Trial

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 issues critical 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 simply to 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 the 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 the 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 this view [48].

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" was the direct cause of 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 responded on several fronts. 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. In addition, the 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 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 the 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 upgrade 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 the 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 as implemented could have had any significant effect on the alleged negative pressure problems.

Second, the owner did provide a mock-up of what he 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 were found to have mechanical problems causing them not to dehumidify. And finally, the monitored data, taken from continuous readings by monitoring equipment, were so anomalous that either the data were 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 his position and undermined his 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 the 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 also 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 put 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 approve defective work or that the 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 required 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 [49].

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 the design is deficient [50]. This is a particularly vital public safeguard because it is the using public who often are the victims of a failed construction. The contractor has no affirmative duty to investigate professionally 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 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 plumb 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 a 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 possibility 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 likely will scrutinize contract requirements for roofing and exterior cladding to suggest that he was responsible for nothing not specifically required in the 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 a 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 specifications 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 same conditions as those 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 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 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 résumé 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 on 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 through-the-wall HVAC units. Only later was it discovered that this inflow of air was caused by the owner 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 the 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 severely liable [51].

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. First and foremost, the best way to avoid water defects in construction is to require that mock-ups of the structure be built and adequately tested before a structure is built. In addition, an owner should also require field water testing of the building envelope. Based on the mistakes that were made in the prior case study 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. Further, 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 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 its 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 unfortunately 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.

REFERENCES

[1] *Black's Law Dictionary* (8th ed. 2004).

[2] See Acosta v. Glenfed Dev. Corp., 128 Cal.App. 4th 1278 (2005).

[3] 13 Am. Jur. 2d Building and Construction Contracts § 13 (2000 & Supp. 2004); 17A C.J.S. Contracts § 494(2) (1963 & Supp. 2004). See, e.g., Tate-Jones & Co. v. Union Electric Steel Co., 126 A. 813, 815 (Pa. 1924).

[4] See, e.g., Wilkinson v. Landreneau, 525 So. 2d 617, 620 (La. Ct. App. 1988); Parkes v. Opfermann, 119 A.2d 624, 625 (Pa. Super. Ct. 1956).

[5] United States v. Spearin, 248 U.S. 132 (1918). See generally 6 A.L.R. 3d 1394, 1397-1403, § 2 (1966 & Supp. 2004).

[6] Spearin, 248 U.S. at 136.

[7] See, e.g., Stuyvesant Dredging Co. v. United States, 834 F.2d 1576, 1582-83 (Fed. Cir. 1987) (distinguishing between descriptive and performance specifications).

[8] The only exception is where the contractor is able to prove that, under the descriptive specifications, the strength re-

quirements were impossible to reach. In that case, the failure is attributable to design error, as discussed *infra*.

[9] See, e.g., Aetna Casualty & Surety Co. v. Leo A. Daly Co., 870 F. Supp. 925, 935 (S.D. Iowa 1994); Pittsburgh Nat'l Bank v. Welton Becket Assocs., 601 F. Supp. 887, 890-92 (W.D. Pa. 1985); Henggeler v. Jindra, 214 N.W.2d 925, 926 (Neb. 1974); Mann v. Clowser, 59 S.E.2d 78, 84-85 (Va. 1950); 13 Am. Jur. 2d Building and Construction Contracts § 329, *supra*.

[10] 37 A. 545, 546-47 (Pa. 1894).

[11] 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, 475 N.E.2d 273, 281 (Ill. App. Ct. 1985); City of Charlotte v. Skidmore, Owings & Merrill, 407 S.E.2d 571, 578-79 (N.C. Ct. App. 1991).

[12] See, e.g., Robert G. Regan & Co. v. Fiocchi, 194 N.E.2d 665 (Ill. App. Ct. 1963); Evan Johnson & Sons Constr., Inc. v. Mississippi, 877 So. 2d 360, 366-67 (Miss. 2004).

[13] 513 F.2d 588 (Ct. Cl. 1975).

[14] *Id.* at 594-98.

[15] Id. at 598; see also Blount Bros. Corp. v. United States, 872 F.2d 1003, 1007-08 (Fed. Cir. 1989) (finding that it would have been impossible for contractor to provide specified gravel aggregate even where contractor had more experience dealing with gravel than government, where government had been unable to locate any gravel anywhere which would have met its specifications).

[16] See generally Lewis v. Anchorage Asphalt Paving Co., 535 P.2d 1188 (Alaska 1975), *appeal after remand*, 579 P.2d 532 (Alaska 1978), *appeal after remand*, 629 P.2d 65 (Alaska 1981).

[17] See, e.g., Mann v. Clowser, 59 S.E.2d 78, 85 (Va. 1950) (holding that the contractor has a duty to make full and fair disclosure of the consequences of changes in the construction which the contractor knows or should know might cause structural defects from the nature of the undertaking or his experience).

[18] See, e.g., Rippy v. Phipps, 475 P.2d 646, 647-48 (Colo. Ct. App. 1970) (contractor proceeded with construction of a dam and reservoir without advising the owner of soil conditions it had discovered which it knew or should have known would make the site unsuitable for the dam and reservoir); George B. Gilmore Co. v. Garrett, 582 So. 2d 387, 393 (Miss. 1991) (finding contractor liable for failure to warn homeowner of unsuitable subsurface soils); 73 A.L.R. 3d 1213 (1976 & Supp. 2004).

[19] See, e.g., Bloomsburg Mills, Inc. v. Sordoni Constr. Co., 164 A.2d 201 (Pa. 1960).

[20] *Id.*

[21] *Id.* at 203 (citations omitted).

[22] See, e.g., id.; Federal Mogul Corp. v. Universal Constr. Co., 376 So. 2d 716 (Ala. Civ. App. 1979) (holding that architects impliedly warrant that their plans and specifications for construction of a building are sufficient to make the structure fit for the intended purpose).

[23] See, e.g., Beachwalk Villas Condominium Ass'nv. Martin, 406 S.E.2d 372 (S.C. 1991); Hill v. Polar Pantries, 64 S.E.2d 885 (S.C. 1951); Eastern Steel Constructors, Inc. v. City of Salem, 549 S.E.2d 266 (W. Va. 2001).

[24] See, e.g., R. J. Longo Constr. Co. v. Transit Am. Inc., 921 F. Supp. 1295 (D.N.J. 1996) (applying New Jersey law); Johnson-Voiland-Archuleta, Inc. v. Roark Assocs., 572 P.2d 1220 (Colo. Ct. App. 1977); Castaldo v. Pittsburgh-Des Moines Steel Co., 376 A.2d 88 (Del. 1977); Audlane Lumber & Builders Supply, Inc. v. D.E. Britt & Assocs., 168 So. 2d 333 (Fla. Dist. Ct. App. 1964); City of Mounds View v. Walijarvi, 263 N.W.2d 420 (Minn. 1978); Adobe Masters, Inc. v. Downey, 833 P.2d 133 (N.M. 1994); SME Industries, Inc. v. Thompson, Ventulett, Stainback & Assocs. Inc, 28 P.3d 669 (Utah 2001); Garman, Inc. v. Williams, 912 P.2d 1121 (Wyo. 1996).

[25] See, e.g., *Heath v. Huth Eng'rs, Inc.*, 420 A.2d 758, 759 (Pa. Super. Ct. 1980) (finding engineering firm liable to decedent third party for, *inter alia*, negligently failing to inspect the work properly), 13 A.L.R. 5th 289, 437-40, §§ 45-47 (1993).

[26] See AIA Standard Form Agreement § 2.65.

[27] 503 F. Supp. 419 (N.D. Ohio 1980), *aff'd*, 669 F.2d 415 (6th Cir. 1982).

[28] *Id.* at 436.

[29] *Id.*

[30] *Id.* at 437

[31] 559 So. 2d 168 (Ala. 1990) [hereinafter "*Watson*"].

[32] *Id.* at 170.

[33] *Id.*

[34] *Id.* at 173.

[35] *Id.* at 174.

[36] *Id.*

[37] 420 A.2d 758 (Pa. Super. Ct. 1980).

[38] See *id.* at 759.

[39] See *id.*, see also *Palmer v. Brown*, 273 P.2d 306, 317 (Cal. Ct. App. 1954) (holding that contractor and architect may be concurrently negligent and liable for owner's damages in case where architect undertook duty to supervise the work).

[40] 523 F.2d 98 (3d Cir. 1975).

[41] *Id.* at 101.

[42] AIA Standard Form § 2.6.10.

[43] *Id.*

[44] See, e.g., In re Designed Ventures, Inc., 132 B.R. 677, 678-79 (Bankr. D.R.I. 1991) (finding that architect owes duty of care to surety in certifying payments); Browning v. Maurice P. Levien & Co., 262 S.E.2d 355, 358 (N.C. Ct. App. 1980) (holding that 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).

[45] 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); Whitfield Constr. Co. v. Commercial Dev. Corp., 392 F. Supp. 982 (D.V.I. 1975) (same); Bates & Rogers Constr. Corp. v. North Shore Sanitary Dist., 414 N.E.2d 1274 (Ill. App. Ct. 1980) (owner impliedly warrants that the plans and specifications it furnishes for the job will enable the contractor to perform the work successfully).

[46] See, e.g., Cincinnati Riverfront Coliseum v. McNulty Co., 504

N.E.2d 415, 419 (Ohio 1986) (holding that it was an issue of fact for the 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).

[47] The names of the participants have been changed as a courtesy to the losing parties and experts.

[48] See, e.g., Baldwin-Lima Hamilton Corp. v. United States, 434 F.2d 1371, 1371-72 (Ct. Cl. 1970); Roberts v. United States Great Am. Co., 357 F.2d 938, 949 (Ct. Cl. 1966); Will v. Carondelet Savings & Loan Ass'n, 508 S.W.2d 711, 715-16 (Mo. Ct. App. 1974).

[49] See Beacon Constr. Co. v. United States, 314 F.2d 501 (Ct. Cl. 1963) (holding that 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); accord Berg v. United States, 455 F.2d 1037 (Ct. Cl. 1971); cf. Ridley Inv. Co. v. Croll, 192 A.2d 925 (Del. 1963) (if contractor warns the owner of a defect and the owner directs the contractor to proceed, the contractor cannot be liable to the owner); accord Glass v. Wiesner, 238 P.2d 712 (Kan. 1951).

[50] See, e.g., Triax Pacific, Inc. v. West, 130 F.3d 1469, 1475 (Fed. Cir. 1997) (noting that this doctrine has been applied only where errors are "patent and glaring"); accord Pike v. Howell Building Supply Co., 748 So. 2d 710, 712-13 (Miss. 1999).

[51] See Liberty Mut. Ins. Co. v. Vanderbush Sheet Metal Co., 512 F. Supp. 1159 (E.D. Mich. 1981); Northern Petrochemical Co. v. Thorsen & Thorshov, Inc., 211 N.W.2d 159 (Minn. 1973).

MNL18-EB/Oct. 2009

27

A Conceptual System of Moisture Performance Analysis

Mark T. Bomberg[1] and Cliff J. Shirtliffe[2]

IN A MANUAL SUCH AS THIS ONE, INDIVIDUAL AS-pects 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. The following chapter, added in the second edition of this manual, will continue the topic even further, leading the reader towards the development of methods for assessment of moisture-originated damage.

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. 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 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.

[1] *Research Professor, Syracuse University, Syracuse, NY 13244.*
[2] *Previously Senior Research Officer with Institute for Research in Construction; National Research Council of Canada, Ottawa, Canada K1A 0R6.*

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 accordance with the *Oxford American Dictionary*, we use term barriers for all elements that control advance (retard) flows of heat, air, or moisture.

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 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.

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 interstitial 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 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

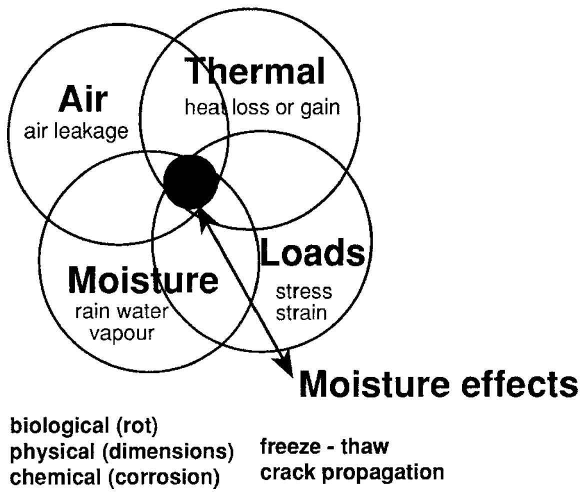


Fig. 1—Interaction between heat, air, and moisture transfer phenomena.

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. As a footnote, one may note that while performance analysis should include all levels of hierarchy starting from that of a building and going down to the building material, often it is not possible to use it below level of assembly. Materials are be evaluated for their contribution to the performance of the assembly.

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].

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

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.[3] 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 critical moisture content (CMC) and cumulative exposure time (CET) with respect to the specified effect, i.e., the sum of the periods when moisture content exceeds the critical moisture content with respect to a specific effect of moisture.[4]

[3] A comment on HAM modeling: in durability considerations one must also calculate moisture flows in the region above capillary moisture content. While already in 1972, during the conference on fundamentals of moisture flow in porous media, two different approaches were presented:

(1) using air flow through the capillary water field as a separate equation (Morel-Sytoux), and
(2) using air diffusion through the capillary water field as a correction to moisture influx into the specimen (Bomberg)—until today, none of the commercially available HAM models has addressed this issue.

[4] There are a few questions that must be answered before applying this methodology: a limiting condition may be selected at different levels of the performance deterioration, anywhere from micro-cracking to macro-cracking or spalling—the latter is used in this chapter. Finally, several damage mecha-

The first characteristic, the critical 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 a short time basis (e.g., one or a few days); however, after many weeks, months, or years of exposure, these processes may result in 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

$$\text{CET} = \text{Sum}(I \cdot F_{ex}) \quad (1)$$

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 the 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, moisture content (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 critical 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 of a material may be defined as its ability to withstand, without significant deterioration, the periods of freezing that actually occur throughout the whole pe-

nisms such as restrained shrinkage or swelling and even that created by osmotic forces in salt transport may need to use a criterion reformulated into the stress-strain condition rather than the simple critical moisture content. Yet this chapter is focused on the general approach more than the specific models for calculation.

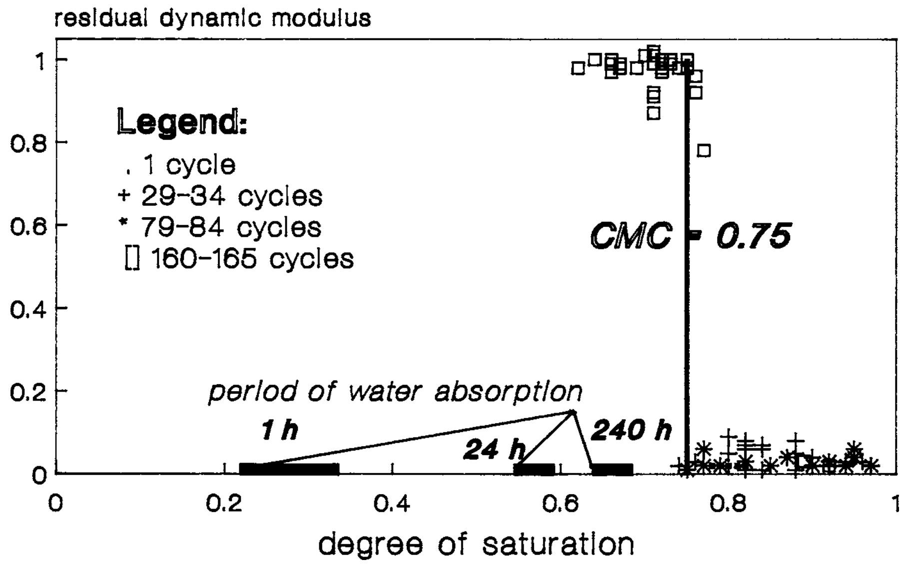


Fig. 2—Residual dynamic Young's modulus in freeze-thaw testing of a well-burnt clay brick with density 1860 kg/m^3 versus degree of moisture saturation for series of tests from 1 to 165 cycles.

riod 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 dra-

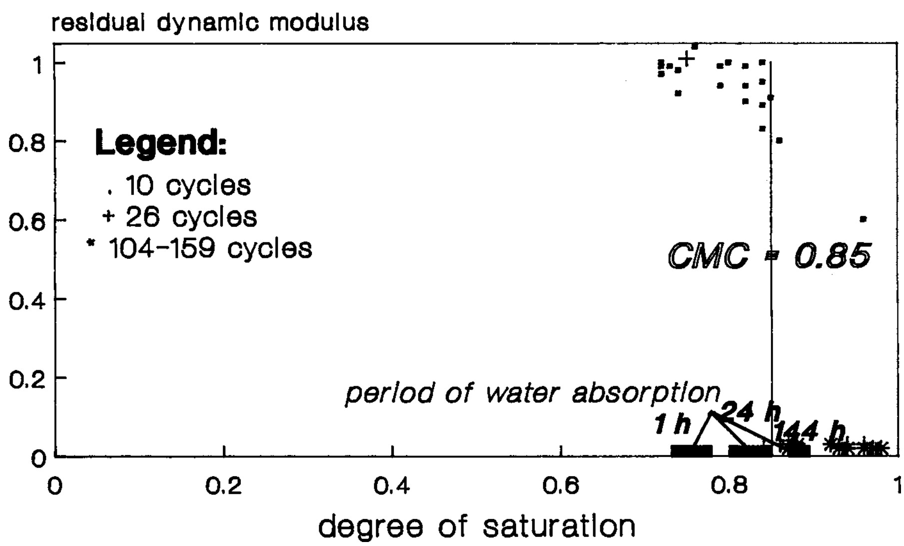


Fig. 3—Residual dynamic Young's modulus in freeze-thaw testing of an underburnt clay brick with density 1690 kg/m^3 versus degree of moisture saturation for series of tests from 10 to 159 cycles.

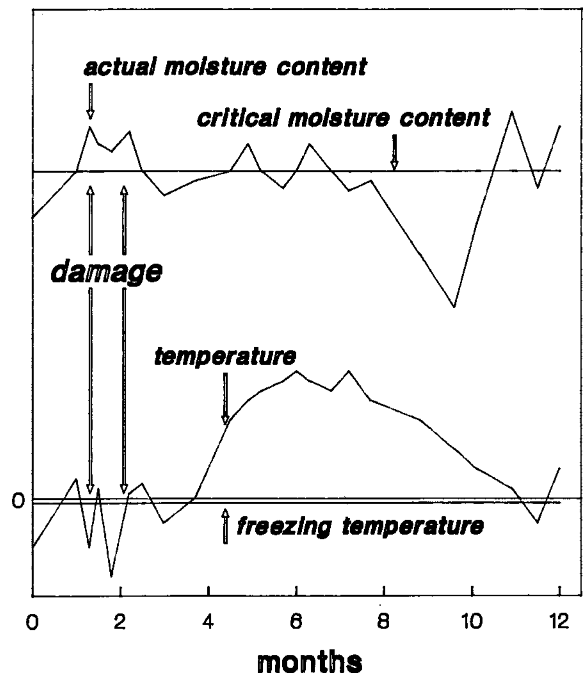


Fig. 4—Hypothetical curves of temperature and degree of actual saturation shown to highlight coincidence of conditions when frost damage is likely to occur.

matic reduction in the residual dynamic modulus.[5] 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 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 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 [C666/C666M-03(2008)]. 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 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.)

[5] The discontinuity criterion is selected here as the damage criterion. While some researchers may argue that a certain degree of cracking should be selected as the damage criterion, the authors believe that the physical failure of such yield of ductile materials and discontinuity of the brittle material is much better defined and easier to reproduce between different laboratories. In particular, when multiple cycling can be replaced by a single freeze-thaw cycle.

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 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.

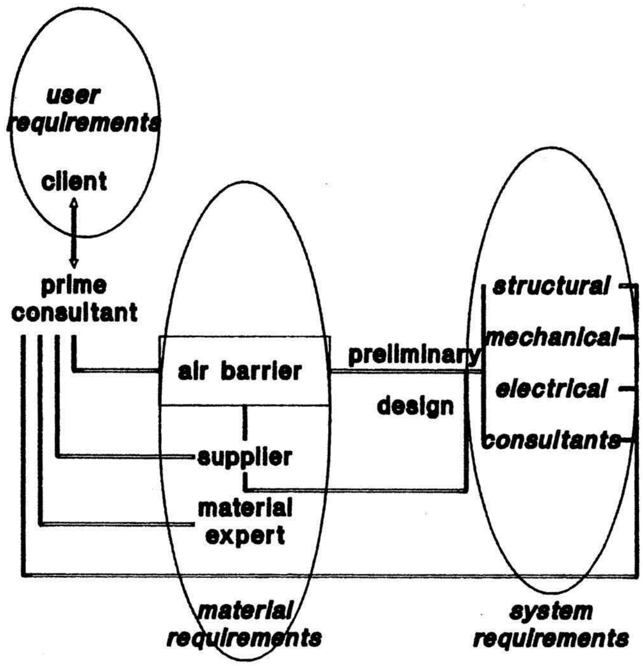


Fig. 5—Flow of information during design of air barrier (see text).

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 prediction 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

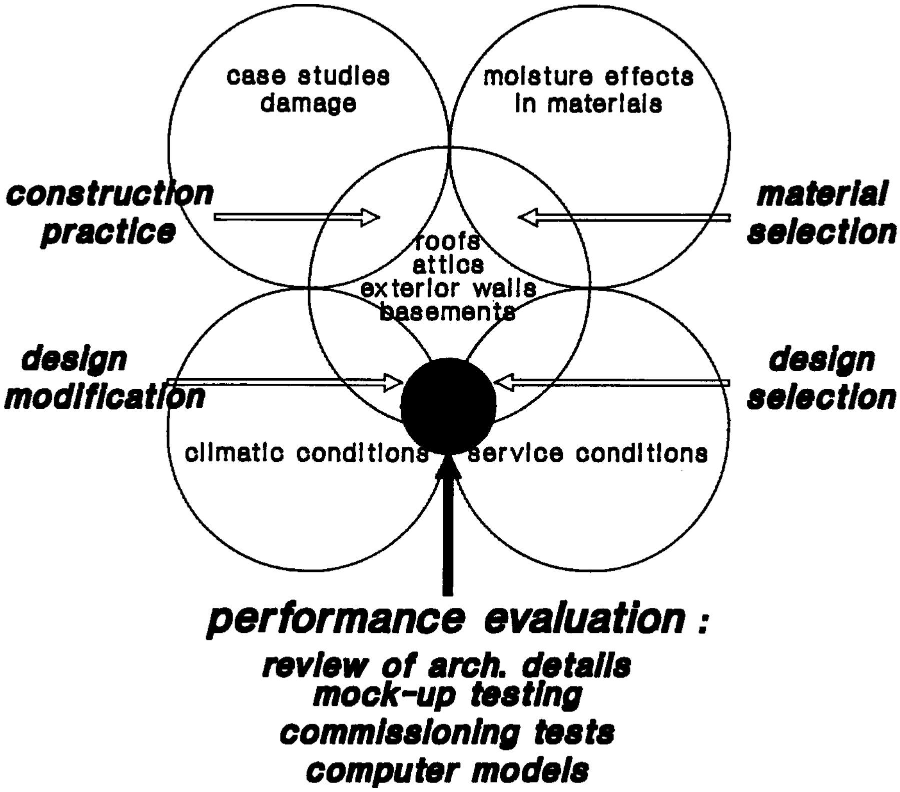


Fig. 6—Evaluation of performance on the level of building element and system.

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.

One should note that the cumulative deterioration is involved in the actual process and that it may take several years before the system reaches our criterion of the damage; yet the calculation model deals with the envelope of the deterioration process and therefore need not to extend for more than one yearly cycle. Furthermore, as the model deals with the whole building enclosure, the durability of the material is evaluated in the context of its relation to the full building system.

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.

Developments During the Last Decade

Ten years later, when updating this text for the second edition of the ASTM moisture manual, one may review the progress achieved in this area. Indeed, the unidirectional freeze-thaw testing became much more popular, see Refs. [27–36]. Yet, in addition to unidirectional testing, we have postulated the separation between the method of introducing moisture into the specimen and the freeze-thaw test. Why has that not happened?

The answer is simple, we still do not rely on heat, air, moisture (HAM) modeling as the means of field performance assessment. The underlining concept presented in this chapter required comparing the measured critical moisture content with the actual moisture content calculated from the HAM model.[6] Yet, the required development of HAM models

[6] As one of the reviewers for the second edition of this ASTM manual highlighted, the building science community interest in HAM modeling is fo-

did not happen. Despite of IEA Annex and ASTM publishing moisture manual [37], all that happened is a better description of the obsolete state-of-the-art.

As discussed elsewhere, the HAM models are dwelling on the level of sensitivity analysis, and did not reach the more advanced stage needed for real-time calculations of the moisture content profiles. Some leading building scientists think that current methodology to generate boundary conditions and material characteristics for HAM models is not adequate for the real time calculations. Currently, the HAM models will assist the designer in comparing materials and climates. Yet, these models are not considered reliable enough or capable of accurately predicting the field performance of a building assembly. No progress will be achieved until more of the fundamental work is performed in these two areas.

The editors of this manual decided, therefore, to introduce the next chapter to continue discussion on durability and to explain issues involved in the development of methods for assessment of moisture-originated damage.

Acknowledgments

The authors gratefully acknowledge that comments from Prof. Jan Carmeliet, Leuven and Eindhoven University, helped us in upgrading the text of the second edition of this chapter.

References

[1] Hutcheon, N. B., "Fundamental Considerations in the Design of Exterior Walls for Buildings," DBR/NRC paper No. 3057, National Research Council of Canada, Ottawa, Canada, 1953.

[2] *An Air Barrier for the Building Envelope, Proceedings of Building Science Insight 1986*, NRC Canada, Ottawa, Ontario, 1989.

[3] Tsongas, G. A., "The Effect of Exterior Insulating Sheathing on Wall Moisture," *Insulation Materials: Testing and Applications* (*2nd Vol.*), *ASTM STP 1116*, ASTM International, West Conshohocken, PA, 1991.

[4] Karagiozis, A. N., and Kumaran, M. K., "Computer Model Calculations on the Performance of Vapor Retarders in Canadian Residential Buildings," to be published in *ASHRAE Proceedings*, June 1993.

[5] Building Materials Research Agenda, prepared for U. S. Dept. of Energy, Conservation, and Renewable Energy, Office of Buildings Energy R&D, Building Systems Division, ORNL/Sub/84–97333/1, Oak Ridge National Laboratory, Oak Ridge, TN, April 1986.

[6] Adamson, B., Ahlgren, L., Bergstrom, S. G., and Nevander, L. E., "Byggnadstekniska fuktproblem" ("Moisture Research in Building Technology") Programskrift 12, Swedish Council for Building Research, Stockholm, Sweden, 1970.

[7] Fagerlund, G., "Critical Degree of Saturation—A Tool for Estimating the Frost Resistance of Building Materials," Division of Building Technology, Lund Institute of Technology, Lund, Sweden, 1970.

[8] Sandberg, P. I., "Moisture Balance in Building Elements Exposed to Natural Climatic Conditions," Report 43, Division of Building Technology, Lund Institute of Technology, Lund, Sweden, 1973.

[9] Bomberg, M., "Moisture Flow Through Porous Building Materials," Rep 52, Division of Building Technology, Lund Institute of Technology, Lund, Sweden, 1974.

[10] Wright, J. R., *The Performance Approach: History and Status, Vol. 2, Performance Concepts in Buildings*, Special Publication No. 361, National Bureau of Standards, Washington DC, 1972, pp. 847–853.

[11] Ventre, F. T., "Documentation and Assessment of the GSA/PBS Building System Program: Background and Research Plan," National Bureau of Standards, Washington, DC, 1983, p. 39.

[12] Rilem Committee 31-PCM Performance Criteria for Building Materials, final report, T. Sneck, and A. Kaarresalo, Eds., Research Notes 644, Technical Research Centre of Finland, Espoo, Finland, 1986.

[13] Ashton, H. E., and Sereda, P. J., "Environment, Microenvironment, and Durability of Building Materials," *Durability Build. Mater.*, Vol. 1, 1982, pp. 49–65.

[14] *Performance Concept in Building, 3rd ASTM/CIB/RILEM Symposium*, Laboratorio National de Engenharia Civil, Lisbon, Portugal, 1982.

[15] Becker, R., "A Method for the Generation of Weighing Factors for Performance Evaluation Systems," *Build. Environ.*, Vol. 20, 1985, No. 4, pp. 195–200.

[16] Robinson, T., "Moisture Challenges in Canadian Energy Efficient Housing," *Journal of Thermal Insulation and Building Envelopes*, Vol. 16, Oct. 1992, pp. 112–120.

[17] *Condensation and Energy, Sourcebook, Report Annex* XIV, Vol. 1, International Energy Agency, Leuven, Holland, March 1991.

[18] Anderson, A. C., "Verification of Calculation Methods for Moisture Transport in Porous Building Materials," D6, Swedish Council for Building Research, Stockholm, Sweden, 1985.

[19] Burch, D. M., Thomas, W. C., Mathena, L. R., Licitra, B. A., and Ward, D. B., "Transient Moisture and Heat Transfer in Multilayer Nonisothermal Walls—Comparison of Predicted and Measured Results," *Thermal Performance of the Exterior Envelopes of Buildings IV*, Orlando, FL, ASHRAE, Atlanta, GA, 1989.

[20] Kohonen, R., "Transient Analysis of the Thermal and Moisture Physical Behaviour of Building Constructions," *Building and Environment*, Vol. 19, No. 1, 1984, pp. 1–14.

[21] Kerestecioglu, A., Swami, M., Fairey, P., Gu, L., and Chandra, S., "Modeling Heat, Moisture and Contaminant Transport in Buildings: Toward a New Generation Software," *Proceedings, Building Simulation '89*, Vancouver, BC, International Building Performance Simulation Association, Sacramento, CA, 1989, pp. 333–340.

[22] Ojanen, T., and Kumaran, M. K., "Air Exfiltration and Moisture Accumulation in Residential Wall Cavities," *Thermal Performance of the Exterior Envelope of Buildings V*, BTECC/DOE/ASHRAE, 1992.

[23] Sereda, P. J., Croll, S. G., and Slade, H. F., "Measurement of the Time-of-Wetness by Moisture Sensors and Their Calibration," *Atmospheric Corrosion of Metals, ASTM STP 767*, ASTM International,, West Conshohocken, PA, 1982, p. 413.

[24] Kashiwagi, D. T., and Moor, W. C., "The Relationship Between Energy Cost and Conservation Measures, Building Design, and Insulation Levels," *Journal of Thermal Insulation and Building Envelopes*, April 1993, pp. 375–394.

[25] Bomberg, M., "Laboratory Methods for Determining Moisture Absorption of Thermal Insulations, I: Review," *J. Therm. Insul.*, Vol. 6, April 1983, pp. 232–249.

[26] Strelka, C. S., "Some Thoughts on Design Procedure," Draft 4, unpublished manuscript, IRC/NRC, 1985.

cused on simplified approach to so-called capillary saturation while precise modeling of moisture profilers at higher MC requires understanding of other driving forces for moisture movement such as salinity differences, freezing depression, and even variation in capillary saturation caused by the preferential filling of pores. Thus, even with so-called "advanced" or "research" HAM models, we are talking about simplified and approximate comparisons.

[27] Kaskel, B. S., “Uni-directional Freezing and Thawing Durability Tests for Brick Masonry Panels,” *ASTM STP 1246*, ASTM International, West Conshohocken, PA, 1996, pp. 149–159.
[28] Peake, F., and Ford, R. W., “The Development of a European Freezing Test for Clay Bricks,” *Masonry International*, Vol. 6, No. 2, Sep. 1992, pp. 47–50.
[29] “Produits céramiques pour parements de murs et de sols. Gélivité-cycles de gel-dégel,” *Norme belge NBN B27–009*, Insitut belge de normalisation, 1996.
[30] Arnott, M. R. O., and Maurenbrecher, A. H. P., “An Alternative Test for Determining the Frost Resistance of Bricks,” Technical note, *The Masonry Society Journal*, Vol. 9, No. 1, Aug. 1990, p. 105.
[31] van der Klugt, L. J. A. R., “Frost Testing by Uni-directional Freezing,” *Br. Ceram. Trans. J.*, Vol. 87, No. 1, Jan.-Feb. 1988, pp. 8–12.
[32] van der Klugt, L. J. A. R., “Frost testing by Uni-directional Freezing/Frostpruefverfahren mit einseitiger Befrostung,” *Ziegelindustrie International*, Vol. 2, 1989, pp. 92–98.
[33] MS. A.3 “Uni-directional Freeze-thaw Test for Masonry Units and Wallettes,” *Mater. Struct.*, Vol. 31, Oct. 1998, pp. 513–519, [RILEM draft recommendation based on Dutch freeze-thaw test].
[34] MS.B.1 “Freeze/Thaw Test of Masonry Panels,” *Mater. Struct.* Vol. 31, Jan.-Feb. 1998, pp. 16–19 [RILEM draft recommendation based on British test].
[35] Dutch Standard NEN 2872, “Testing of Stony Materials: Determination of Frost Resistance—Single-Sided Freezing in a Fresh Water Environment,” 1989.
[36] prEN 772 Part 22, “Methods of Test for Masonry Units—Part 22: Determination of Freeze/Thaw Resistance of Clay Masonry Units,” Draft standard, 1999.
[37] Trechsel, H. R., Ed., *Moisture Analysis and Condensation Control in Building Envelopes*, ASTM MNL 40, ASTM International, West Conshohocken, PA, 2001.

MNL18-EB/Oct. 2009

28

Towards Development of Methods for Assessment of Moisture-Originated Damage

Jan Carmeliet,[1,2,3] Staf Roels,[1] and Mark T. Bomberg[4]

Introduction

OVER THE PAST YEARS, CONSIDERABLE EFFORTS have been made to promote the design and construction of high quality buildings meeting an array of performance criteria. Energy efficiency, indoor air quality, durability, functionality (serviceability), and safety issues became issues challenging researchers and designers within a framework of overall sustainability and cost awareness. Design and construction of a building with regard to a selected performance (e.g., U value) deals with the prediction (during the design stage) and control (after construction) of this quantity with respect to a selected reference value (performance criterion). IEA-Annex 32 [1] listed the following hygrothermal performances for building enclosures: airtightness, thermal resistance (level of thermal insulation), transient thermal response, moisture response of the assembly, and effects of thermal bridges in the assembly. Hens and Carmeliet [2] give an example of such an integrated performance evaluation for masonry with EIFS (Exterior Insulation and Finish System).

Moisture performance assessment presented in IEA-Annex 32 [1] includes the analysis of the structure or material exposed to eight different moisture loads: built in moisture, ground source moisture, wind driven rain and precipitation, sorption from ambient air (surface phenomena), and interstitial condensation as well as miscellaneous moisture sources (moist air or rainwater infiltration). Performance requirements, reference values and good moisture practice guidelines were also presented in IEA-Annex 32 [1]. Advanced heat, air, and moisture (HAM) transport simulation tools take into account all these moisture loads including unexpected events (e.g., rain leakage). This document also mentions the growing awareness of the probabilistic character of "moisture design." In IEA-Annex 24 [3], a methodology to link these HAM transport models to durability evaluation tools was mentioned. The rationale for a performance based durability assessment included the following steps: (1) the selection of the expected period of life (design life); (2) the identification of the different mechanical loads, environmental actions and damage mechanisms; (3) the prediction of the service life either by simple deterministic or more advanced stochastic models. Although IEA-Annex 24 [3] and IEA-Annex 32 [1] recognized the importance of durability, these reports address only general concepts of durability. IEA-Annex 32 [1] mentions that future advanced HAM tools should be developed from a durability perspective and include a risk versus elapsed time analysis.

In a first approach to moisture durability assessment, Bomberg and Allen [4] and Allen and Bomberg [5] extended the limit states design methodology, that is well established in structural design, to the field of moisture durability. Limit states approach requires the selection of the damage mechanism (process of deterioration) and quantify it with the help of a damage evolution function. A damage criterion (also called the performance criterion) is selected, which defines the pass/fail criterion for the analyzed performance aspect.

This chapter reviews and further expands the limit state approach for durability assessment of moisture originated damage. We present four different sections:

- Moisture-originated damage
- Methods of durability assessment
- Recent developments in durability assessment of moisture originated damage
- Further needs: Towards a methodology for integrated HAM performance assessment

Moisture-Originated Damage

Moisture originated damage can be divided into three types of deterioration processes: biological, chemical, and physical. Examples of the first type are mold, fungae, algae, moss, plant growth, and rot in organic materials. Examples of chemical deterioration processes are the transformation of calcite into expansive gypsum in limestone in a sulfurous environment, alkali-silica reactions in concrete, reinforcement corrosion in concrete due to carbonation and chloride attack, the dissolution and leaching of calcium in concrete. Examples of physical deterioration are frost damage, damage due to restrained hygrothermal retraction/shrinkage and expansion/swelling, and deterioration due to expansive salt

[1] *Department of Civil Engineering, Laboratory of Building Physics, Katholieke Universiteit Leuven, Kasteelpark Arenberg 40, 3001 Heverlee, Belgium.*
[2] *Chair of Building Physics, Institute of Technology in Architecture, Department of Architecture, ETH Zürich, Wolfgang-Pauli-Strasse 15, CH-8093, Switzerland.*
[3] *Laboratory of Building Science and Technology, EMPA Material Science and Technology, Überlandstrasse 129, CH-8600, Dübendorf, Switzerland*
[4] *Department of Mechanical and Aeronautical Engineering, Syracuse University, 149 Link Hall, Syracuse, NY 13244.*

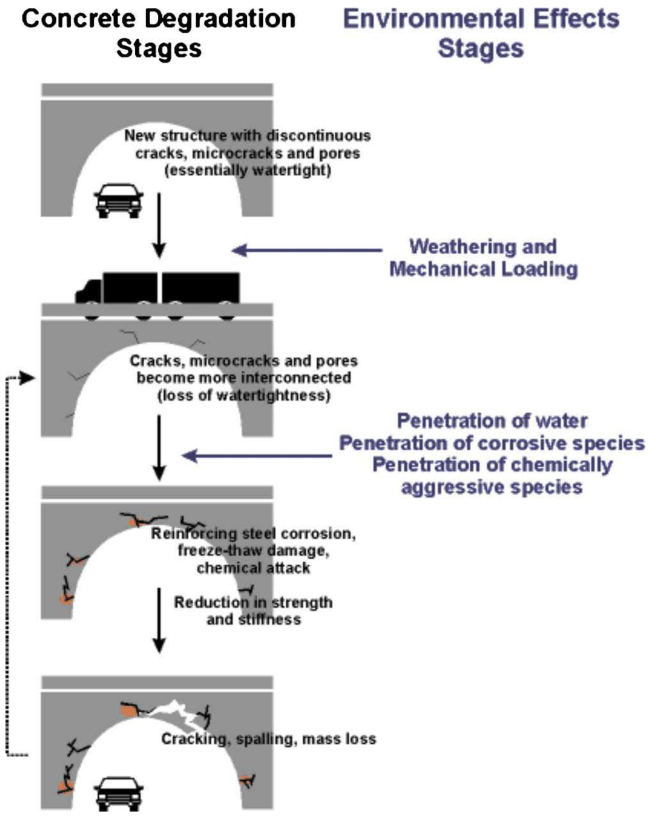


Fig. 1—Deterioration processes in concrete. The different degradation stages from initial to complete degraded structure are presented together with the different stages of environmental action [6].

crystallization and hydration. Biological, chemical, and physical deterioration processes may lead to mechanical and structural degradation in the form of loss of stiffness, excessive deformation, cracking, delamination, spalling, and, in severe cases, to structural failure.

Different deterioration mechanisms may coexist or one damage type may initiate or accelerate another. As an example, we describe the deterioration process in concrete (Fig. 1, [6]). Initially concrete is a porous material with small discontinuous defects and microcracks due to, e.g., phenomena such as autogeneous shrinkage or self-dissication. In a first deterioration stage, microcracks grow under repeated climatic loading, may become interconnected, and, finally, localize into macrocracks. Macrocracks allow a rapid penetration of water with dissolved corrosive or chemically aggressive species into the material itself. This penetration of fluids (or loss of water tightness) initiates a second deterioration stage characterized by corrosion of the steel reinforcement, freeze-thaw damage, chemical attack leading to a reduction of strength and stiffness. Finally, serious cracking, spalling, mass loss, or even complete failure of the concrete structure may occur. Understanding the deterioration process thus includes insight in the ongoing different damage mechanisms including their kinetics and interaction in different stages of the process.

Different notions of service life may exist when dealing with a deterioration process of a structure. With respect to the degradation process of concrete, failure may be defined

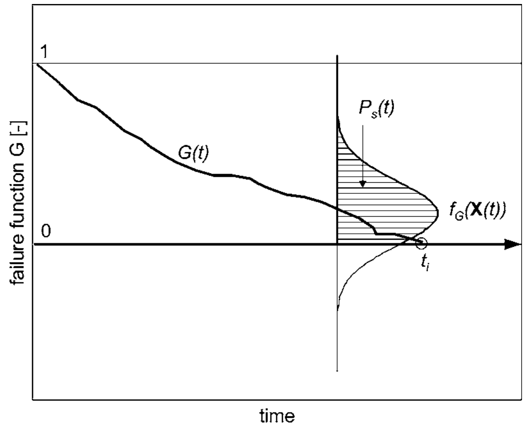


Fig. 2—Time evolution of the failure function $G(t)$. At $G(t_i)=0$, with t_i the life time, failure occurs. The probability density function f_G defines the life time function $P_f(t)=1-P_s(t)$.

as structural collapse, spalling of material, extensive cracking, loss of water tightness, or the onset of macrocracking.

Methods of Durability Assessment

Since all materials finally degrade with time, we quantify durability by the actual period of use or service life of a building component or assembly. Service life depends on the physical characteristics of the materials in the building assembly, indoor and outdoor climates, service conditions, as well as on the state of deterioration at the starting point of the analysis. The deterioration process of a building component in its most general form can be described by a time dependent failure function $G(t)$ (Fig. 2)

$$G(t) = R(t) - S(t) \tag{1}$$

with R the performance limit (damage criterion) and S the structural response, i.e., the actual response of material or structure. If the failure function is positive, $G(t)>0$, failure will not occur during the period t. Failure occurs when $G(t)=0$. The time t_i, where $G(t_i)=0$, is referred to as service life. Service life is obviously affected by the repair and maintenance schedule. Figure 3 gives as an example the influence of preventive maintenance and minor repair on the failure function. Equation (1) and Fig. 4 show that both the performance limit R and the structural response S may change during the period of service life. An example is degradation of strength (decrease of R) due to damage development and, subsequently, the build-up of higher internal stresses due to the ingress of liquid water deeper into the damaged material (increase of S).

The structural response is described by a set of independent variables $\mathbf{X}$ involving thermal, hygric, mechanical, chemical, and biological loads and boundary conditions, geometrical and material characteristics (including degree of the existing damage). The failure function is thus given by the function $G(\mathbf{X}(t))$.

In many cases, caused by the stochastic nature of the independent variables $\mathbf{X}$, the deterioration process is stochastic. The failure function G is then described by a time dependent statistical distribution $f_G(\mathbf{X}(t))$ (Fig. 2). Durability is defined as the probability that the material reaches the end of the design life without failure, or

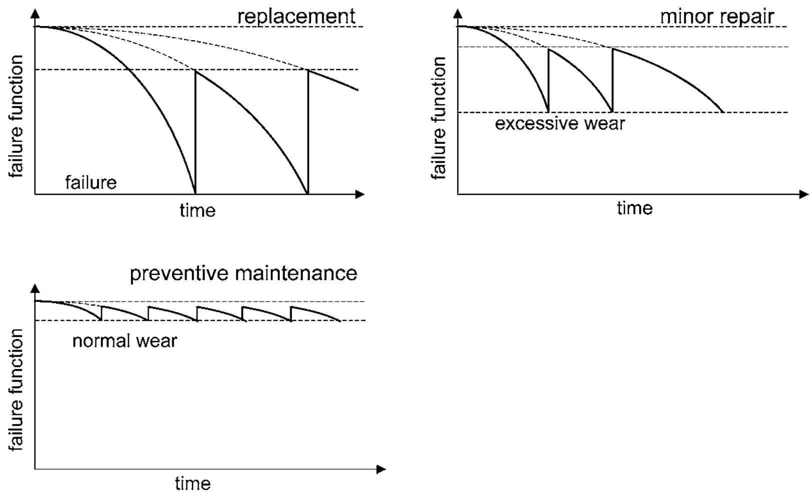


Fig. 3—Time evolution of the failure function. Influence of different maintenance procedures: replacement, minor repair, and preventive maintenance.

$$P_s(t) = P[G(X(t)) > 0] \tag{2}$$

with $P_s(t)$ the probability of adequate performance and P the probability operator. The probability of adequate performance $P_s(t)$ can be determined as the integral over the domain of no failure ($G \geq 0$)

$$P_s(t) = \int_{G\geq 0} f_G(\mathbf{X}(t))\mathrm{d}g \tag{3}$$

The service life function $P_f(t)$ (the probability of failure) is defined as $P_f(t) = 1 - P_s(t)$. For the two basic random variables: performance limit R (resistance) and structural response S, the failure probability is the overlap between the probability density functions of R and S (Fig. 4). However, in many simplified approaches a deterministic and time independent limit state is used.

To determine the service life function $P_f(t)$ for moisture originated deterioration the following steps are necessary:

1. Identify the deterioration mechanisms;
2. Formulate a mathematical model of the deterioration process (damage evolution function);

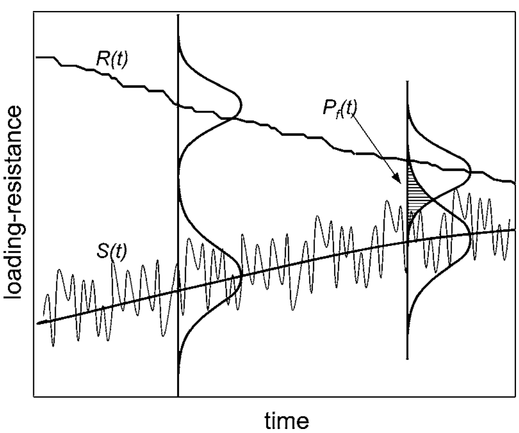


Fig. 4—Time evolution of the performance limit *R* (resistance) and response *S* (load) function. The failure probability is the overlap between the probability density functions of *R* and *S*.

3. Select an appropriate damage criterion;
4. Formulate a statistical description of the basic variables $\mathbf{X}$: distribution and correlation functions;
5. Formulate a stochastic calculation method to evaluate the integral in Eq. (3).

A first concern is the appropriate choice of a durability indicator, representative for deterioration process, and a damage criterion. A durability indicator and damage criterion can be selected among different measures such as loss of load bearing capacity, extensive deformation, health and comfort (e.g., spore germination or mycelium growth for mold problems), esthetics (visible cracking in a stucco), economics (costs for repair, maintenance, replacement), or ecological (life cycle cost). The following types of durability indicators commonly used in building physics are used [7]:

1. *The critical condition is exceeded once*. This concept is based on the return period, defined as the time between two critical loadings. Once the required design life is defined, the maximum allowable load can be determined from a given time sequence of load applications.
2. *Number of occurrences when critical condition is exceeded*. This type of durability indicator is used when dealing with damage originating from repeated loading (e.g., fatigue damage).
3. *Critical cumulative exposure*. This indicator relates to the accumulative dose or time a critical condition is exceeded (see Chapter 27 in this manual). The cumulative exposure CE is given by

$$CE = \sum E\Delta t \tag{4}$$

with Δt the time increment of exposure. The exposure factor E can be interpreted as a measure of the deterioration risk with values between 0 and 1. When the damage criterion is not exceeded, E equals 0. As an example, the deterioration process such as corrosion or wood rotting may start at temperature T_1 at slow rate but the rate increases with temperature and reaches the maximum at temperature T_2. For temperatures below $T_1 E$ is zero, between T_1 and $T_2 E$ is a function that grows from 0 to 1 and stays equal to 1 for temperature higher than T_2.

An example of a durability indicator Type 1 is the exceeding of the tensile strength by an extreme tensile thermal stress [8–10]. An interesting observation can be made when reviewing different approaches to freeze-thaw durability. A first choice may be a Type 2 indicator, where the number of freezing-thawing cycles is chosen as damage criterion. However, experiments do not show a good correlation between the number of cycles and degree of frost damage. Fagerlund [11] showed that a better durability indicator for frost is the critical moisture content. He showed that below the critical moisture content for frost no damage occurs, while above frost damage develops depending on the actual moisture content. Having determined the critical moisture content for frost (for a given degree of salinity in the material), one may use a HAM transport model to check if the actual moisture content exceeds the critical moisture content for frost at the same time as the freezing temperature occurs in the analyzed material layer.

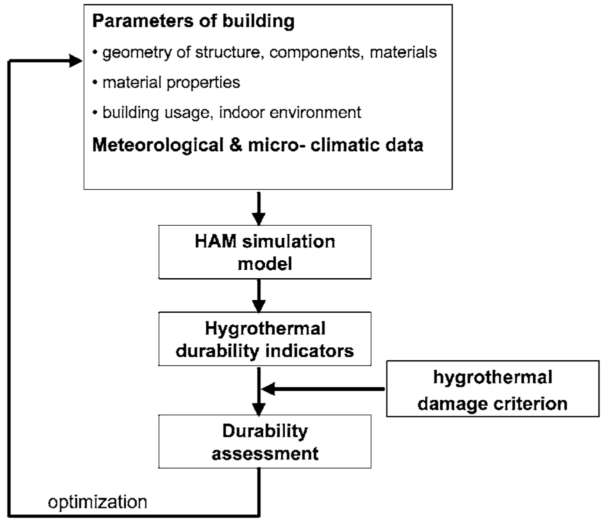
An example of a Type 3 durability indicator is the wetting time (the cumulative time when the critical moisture content is exceeded) which is used as durability indicator for mold growth or corrosion. We note that Type 2 and 3 durability indicators are often used for time dependent deterioration processes (e.g., wood rot, mold, and corrosion). Since it is difficult to explicitly model the time-dependent deterioration process itself, the analysis is mostly limited to HAM simulation of the moisture response. Consequently, a moisture response indicator (e.g., wetting time or moisture content of the material) is used as durability indicator and a critical moisture response is chosen as the damage criterion. As already mentioned, durability assessment methods based on *hygrothermal response* (Fig. 5(*a*)) are common in building physics because there are no adequate models for describing the actual deterioration processes.

Another option is to model the moisture-originated damage process itself. Failure is now assessed by comparing a damage evolution function with a critical value (damage criterion, see Fig. 5(*b*)). This option is called the *damage response* durability assessment method. Damage response methods can explicitly account for coupled effects: the influence of damage on material properties or the change of damage criterion due to damage (dotted lines in Fig. 5(*b*)). In the following sections we describe in more detail the hygrothermal and damage response durability assessment methods.

Hygrothermal Response Based Durability Assessment

In this approach the hygrothermal response indicator is compared with the critical level. The choice of indicators and critical levels is based on experimental testing of hygrothermal conditions associated with damage initiation and damage growth. Empirical models are formulated which correlate different damage growth regimes with hygrothermal indicators. In building physics, this approach is used for mold growth, wood rot, and frost damage. Possible indicators are a critical moisture content (CMC) or a combination of critical moisture content with other necessary conditions for deterioration, such as temperature.

Chapter 27 in this manual [12] presented a sequence of steps used in a design of an assembly that includes durability assessment based on hygrothermal response, namely:



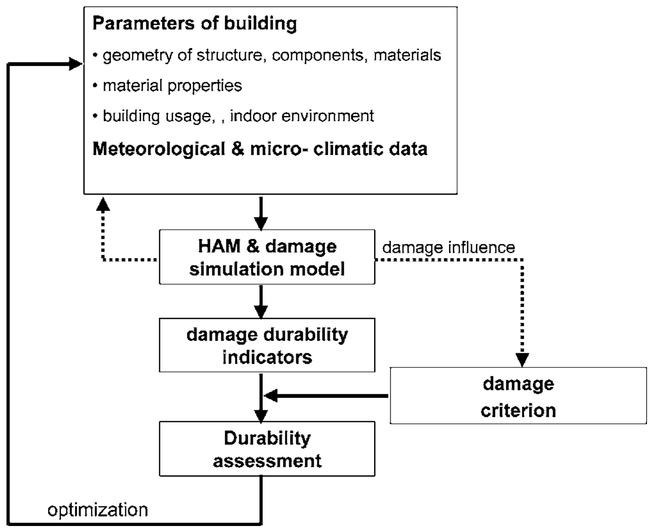


Fig. 5—(a) Flowchart for the hygrothermal response durability assessment method. (b) Flowchart for the damage response durability assessment method.

1. Selecting the material for initial analysis.
2. Identifying the environmental actions (sources of moisture).
3. Identifying transfer mechanisms (types of moisture flows and interactions between heat, air, and moisture and mechanical loads).
4. Predicting the distribution of moisture in the analyzed element at a given time under action of mechanical loads and environmental actions.
5. Identifying the damage criterion (permissible level of the selected hygrothermal parameters, e.g., critical moisture content and temperature).
6. If the failure is probable, modify the material selection in the assembly.

The example discussed in Chapter 27 is freeze-thaw action where damage can only occur above the critical moisture content and at temperatures below zero. Other examples of hygrothermal response indicators are: the mold

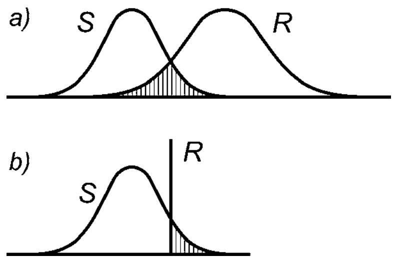


Fig. 6—(a) Performance limit *R* and response *S* probability density function. The failure probability is the overlap between the probability density functions of *R* and *S*. (b) Deterministic performance limit function *R* and probabilistic response function *S*.

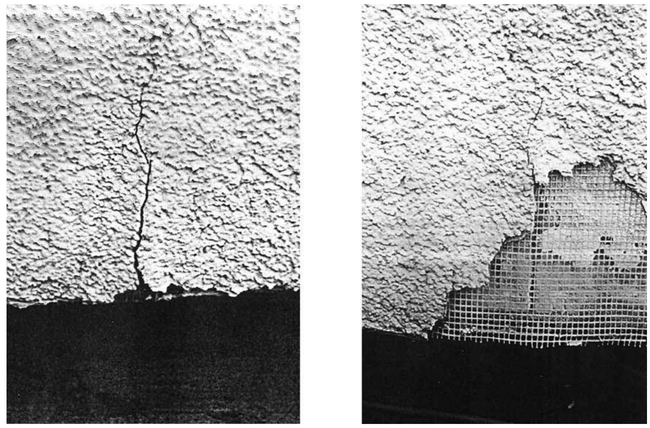


Fig. 7—Two stages in the deterioration process of an EIFS lamina. (a) Macrocrack development in lamina reinforced with a glass fiber fabric. (b) Delamination and complete failure of lamina due to frost. The water ingress beyond the lamina occurred through the macrocrack.

growth index [13], the frost durability factor [11], the RHT index [14], and the critical equilibrium humidity for dust mite activity [15].

Another type of hygrothermal response indicator was used by Janssens [16], where the onset of drainage of condensate was taken as the damage criterion when analyzing the durability of lightweight roof system exposed to interstitial condensation. Sedlbauer [17] developed a biohygrothermal model to predict the hygrothermal conditions of germination of spores in unsteady boundary conditions.

A lot of moisture originated damage processes are of the stochastic nature. In the hygrothermal response analyses the stochastic nature is taken into account by considering the hygrothermal material properties [18–20], the geometry and workmanship (gaps and defects [16]), inside and outside boundary conditions [21], human behavior such as moisture production [21,22] to be stochastic. The Critical Moisture Content (CMC) as damage criterion in these approaches is often considered to be deterministic (Fig. 6(*b*)). When it is necessary to take the stochastic nature of the damage process into account, the damage criterion is considered to be a random variable (Fig. 6(*a*)).

To evaluate the failure probability, different stochastic solution procedures are used. The Monte Carlo simulation method, because of its simplicity, is most frequently used to estimate mean response, variance, or failure risk. Recently first-order reliability methods are explored in building physics to calculate failure risks [23].

As previously mentioned, the damage criterion is compared with moisture response that is calculated with an advanced HAM model. Any simulation model has its validity conditions and its simplification assumptions concerning modeling of the involved physical phenomena. The reliability of the predicted responses also highly depends on the quality of the input data. As we shall discuss later, in recent years, several improvements have been proposed for input data to HAM models including moisture transport properties and boundary conditions such as driving rain on facades.

Damage Response Based Durability Assessment

In the damage response based approach the hygrothermal response and the resulting damage process are modeled directly. In this method, a damage criterion can be related to the damage process itself. Examples are damage initiation, maximal mechanical loading (tensile, compressive, or bending strength), extensive deformation (bending), macrocrack growth, crack width, instability [24], or structural collapse as well as to the effects environmental actions: corrosion, wood rot, etc. An example of the last is rain leakage originated by pitting corrosion in a zinc roof [25]. To evaluate the risk of rain leakage due to underside pitting corrosion, Zheng [25] developed a statistical model predicting the time dependent distribution of pit depths. Even an influence of the damage on the moisture behavior can be considered as damage function: such as loss of water (fluid) tightness due to extensive cracking [26].

Example of Damage Response Based Durability Assessment: Cracking of Lamina in Exterior Insulation Finish Systems

To illustrate the damage response based durability assessment method, the stochastic method as proposed by Carmeliet [27] is presented for analyzing the durability of EIFS lamina exposed to hygrothermal cycling caused by the exterior climate. An example of the considered damage pattern is given in Fig. 7. The different steps in evaluating the service life function are:

- *Identification of the damage mechanism*
  Rendering and lamina exposed to diurnal thermal variations (e.g., solar radiation during sunny days) experience nonuniform wetting/drying resulting in the build-up of eigenstresses. During the drying regime, the outer layer of the lamina is prevented from shrinkage by the underlaying layers. This leads to the development of tensile stresses in the outer layer (Fig. 8(*a*)). When the tensile strength is exceeded, microcracks originate. During cyclic loading these microcracks grow and coalesce into macrocracks. The macrocracks then grow from the outside to the inside of the lamina and finally lead to complete fracture of the lamina (Fig. 7(*a*)). In a second stage water ingress beyond the layers of lamina (through the crack) results in a complete degradation of the lamina (Fig. 7(*b*)).
- *Formulation of a deterministic damage model*
  The initiation of damage, growth, and localization of damage into macrocracks is described by a nonlocal

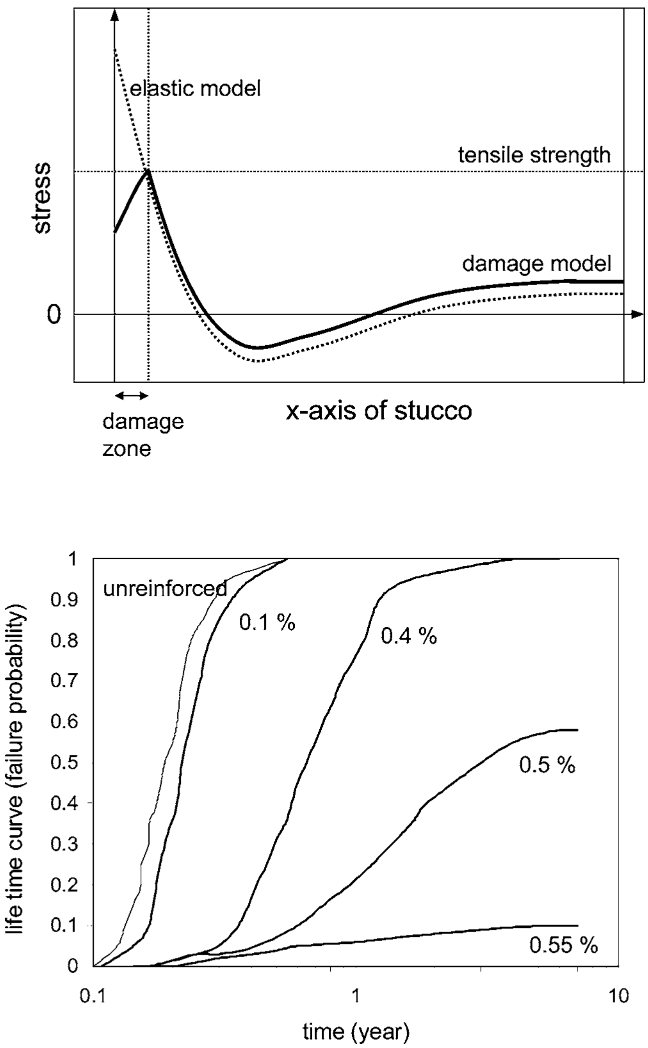


Fig. 8—(a) Distribution of the stress over the thickness of the lamina according to the elastic model and the damage model. Where the tensile strength is exceeded a damage zone characterized by microcracking develops and leads to a relaxation of the stresses. (b) Life time curves for unreinforced and reinforced laminas with different reinforcement volume percentages.

damage model [27]. In this model damage is considered to lead to a reduction of the stiffness of the material, or $E = (1-D)E_0$, with E_0 the initial stiffness and D the damage variable. D equal to zero means no damage, while $D=1$ indicates a total cracking of the material. The (uniaxial) constitutive law reads

$$\sigma = (1-D)E_0(\varepsilon - \varepsilon_0) \tag{5}$$

with σ the stress, E_0 the initial stiffness, ε the total strain, and ε_0 the free strain. The loading consists of the free hygrothermal shrinkage/swelling strains ε_0, which can be determined from the known temperature and moisture field in the EIFS system. The free hygrothermal strain is given by

$$\varepsilon_0 = \varepsilon_{0\theta} + \varepsilon_{0\phi} \tag{6}$$

with $\varepsilon_{0\theta}$ the thermal and $\varepsilon_{0\phi}$ the hygric free strain. The damage model is implemented in finite element code. It is assumed that the stiffness E is independent of moisture content and that the moisture transport properties do not change with damage. The reinforcement fabric is modeled as an elastic ideal brittle layer and the bonding to the lamina is modeled using a slip-shear interface model. The temperature/moisture field is determined using a control volume technique solving the coupled heat/moisture transport equations with appropriate boundary conditions.

- *Choice of an appropriate damage indicator*
  This choice should be based on the characteristics of the damage process, where damage first starts at the outer layer, then forming a macrocrack, which finally grows to the inside. A possible choice of damage criterion is the formation of a macrocrack over the total thickness of the stucco, which may initiate the total failure of the stucco by ingress of water beyond the stucco. Carmeliet [27] made a conservative choice by selecting the initiation of a macrocrack at the outer layer of the stucco, or $D_{x=0}=1$, as the damage criterion. This choice was motivated by the fact that the appearance of a macrocrack at the outside may initiate an esthetical degradation process of the lamina by staining of the macrocrack.
- *Statistical description of the basic variables* **X**
  Based on extensive material testing and sensitivity analysis it was found that among all the possible stochastic variables, the initial damage (or damage threshold) in the lamina is the most important parameter determining the durability. The distribution of initial damage (defects, microcracks due to autogeneous shrinkage, air bubbles) is modeled by a correlated random field, described by a distribution and correlation function. Also the fracture energy (energy necessary for a unit extension of the crack) is considered as a random variable correlated with the initial damage.
- *Stochastic calculation method*
  The service life function can be proven equal to the cumulative distribution function (cdf) of the lifetimes t_i. The cdf is calculated according to the Monte Carlo simulation technique. First, different realizations of the random field with initial damage are generated. Then, using the described damage model, the time until macrocrack initiation, or service life t_i is calculated.

Figure 8(*b*) gives as an example the service life curve calculated for an unreinforced lamina and laminas reinforced with different reinforcement volume percentages. The reinforcement is a glass fiber fabric. The unreinforced lamina has a limited lifetime. After one year the probability of macrocrack initiation is 100 %, meaning the stucco will fail at a given position after one year. Adding reinforcement ($V_f=0.1$, 0.4 %), we observe extension of the service life but the maximum probability of failure remains 100 %. For a reinforcement volume percentage of 0.5 %, the maximal failure probability decreases to 60 %, meaning that for 40 % of analyzed lamina macrocrack initiation does not occur. For a reinforcement volume percentage higher than 0.55 %, the failure probability becomes very low and no substantial improvement of durability can be obtained by further increasing the reinforcement percentage. The optimal reinforcement volume percentage is obtained. Carmeliet [27] also analyzed the influence of the type of lamina (the hygroscopicity and shrinkage behavior), the color, and the position of the reinforcement in the lamina on the EIFS durability.

Discussion on Methods for Durability Assessment

In this section we presented a general stochastic approach to durability assessment. Damage based approaches are clearly superior leading to a more accurate prediction of the service life of the building component because the damage based approach may:

- account for the time dependence of the damage process;
- account for the statistical nature of the damage process;
- choose a more appropriate damage criterion for the actual damage process;
- account for the coupling between loads, environmental actions, hygrothermal response, and the damage process.

  A survey of the literature shows, however, that the use of damage based assessment is limited [25,27]. This is caused by the lack of adequate models for predicting the damage process. Today, the durability assessment is mainly based on the analysis of the moisture response of building material or component.

Recent Developments in Durability Assessment of Moisture Originated Damage

As stated above, a damage based durability assessment method requires an accurate modeling of the environmental actions, the hygrothermal response, and the damage process. In this section, we briefly present new developments with regard to:

- *Environmental actions*: a numerical approach based on computational fluid dynamics (CFD) and particle tracking for the accurate prediction of driving rain loads on building facades has been presented;
- *Hygrothermal response*: new hygrothermal simulation models have been developed and validated; methods have been presented for an accurate determination of moisture transport properties;
- *Damage process*: coupled heat and mass transport and continuum (smeared) damage models have been developed in the framework of poromechanics. More recently discrete damage and transport models have been fully coupled also taking into account preferential flow in cracked media.

Advanced Modeling of Atmospheric Boundary Conditions

Wind-driven rain (or driving rain), i.e., rain that is carried by the wind and given a horizontal velocity component, is one of the most important moisture sources for building envelopes. Therefore, driving rain must be adequately taken into account as a boundary condition when assessing the moisture response and durability of building facades. It is generally accepted that the driving rain increases proportionally with (normal) wind speed and horizontal rainfall intensity

$$R_{dr} = \alpha U \cos \theta R_h \tag{7}$$

with R_{dr} the driving rain intensity impinging on a building facade, U the wind speed, θ the angle between the wind direction and the normal to the facade, $U \cos \theta$ the wind speed normal to the building facade also called the normal wind

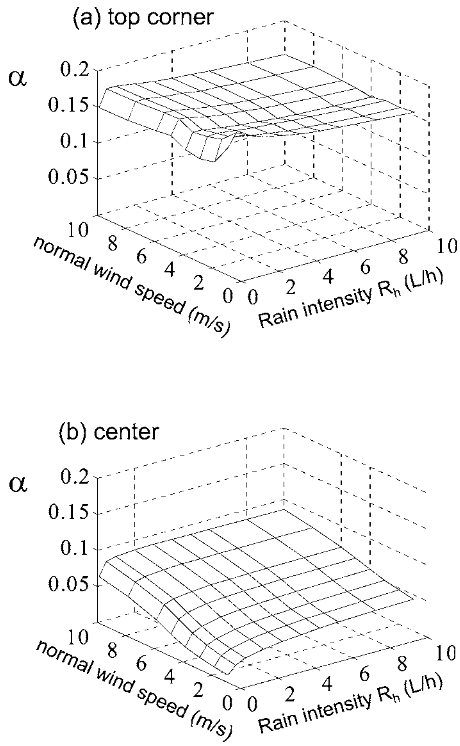


Fig. 9—Wind-driven rain coefficient α as function of the normal wind speed and horizontal rain intensity R_h for top corner (a) and center (b) of a cubic (10 by 10 by 10 m^2) building's facade.

speed, and R_h the horizontal rain intensity, or the rain intensity on a horizontal surface undisturbed by building or other effects. To take into account local phenomena induced by the topography and by the building itself, a driving rain coefficient "α" is introduced. The wind-driven-rain coefficient is generally taken constant for the whole building or for a given position on the building [28]. In Blocken [29] and Janssen et al. [30] it was shown that the driving rain coefficient depends on the rain event and thus varies with time. Blocken [29], Blocken and Carmeliet [31–34] proposed a numerical method that allows for the calculation of both the spatial and temporal distribution of driving rain on building facades based on generally available climatic data. The driving rain on the facade is calculated following a computational fluid dynamics (CFD) approach [35–39]. First the wind flow pattern around the building is calculated using CFD. The trajectories of the raindrops are calculated using 3-D Lagrangian particle tracking. Based on these CFD calculations a graph of the driving rain coefficient α against horizontal rain intensity R_h and normal wind speed $U \cos \theta$ for a given position on the facade can be determined. Figures 9 give as an example the $\alpha(R_h, U \cos \theta)$ chart for a cubic building (10 by 10 by 10 m^3) [30]. Given climatic data (wind speed, wind direction, rainfall intensity) the driving rain intensity can be calculated and taken as boundary condition for a HAM calculation model [40]. As an example, we give in Fig. 10 the variation of the calculated average and surface moisture content for a ceramic brick during December for the Essen climate (southwest orientation). We observe that a constant α-value as given by prEN 13013-3 [28] underestimates the moisture content in the brick. In Janssen et al. [30] methods were pro-

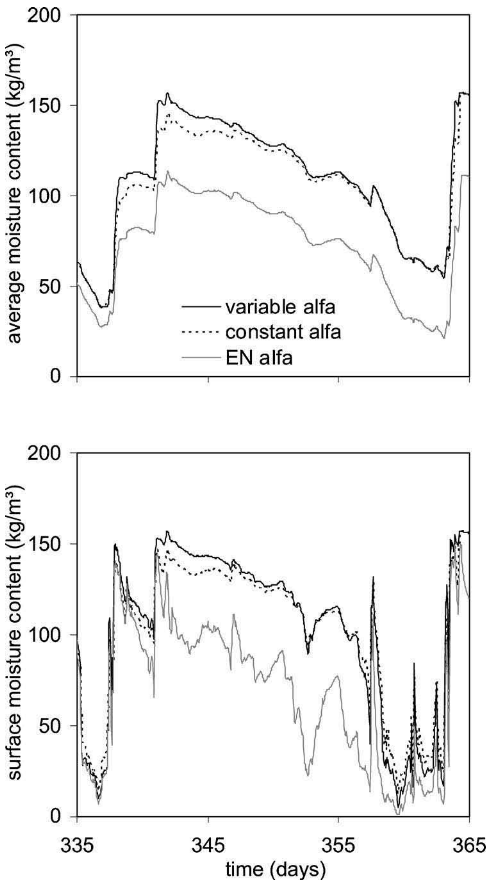


Fig. 10—Average (top) and surface (bottom) moisture contents of the ceramic brick for Southwest orientation (location center) in December: variable α, constant α as given in Janssen et al. [30], and α according to prEN 13013-3 [28].

posed to derive more accurate constant α-values from the $\alpha(R_h, U \cos\theta)$ chart. We observe that these constant α-values give better approximations compared to the constant α-values as given by prEN 13013-3 [28]. However, when analyzing possible runoff of rainwater on building facades, a time varying α-value is favorable. This means that for future use of driving rain as a boundary condition in numerical HAM models, a database of $\alpha(R_h, U \cos\theta)$ charts for different locations on different building types should be developed and connected to the existing HAM models. The prediction of wind-driven rain loads on building facades has been applied to the estimation of wind-driven rain infiltration loads. For example, Teasdale-St-Hilaire et al. [41,42] have developed a deterministic approach for a wetting methodology that simulates wind-driven rain infiltration for building envelope hygrothermal testing. In the methodology, water is inserted into the wall structure behind the cladding in a drop-by-drop fashion at a rate, frequency, and duration determined by a statistical analysis of long-term hourly weather data. The fraction of water that infiltrates through an intentional envelope defect is found by conducting a water leakage test based on ASTM E331-00(2009) [43].

Advanced Modeling of Moisture Transport Characteristics

Essential to a correct numerical prediction of the moisture response of building materials and components is:

- a validated HAM (heat, air, moisture) transport model;
- moisture transport characteristics, i.e., the moisture storage and permeability (moisture conductivity) for all materials involved in the analyzed building assembly.

Requirements for numerical HAM models and its validation are formulated by an international group and discussed by Hagentoft et al. [44]. More difficult is, however, ensuring that the moisture transport properties used in the HAM simulation are adequate for the given analysis. This difficulty stems from two reasons:

- each HAM model uses individually tailored sets of material characteristics,
- despite research [45–47] and despite an international proposal of recommendations for material characterization [48], recent hygrothermal databases include materials characteristics, which are not characterized in a fully rigorous manner. As an example, we mention the calculation of permeability from diffusivity and moisture retention curve leading to unrealistic values.
- For numerical modeling, material characteristics in functional form are advantageous. Which functions are most favorable to describe the moisture transport properties is still a matter of scientific debate. Moreover, the parameters describing these functions are until now only available for a limited number of materials. When functional descriptions of moisture transport characteristics are unavailable, tabular data (data points) with possible interpolation between them are still most often used.

On the other hand substantial progress has been made both on the scientific and engineering level to develop a consistent methodology of material characteristics determination. First, we give a short overview of scientific advances in moisture transport modeling. Then, we present an engineering approach based on the work of Grunewald et al. [49] and Scheffler et al. [50].

The moisture capacity is defined as the derivative of the moisture content curve to the driving potential: $\partial w / \partial p_c$ or $\partial w / \partial \phi$ with w the moisture content, p_c the capillary pressure, and ϕ the relative humidity. Necessary data can be obtained by a combination of different measurement techniques including pressure plate technique, mercury intrusion, micrography, and sorption isotherms [46,51]. Carmeliet and Roels [52] compared different parametric functions for describing the moisture capacity and showed that bimodal functions are preferable for approximating the moisture capacity both in hygroscopic and over-hygroscopic regions. To limit the experimental effort, a minimal number of optimally located data points is needed to identify the parameters. A model based on the presence of inkbottle pore systems was successfully applied to explain and predict hysteresis in moisture properties [45,53].

Descamps [54], Carmeliet et al. [55], and Carmeliet and Roels [56] proposed a multiscale pore network model as a practical method for estimating the moisture permeability covering hygroscopic and over-hygroscopic region including both water vapor and liquid water transfer. The proposed method requires as input the pore volume distribution (or capillary pressure curve), the capillary absorption coefficient and the water vapor permeability, as determined by standard experiments. Carmeliet et al. [57] proposed a new methodology for determining the liquid water diffusivity from the measured moisture content profiles. A critical overview of different nondestructive techniques for measuring the time evolution of moisture content profiles during water uptake is given in Roels et al. [58]. These authors also propose a parametric description for the moisture diffusivity covering both hygroscopic and overhygroscopic regions.

In the engineering moisture transport model [49], a minimal set of parameters for hygrothermal material characterization as input to HAM simulation programs is proposed. These basic parameters are determined in standard experiments: bulk density, porosity, thermal conductivity, sorption and retention data, water uptake experiments, water vapor diffusion, and drying experiments. The determination of the material model is based on a three-step approach:

1. Moisture capacity: selection of suitable material functions with sufficient flexibility to describe the nonlinear dependency (e.g., Gauss probability functions). In this step the moisture storage function is adjusted to measurement data.
2. Moisture transport characteristics. In this step a simple pore model is used to derive a conductivity (permeability) function, which is further calibrated with the capillary uptake experiment and water vapor permeability measured at high RH. The functional parameters are determined by indirect comparing the measured and simulated moisture response.
3. Validation. Comparison between measured and predicted behavior from experiments not having used for the identification. Isothermal drying experiments are used for this purpose.

Advanced Modeling of Coupled Moisture Transport and Damage Processes in Porous Building Materials and Structures

Poroelasticity

In this section, we present the poromechanical approach for taking into account the influence of moisture on the elastic behavior of porous materials. In Eq (5) the classical approach of introducing moisture effects using initial or free strains was presented. This approach, however, does not fully account for all coupling effects between moisture and mechanical behavior: changes in moisture saturation lead to a change in stiffness, strength, and to swelling or shrinkage. Using an uncoupled approach, these effects are described by empirical law, which requires intensive experimental testing. These moisture influences, however, originate from the same physical mechanisms situated at lower material scale. The poroelasticity offers a theoretical framework to take into account all coupling effects in a thermodynamically consistent manner.

Porous materials such as concrete and rocks are hydrophilic porous materials and contain a substantial specific pore surface area. As a result, they exhibit intense fluid-solid interactions because of molecular and surface forces. The induced forces are known to be extremely sensitive to the saturation level. Solid-fluid interaction forces are due to molecular adsorption forces along pore walls [59], water film pressure or spreading pressure [60], microscopic capillary pressures due to surface tension effects, and swelling (disjoining or interlayer) pressures due to the presence of interlayer water, e.g., in the laminar sheets of C-S-H (calcium-silicate-hydrate) in concrete [61–64]. Note that all these pressures are in reality 2-D interface or surface stresses. Pore pressures, due to the pressurization of the free pore water, are not considered in this paper since they are not governed by fluid-solid surface forces.

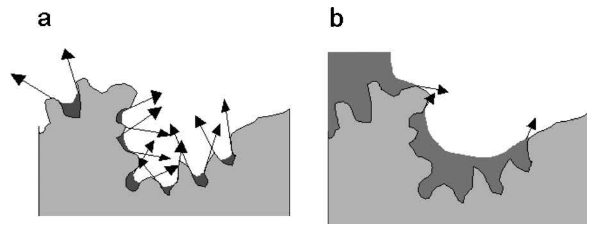


Fig. 11—Building of water menisci on the rough pore surface and surface tension effects at two different pore relative humidities. At low saturation (a) many menisci exist with low radius leading to high compressive prestresses to the solid matrix. At higher saturation (b) the radius increases and the amount of menisci decreases, leading to lower compressive prestresses.

First, let us review in more detail the effect of surface tension effects (capillary pressure), when water menisci build up in the porous material with increasing pore relative humidity. The pore surface can be considered as a very rough surface with a lot of possible places for building up water menisci or membranes introducing surface tension effects (Fig. 11). Commonly it is assumed that liquid water perfectly wets the solid (the contact angle equals 0°). Then $\gamma_{lg} = \gamma_{sg} (= \gamma)$ and $\gamma_{sl} = 0$, with $\gamma_{\alpha\beta}$ the surface tension in the $\alpha\beta$ interface (the subscript s refers to solid, g to gas, and l to liquid phase). Laplace's law describes the capillary pressure over the liquid water–water vapor interface

$$p_c = p_g - p_l = \frac{2\gamma}{R} \tag{8}$$

with R the radius of the spherical meniscus and $\gamma = \gamma_{lg}$. Since water is in tension the solid matrix will be exposed to compressive forces due to the action-reaction principle. At low relative humidity, we observe a large number of possible sites for membranes to build up (Fig. 11(*a*)). The membranes at these places have a relatively low equivalent radius R. Therefore, high compressive forces (or prestresses) are present. As the degree of saturation increases, the radius of the spherical membrane increases and at the same time the number of sites decreases (Fig. 11(*b*)). This results in an important decrease of the compressive prestresses with increasing degree of saturation.

Next, we will assume that all pore water in the microstructure is locally in thermodynamic equilibrium. Therefore, changes in microscopic capillary pressure will almost instantly result in changes of microscopic spreading pressure, swelling pressure, and interlayer water pressure. The net result of all moisture induced microstresses on the liquid can then be expressed at the macroscale by one macroscopic liquid pressure p_l. This macroscopic liquid pressure can be seen as the average result of all the microscopic pressures acting at the pore scale. Assuming the gaseous phase in thermodynamic equilibrium with the outside (p_g at constant atmospheric pressure) the macroscopic liquid pressure p_l can be replaced by the macroscopic capillary pressure p_c, which is commonly used in fluid transport modeling [65]. In this context, the macroscopic capillary pressure can be considered to be representative of the combined effects of all complex microscopic fluid-solid interaction forces.

All fluid-solid interaction forces show a tendency from high compressive prestresses (or low tensile prestresses) to low compressive prestresses (or high tensile prestresses) as saturation increases. As usually assumed, when upscaling these microstresses to the macroscale, the deviatoric prestresses completely balance and vanish. Only hydrostatic prestresses due to fluid-solid interaction are considered. Assuming isotropic, homogenous, and isothermal behavior, the incremental constitutive equation reads

$$d\sigma = K(\varepsilon,p_c)d\varepsilon + b(\varepsilon,p_c)dp_c \tag{9}$$

with σ the hydrostatic stress, ε the volumetric strain, K the tangent drained bulk modulus, p_c the capillary pressure, and b the tangent Biot or coupling coefficient. The tangent coupling coefficient b is normally proportional to the degree of saturation S

$$b = \left(1 - \frac{K}{K_s}\right)S = b'{*}S \tag{10}$$

with K_s the bulk modulus of the solid matrix. We assumed in Eq (9) that the gas pressure in the ideal mixture (water vapor and dry air) is in equilibrium with the environment and remains constant, or $dp_{mix}=0$. The study is limited to isothermal isotropic and uniaxial experiments. In this case, Eq (9) becomes

$$d\sigma_{11} = E(p_c)d\varepsilon_{11} + (1-2\nu)b'{*}S(p_c)dp_c \tag{11}$$

with E the isothermal Young's (tangent) modulus dependent on the capillary pressure and ν the Poisson ratio (which we assume to be independent of the capillary pressure). The relation between degree of saturation and capillary pressure is described by the capillary pressure curve $S(p_c)$. Integrating Eq (11) we get

$$\sigma_{11} = E(S)\varepsilon_{11} + b'(1-2\nu)\int_{p_c} S(p_c)dp_c \tag{12}$$

Let us now perform a free swelling/shrinkage experiment. A specimen is allowed to freely shrink/swell when changing the relative humidity, or $d\sigma_{11}=0$. According to Kelvin's law changes in relative humidity can be related to changes in capillary pressure

$$d\phi = -\frac{\phi}{\rho_l R_v T}dp_c \tag{13}$$

with R_v the gas constant for water vapor, T the absolute temperature, and ρ_l the volume density of liquid water. Using Eqs (11) and (13) with $d\sigma_{11}=0$, the swelling strain increment becomes

$$d\varepsilon_{11} = \frac{b'\rho_l R_v T}{(1-2\nu)E(S)}\frac{S(\phi)}{\phi}d\phi = \beta(\phi)d\phi \tag{14}$$

The coefficient β can be interpreted as the shrinkage coefficient which, according to the equation, is a function of the relative humidity, the stiffness of the material, and the coupling coefficient, which are parameters with a clear physical significance. In Fig. 12(*b*) the hygric strain predicted according to Eq (14) is compared to the experimental hygric strain as obtained in a free swelling experiment [66]. The material is a cellulose fiber cement composite. The elastic modulus was measured in a tensile experiment and equal to 12,370 MPa. The Poisson ratio is equal to 0.25. The coupling coefficient b' is found to be 0.79. The result shows the ability of the poroelastic theory to predict hygric shrinkage based on material properties with a physical meaning.

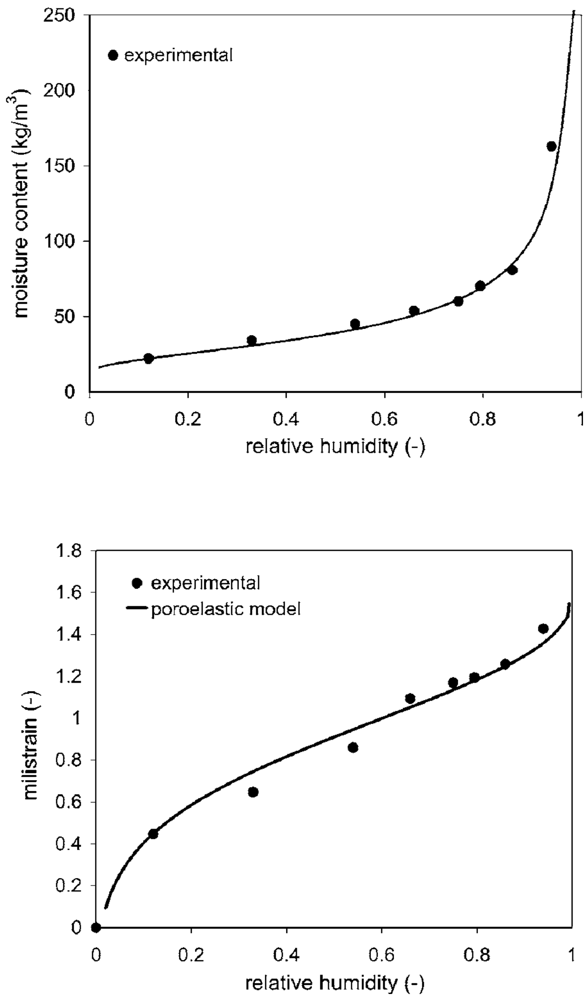


Fig. 12—(a) Experimental and fitted hygroscopic curve for cellulose fiber cement. (b) Comparison of the measured and predicted hygric strain.

Modeling Moisture Originated Damage Using Mixed Discrete and Continuum Approaches

Poroelasticity offers a framework to include moisture effects on the mechanical behavior of porous materials. Recently, poromechanical models have been extended to take into account damage and fracture processes. Poromechanical approaches are coupled to damage-plasticity models [67–71]. Based on these concepts, a coupled chemomechanical model describing chemical expansion [72] and calcium leaching [73] in saturated porous media has been formulated. These damage-plasticity models are continuum models, where localization in a macrocrack is handled using smeared or higher order approaches. The penetration of fluids through cracks is usually modeled by an increased per-

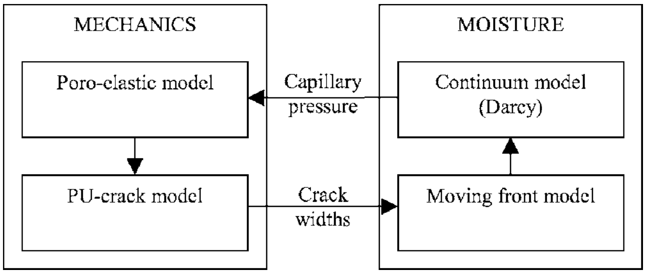


Fig. 13—Flow chart for the coupled discrete/continuum model.

meability in a certain zone, using empirical laws based on average crack widths. Drawback of a continuum model is that a crack strain over a band governs the damage process rather than a crack width. In this way the continuum model does not take into account the peculiar features of cracks with varying width and connectivity, which may highly influence the resulting permeability,see Ref. [74] among others. Apart from that, when trying to model the steep moisture fronts in the fracture, one is confronted with numerical instabilities [75]. This is a result of the highly nonlinear nature of the constitutive relationships and the strong contrast between physical transport properties of fractures and matrix.

To overcome this problem Roels et al. [76] presented a discrete model for the simulation of cracking and liquid flow in fractures. This discrete model for the fracture is coupled to poromechanical continuum models, describing the mechanical behavior and transport in the uncracked porous matrix (Fig. 13). The discrete model for the damage process is a partition-of-unity (PU) crack model [77]. Cracks are modeled as displacement continuities, which can run freely through the finite element mesh. To simulate moisture transport in the fractured porous matrix, a 1-D discrete model for liquid flow in a fracture is combined with a finite element model that solves the unsaturated liquid flow in the uncracked matrix [78]. To exemplify the potential of the proposed model, we show the load-deflection curves for a beam at different uniform moisture content subjected to three point bending (Fig. 14). The material is Berea sandstone. A

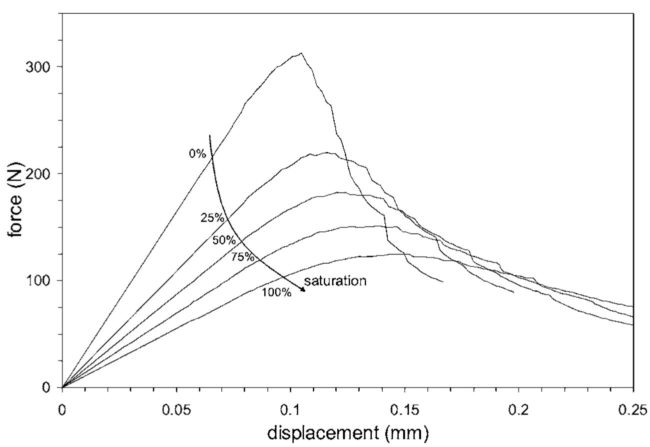


Fig. 14—The influence of a different (uniform) degree of saturation on the mechanical response during a three point bending test. With increasing saturation the maximal force diminishes and the damage behavior becomes more and more ductile.

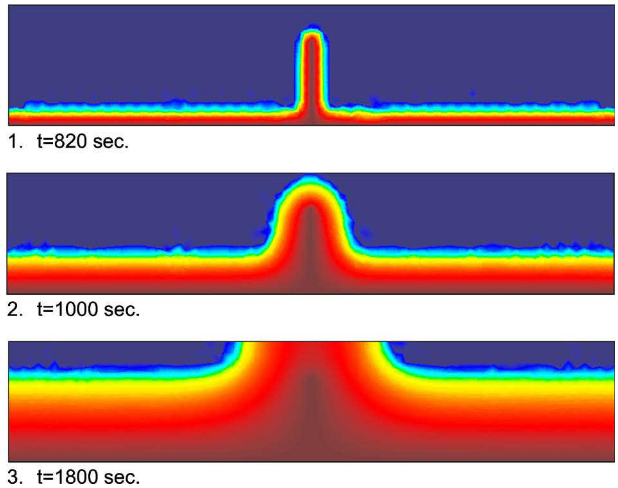


Fig. 15—Simulated moisture uptake in a loaded beam showing a macrocrack. The preferential wetting around the fracture is clearly observed.

substantial decrease of the maximal force can be noted with increasing moisture content. Furthermore, the response curves become more and more ductile when saturation increases. In a second example the beam is first loaded until cracking appears. Then, the beam is brought in contact with a free water plane at the bottom side. The moisture content profiles in the beam are given in Fig. 15. The waterfront in the fracture reaches the top side of the fracture in less than a second. From then on the fracture acts as an extra water source for the surrounding matrix over almost the total height of the beam.

Conclusions from the Review of the Recent Developments

The durability assessment includes the estimation of the probability of failure over the design life. Such an approach is based on the following steps: identification of the mechanism's response and deterioration, formulation of a mathematical model describing the mechanical loads and environmental actions as well as the resulting deterioration processes, the choice of appropriate durability indicators, and the statistical description of the basic variables. Finally, the service life function is evaluated using a stochastic calculation method. Different types of durability indicators may be used: a single occurrence of exceeding a critical level, the number of occurrences that a critical condition is exceeded, and the critical cumulative exposure.

Currently, the durability assessment is mainly based on the analysis of the hygrothermal response of building material or component. Damage based assessments are clearly superior leading to a more accurate prediction of the service life of the building component. Damage based approaches account both for the time dependence of hygrothermal response, and damage process. They can account for the coupling between hygrothermal loading, hygrothermal response and damage process. One may choose a more appropriate damage criterion and account for the statistical nature of hygrothermal response and damage process. The damage based methods necessitate not only a HAM transport model, but also the coupling to a damage evolution model. Coupled heat and mass transport and (continuum) damage models have been developed in the framework of poromechanics. More recently, discrete damage and transport models have been developed in a consistent manner taking into account, e.g., preferential flow in cracked media. Furthermore, this chapter reported new developments for prediction of driving rain loads on building facades and progress on determination of moisture transport properties.

Further Needs: Towards a Methodology for Integrated HAM Performance Assessment

In the preceding chapter we presented current developments in durability assessment. The need for further research in damage modeling coupled to HAM models was addressed. However, also in HAM modeling further developments are needed. The further needs in HAM research are addressed in this section.

The current numerical models to evaluate the hygrothermal behavior of building enclosures evolved from the Glaser method and, although commonly referred to as HAM-models (heat, air, and moisture), the influence of air transfer on the heat and moisture transport processes is still often neglected. A major reason is the vastly different timescales of the transport processes that pose severe problems in the numerical calculations. Use of a stabilized solution method for the transfer equations should, however, allow incorporating air transfer in hygrothermal simulations. Correct airflow analysis requires a correct implementation of the outside boundary conditions. Nowadays often a climatic data file of a nearby weather station is used, neglecting important local phenomena as differential air pressure differences and differential driving rain loads over the building envelope, film forming and run-off, differential solar radiation, and shadowing. In perspective of modeling airflows through envelopes and optimizing ventilation strategies, a correct prediction of the distribution of the air pressure differences is a prerequisite. Because of economical benefits, the use of CFD will become more and more widely used. However, and in particular, for structures with specific geometry (sharp shapes/edges) there is an important lack of validated situations on the basis of full-scale measurements. This is crucial for high wind speed regimes (with a focus on gust wind pressures on the building) but also for low wind speed regimes (for ventilation and comfort-related issues).

Regarding driving rain, a lot of progress has been made in the analysis and prediction of driving rain load on building facades. However, a thorough analysis of the influence of geometric details present in the facade such as small projections and of the influence of the surrounding environment (microclimate) on the driving rain load is lacking. Therefore, a first need is the detailed prediction of the microclimatic driving rain load. Furthermore, a correct incorporation of all contact and surface phenomena remains a missing link between the prediction of driving rain load over the building envelope and the hygrothermal simulations of the building enclosures. In relation to driving rain, leakage as possible internal moisture source for building enclosures has to be taken into account. There is still a need for a scientifically-based methodology for durability assessment when dealing with risks for leakage.

Also the indoor environment in HAM-models often only interferes as a simplified boundary condition. To more accurately predict indoor heat-air-moisture conditions integrated building simulation models are needed. At the moment, the main issue of building simulation models is the prediction of thermal conditions inside the building and of total energy consumption of the building. If included, moisture issues are commonly simplified to vapor transport and a certain moisture storage capacity of the interior. Recently, some steps have been made to merge building simulation models and hygrothermal building envelope models [79]. At the same time, advances in computational fluid dynamics (CFD) showed its possibilities to simulate bulk airflow both inside and around buildings. The current lack of a fully integrated approach towards building heat, air, and moisture engineering still impedes an adequate performance prediction for several applications. As an example, we mention the design of lightweight building constructions. The performances of lightweight building assemblies are extremely sensitive to convective heat and vapor transfer resulting from air leakage through the joints, cracks, and perforations, common to most existing methods of construction. In order to come to an adequate control of heat and moisture transfer in lightweight building components, the modeling capabilities of the existing HAM-tools should be coupled with models for the interior and exterior climate (indoor moisture load, indoor air pressure, gradients of wind pressure…). Accurate model predictions may form the basis for design criteria for air barriers, wind barriers, underlay systems, etc.

The major need for a whole building performance analysis concerns the simultaneous prediction of the temperature and humidity conditions of the indoor air and of the materials in the building envelope and interior. This asks for a correct coupling between indoor climate, building envelope, and outside climate. Hereby, building enclosures may no longer be treated as isolated, one-dimensional homogeneous components, but the interaction of the different building envelope parts on one another—as linked by the indoor environment—has to be incorporated. Therefore a first need is to model internal bulk flow in and between rooms. Current modeling can be categorized into three approaches with increasing resolution and complexity: (1) Building energy balance models (BES) that basically rely on guessed or estimated values of airflow; (2) Zonal airflow network (AFN) models that are based on (macroscopic) zone mass balance and inter-zone flow-pressure relationships typically for a whole building; and (3) CFD that is based on energy, mass, and momentum conservation in all (minuscule) cells that make up the flow domain (typically a single building zone). Regarding CFD, a lot of progress has been made in this field, but a reliable conflation of CFD, building simulation, and HAM envelope models is not so straightforward and remains extremely time consuming. Water vapor transport from/to walls and interior elements (so-called moisture buffering) is only recently taken into account in the moisture balance [79]. In order to use CFD for modeling HAM transport in buildings, classical CFD has to be extended and coupled to a HAM transport model for porous materials. Current state-of-the-art CFD does not offer the possibility to describe in an efficient and satisfying manner the interaction between fluid and solid material (boundary layer problem) for complex geometries. In these cases, the boundary layer problem can only be solved using very fine grids leading to unreasonable calculation times. The time constants of the convective (sensible) and latent heat transport differ an order of magnitude, leading to specific problems in attaining stable numerical solutions. Also moisture transport in porous materials adds a third time scale. The enrichment of classical CFD to a CFD-HAM model and the formulation of efficient solutions strategies necessitates an in-depth study.

So, although the need for whole building performance engineering is obvious, the challenge will be how to integrate or couple the different numerical models. We define coupled (integrated) simulation as two (or more) separate simulation tools, each of them solving a separate set of equations, exchanging time-step data in a prescribed manner. A coupled simulation usually involves the following components: (1) domain solvers: it must be clear which numerical code calculates which terms in the overall solution scheme; (2) geometry modeler and grid generator or both; (3) master program which coordinates the coupling procedure, e.g., frequency and point in the solution procedure where data are exchanged between the codes, definition of the variables that will be passed between the codes, method of time step control. Based on the interaction between the domain solvers, we further categorize coupled simulation into two categories: *internal coupling*, where the domain application is tailored to work specifically within a certain environment. Usually the code needs to be rewritten for this; and *external coupling*, where the domain application is not changed to cooperate with other domain application. External coupling is advantageous because of two main reasons: (1) individual domain applications have evolved separately over the years and are well proven. Making these different domain applications to communicate with each other would be a great advance to the building industry. Rewriting the code can be seen as a setback from these independent advances in the separate domains. (2) Each individual domain can be developed further independently. There is no need to worry about keeping up with the latest development in each domain. Let each domain expand and progress in their respective directions. As it is known how the domains can communicate with each other, it is possible to take advantage of these latest developments.

REFERENCES

[1] IEA-Annex 32, "Building Envelopes in a Holistic Perspective," International Energy Agency (IEA), Energy Conservation in Buildings and Community Systems (ECBCS), Annex 32, Task A, Leo Hendriks and Hugo Hens, Laboratorium Bouwfysica, K.U. Leuven, Leuven.

[2] Hens, H. and Carmeliet, J., "Performance Prediction for Masonry Walls with EIFS Using Calculation Procedures and Laboratory Testing," *Journal of Thermal Envelope and Building Science*, Vol. 25, 2002, pp. 167–187.

[3] IEA-Annex 24, "Heat, Air, and Moisture Transfer through New and Retrofitted Insulated Envelope Parts (Hamtie)," International Energy Agency (IEA), Energy Conservation in Buildings and Community Systems (ECBCS), Annex 24, Task 5: "Performances and Practice, The Impact of Heat, Air and Moisture Transport on Energy Demand and Durability," Carl-Eric Hagentoft, Laboratorium Bouwfysica, K.U. Leuven, Print Acco Leuven, 1998.

[4] Bomberg, M. and Allen, D., "Use of Generalized Limits State Method in Design of Building Envelopes for Durability," *J. Thermal Ins. and Bldg. Envs.*, Vol. 20, July 1996, pp. 18–39.

[5] Allen, D. and Bomberg, M., "Limits State Method in Design of Building Envelopes for Durability," 7th Canadian Building Science and Technology Conference, Toronto March 20–21, 1997.

[6] Mehta, P. K., "Durability-Critical Issues for the Future," *Concr. Int.* 1997, pp. 27–33.

[7] Harderup, E., "Methods for Determining of the Risk of Critical Moisture Conditions with Natural External Climate," *Proceedings Building Physics in the Nordic Countries*, VTT, Finland, 1996.

[8] Gertis, K., Kiessl, K., Nannen, D., and Walk, R., "Wärmespannungen in Thermohaut-Systemen Voruntersuchung unter idealisierten Randbedingungen," *Die Bautechnik*, Vol. 5, 1983, pp. 155–162.

[9] Nannen, D. and Gertis, K., "Thermische Spannungen in Wärmedämmverbund-systemen," *Bauphysik* Vol. 6, No. 4, 1984, pp. 126–136.

[10] Fink, R., *Eigenspannungen in Zweischichtsystemen, Bauphysik*, Vol. 13, No. 3, 1991, pp. 85–91.

[11] Fagerlund, G., "Assessment of the Service Life of Materials Exposed to Frost," Div. of Building Materials, Lund University, Sweden. Durability of Building Materials and Components 7, Stockholm Sweden, May 1996.

[12] Bomberg, M. T. and Shirtliffe, C. J., "A Conceptual System of Moisture Performance Analysis," Manual on Moisture Control in Buildings, *ASTM Manual 18*, ASTM International, West Conshohocken, PA, 1994, pp. 453–461.

[13] Hukka, A., and Viitanen, H., "A Mathematical Model of Mold Growth on Wooden Material," *Wood Sci. Technol.* Vol. 33, No. 6, 1999, pp. 475–485.

[14] Kumaran, M. K., Mukhopadhyaya, P., Cornick, S., Lacasse, M., Maref, W., Rousseau, M., Nofal, M., Quirt, J., and Dalgliesh, W., "A Methodology to Develop Moisture Management Strategies for Wood-frame Walls in North America: Application to Stucco-clad Walls," *6th Symposium on Building Physics in the Nordic Countries*, 2002.

[15] Baker, P., Hunter, C., Galbraith, G. H., McLean, R. C., and Sanders, C., "Measurement and Prediction of Indoor Microenvironment for the Control of Biocontaminants," *CIB W40 Conference Papers*, Centre for Research on Indoor Climate and Health, School of Engineering, Science and Design, Glasgow, 2004.

[16] Janssens, A., "Reliable Control of Interstitial Condensation in Lightweight Roof Systems," Ph.D. Thesis, Katholieke Universiteit Leuven, Departement Burgerluke Bouwkunde, Leuven, Belgium, 1998.

[17] Sedlbauer, K., Vorhersage von Schimmelpilzbildung auf an in Bauteilen, "Prediction of Mold Manifestation On and In Building Parts," Dissertation Universität Stuttgart, 2001.

[18] Karagiozis, A. and Salonvaara, M., "Parametric Study on Material Properties Using Stochastic Modeling," IEA Annex 24 Task 1: Simplified Modeling.

[19] Nielsen, A., "Use of Statistics for Prediction of Risk for Condensation in a Wall Construction," *Moisture Problems in Building Walls, Porto CIB W40 Meeting*, 1985.

[20] Holm, A., "Ermittlung der Genauigkeit van instationären hygrothermischen Bauteilberechnungen mittels eines stochastischen Konzeptes," Dissertation Universität Stuttgart, 2001.

[21] Harderup, L.-E., "Simplified Statistical Method to Determine the Risk of Condensation by Diffusion in Building Elements," *Proceedings of the 5th Symposium on Building Physics in the Nordic Countries*, Chalmers University of Technology, Göteborg, Sweden, 1999, pp. 537–544.

[22] Pietrzyk, K., "Probabilistic Modeling of Air Infiltration and

Heat Loss in Low-rise Buildings," Ph.D. Thesis, ISBN 91-7197-961-1, Chalmers University of Technology, Gothenburg, Sweden, 2000.
[23] Pietrzyk, K., Kurkinen, K., and Hagentoft, C.-E., "An Example of Application of Limit State Approach for Reliability Analysis of Moisture Performance of a Building Component," *Journal of Thermal Envelope and Building Science*, Vol. 28, 2004, pp. 9–26.
[24] Carmeliet, J., and de Borst, R., "Gradient Damage and Reliability: Instability as Limit State Function," *Framcos-2, 2nd Conference on Fracture Mechanics of Concrete and Concrete Structures*, F. H. Wittmann, Ed., Aedificatio Publ., 1995, pp. 1011–1021.
[25] Zheng, R., "Performance of Highly Insulated Zinc Roofs in Moderate Humid Regions," Ph.D. Dissertation, Leuven, K.U.Leuven, 2004.
[26] Reinhardt, H. W., "Penetration and Permeability of Concrete, Barriers to Organic and Contaminating Liquids," Rilem Report 16, E&FN Spon, 1997.
[27] Carmeliet, J., "Durability of Fiber Reinforced Renderings on Outside Insulation: A Probabilistic Approach Based on Nonlocal Damage Theory," Ph.D. Thesis, Laboratory of Building Physics, K.U. Leuven, Belgium, 1992.
[28] prEN 13013-3, "Hygrothermal Performance of Buildings—Climatic Data—Part 3: Calculation of a Driving Rain Index for Vertical Surfaces from Hourly Wind and Rain Data (prenormative text)," 1977.
[29] Blocken, B., "Wind-driven Rain on Buildings—Measurements, Numerical Modeling and Applications," Doctoral Dissertation, Katholieke Universiteit Leuven, Belgium, 2004.
[30] Janssen, H., Blocken, B., Roels, S., and Carmeliet, J., "Wind-driven Rain as a Boundary Condition for HAM Simulations: Analysis of Simplified Modeling Approaches," submitted to *Build. Environ.* 2004.
[31] Blocken, B., and Carmeliet, J., "Driving Rain on Building Envelopes—I: Numerical Estimation and Full-scale Experimental Verification," *Journal of Thermal Envelope and Building Science*, Vol. 24, No. 1, July 2000, pp. 61–85.
[32] Blocken, B. and Carmeliet, J., "Driving Rain on Building Envelopes—II: Representative Experimental Data for Driving Rain Estimation," *Journal of Thermal Envelope and Building Science*, Vol. 24, No. 2, Oct. 2000, pp. 89–110.
[33] Blocken, B. and Carmeliet, J., "Spatial and Temporal Distribution of Driving Rain on a Low-rise Building," *Wind Struct.* Vol. 5, No. 5, 2002, pp. 441–462.
[34] Blocken, B., and Carmeliet, J., "A Review of Wind-driven Rain Research in Building Science," *J. Wind. Eng. Ind. Aerodyn.* Vol. 92, 2004, pp. 1079–1130.
[35] Choi, E. C. C., "Simulation of Wind-driven Rain Around a Building," *J. Wind. Eng. Ind. Aerodyn.* Vols. 46 and 47, 1993, pp. 721–729.
[36] Wisse, J. A., "Driving Rain, a Numerical Study," *Proceedings of 9th Symposium on Building Physics and Building Climatology*, Dresden, Sept. 14–16, 1994.
[37] Karagiozis, A., Hadjisophocleous, G., and Cao, S., "Wind-driven Rain Distributions on Two Buildings," *J. Wind. Eng. Ind. Aerodyn.* Vols. 67 and 68, 1997, pp. 559–572.
[38] Van Mook, F. J. R., "Driving Rain on Building Envelopes," Ph.D. Thesis. Building Physics Group, (FAGO), Eindhoven University of Technology, Eindhoven University Press, Eindhoven, The Netherlands, 2002, 198 pp.
[39] Etyemezian, V., Davidson, C. I., Zufall, M., Dai, W., Finger, S., and Striegel, M., "Impingement of Rain Drops on a Tall Building," *Atmos. Environ.* Vol. 34, 2000, pp. 2399–2412.
[40] Janssen, H., "The Influence of Soil Moisture Transfer on Building Heat Loss Via the Ground," Doctoral Dissertation, Katholieke Universiteit Leuven, Belgium, 2002.
[41] Teasdale-St-Hilaire, A., Derome, D., and Fazio, P., "Development of an Experimental Methodology for the Simulation of Wetting Due to Rain Infiltration for Building Envelope Testing," *Proceedings of the 2nd International Building Physics Conference*, Balkema, Leuven, Belgium, Sept. 14–18, 2003, pp. 455–462.
[42] Teasdale-St-Hilaire, A., Derome, D., and Fazio, P., "Behavior of Wall Assemblies with Different Wood Sheathings Wetted by Simulated Rain Penetration," *Performance of Exterior Envelopes of Whole Buildings IX: International Conference*, ASHRAE, Clearwater Beach, FL, Dec. 5–10, 2004, 15 pp.
[43] ASTM Standard E331–00(2009), "Standard Test Method for Water Penetration of Exterior Windows, Skylights, Doors, and Curtain Walls by Uniform Static Air Pressure Difference," *Annual Book of ASTM Standards*, ASTM International, West Conshohocken, PA, 2000.
[44] Hagentoft, C. E., Kalagasidis, A. S., Adl-Zarrabi, B., Roels, S., Carmeliet, J., Hens, H., Grunewald, J., Kunk, M., Becker, R., Shamir, D., Adan, O., Brocken, H., Kumaran, K., and Djebbar, R., "Assessment Method for Numerical Prediction Models for Combined Heat, Air and Moisture Transfer in Building Components: Benchmarks for One-dimensional Cases," *Journal of Thermal Envelope and Building Science*, Vol. 27, No. 4, April 2004, p. 307-327-352.
[45] Roels, S., "Modeling Unsaturated Moisture Transport in Heterogeneous Limestone," Ph.D. Dissertation, Leuven: K.U.-Leuven, 2000.
[46] Roels, S., Elsen, J., Carmeliet, J., and Hens, H., "Pore Volume Distribution Determination of Limestone Combining Mercury Porosimetry and Micrography," *Mater. Struct.* Vol. 34, 2001, pp. 76–82.
[47] Bomberg, M., Haghighat, F., Grunewald, J., and Plagge, R., "Capillary Transition Point as a Material Characteristic for HAM Models," *4th International Conference on Indoor Air Quality, Ventilation and Energy Conservation in Buildings*, Vol. 2, 2002, pp. 755–763.
[48] Bomberg, M., Carmeliet, J., Grunewald, J., Holm, A., Karagiozis, A., Kuenzel, H., and Roels, S., "Position Paper on Material Characterization and HAM Model Benchmarking," *Nordic Building Physics Symposium*, Vol. 1, 2002, pp. 143–150.
[49] Grunewald, J., Häupl, P., and Bomberg, M., "Towards an Engineering Model of Material Characteristics for Input to Ham Transport Simulations—Part 1: An Approach," *Journal of Thermal Envelope and Building Science*, Vol. 26, No. 4, 2003, pp. 343–366.
[50] Scheffler, G., Grunewald, J., and Häupl, P., "Calibration of an Engineering Model of Hygrothermal Material Characteristics," IEA Annex41-report, Glasgow, Oct. 2004.
[51] Roels, S., Carmeliet, J., Hens, H., Adan, O., Brocken, H., Cerny, R., Pavlik, Z., Hall, C., Kumaran, K., Pel, L., and Plagge, R., "Interlaboratory Comparison of Hygric Properties of Porous Building Materials," *Journal of Thermal Envelope and Building Science*, Vol. 27, No. 4, April 2004, p. 307-305-325.
[52] Carmeliet, J. and Roels, S., "Determination of the Moisture Capacity of Porous Building Materials," *Journal of Thermal Envelope and Building Science*, Vol. 25, No. 3, 2002, pp. 209–237.
[53] Carmeliet, J., Gaublomme, J., and Janssen, H., "Influence of Hysteresis on the Moisture Buffering of Wood," IEA. Annex41-Report, Glasgow, Oct. 2004.
[54] Descamps, F., "Continuum and Discrete Modelling of Isothermal Water and Air Transfer in Porous Media," Ph.D. Thesis, Catholic University of Leuven, Leuven, 1997.
[55] Carmeliet, J., Descamps, F., and Houvenaghel, G., "Multiscale Network Model for Simulating Liquid Water and Water

Vapour Transfer Properties of Porous Materials," *Transp. Porous Media*, Vol. 35, 1999, pp. 67–88.

[56] Carmeliet, J., and Roels, S., "Determination of the Isothermal Moisture Transport Properties of Porous Building Materials," *Journal of Thermal Envelope and Building Science*, 24, 2001, pp. 183–210.

[57] Carmeliet, J., Hens, H., Roels, S., Adan, O., Brocken, H., Cerny, R., Pavlik, Z., Hall, C., Kumaran, K., and Pel, L., "Determination of the Liquid Water Diffusivity from Transient Moisture Transfer Experiments," *Journal of Thermal Envelope and Building Science*, Vol. 27, No. 4, April 2004, pp. 277–305

[58] Roels, S., Carmeliet, J., Hens, H., Adan, O., Brocken, H., Cerny, R., Pavlik, Z., Ellis, A. T., Hall, C., Kumaran, K., Pel, L., and Plagge, R., "Comparison of Different Techniques to Quantify Moisture Content Profiles in Porous Building Materials," *Journal of Thermal Envelope and Building Science*, Vol. 27, No. 4, April 2004 pp. 261–276.

[59] Israelachvili, J. N., *Intermolecular and Surface Forces With Application to Colloidal and Biological Systems*, Academic Press, London, 1985.

[60] Yates, D. J. C., "The Expansion of Porous Glass on the Adsorption of Non-polar Gases," *Proc. Royal Soc. London*, Vol. A224, 1954, pp. 526–543.

[61] Bažant, Z. P., "Constitutive Equation for Concrete Creep and Shrinkage Based on Thermodynamics of Multi-phase Systems," *Mater. Struct.*, Vol. 3, 1970, pp. 3–36.

[62] Bažant, Z. P., Hauggaard, A. B., Baweja, S., and Ulm, F.-J., "Microprestress Solidification Theory for Concrete Creep., I. Aging and Drying Effects," *J. Eng. Mech.* Vol. 123, 1997, pp. 1188–1194.

[63] Powers, T. C., "Mechanism of Shrinkage and Reversible Creep of Hardened Cement Paste," *Proceedings, International Conference on the Structure of Concrete*, Cement and Concrete Association, London, U.K., 1965, pp. 319–344.

[64] Wittmann, F. H., Bestimmung physikalischer Eigenschaften des Zemmentsteins. Deutscher Ausschuss fur Stahlbeton, *Heft 232, W. Ernst & Sohn, Berlin*, 1974, pp. 1–63.

[65] Bear, J., and Bachmat, Y., *Introduction to Modeling of Transport Phenomena in Porous Media*, Kluwer Academic Publishers, Dordrecht, 1991.

[66] Carmeliet, J., "Coupling of Damage and Fluid-Solid Interactions in Quasi-brittle Nonsaturated Porous Materials," *Iutam Symposium on Theoretical and Numerical Methods in Continuum Mechanics of Porous Materials*, Stuttgart, Sept. 5–10, 1999.

[67] Baggio, P., Majorana, C. E., and Schrefler, B. A., "Thermo-hygro-mechanical Analysis of Concrete" *J. Eng. Mech.* Vol. 126, 2000, pp. 223–242.

[68] Coussy, O., *Mechanics of Porous Continua*, John Wiley & Sons, Chichester, 1995.

[69] Coussy, O., Eymard, R., and Lassabatère, T., "Constitutive Modelling of Unsaturated Drying Deformable Materials," *J. Eng. Mech.* 1998, pp. 658–667.

[70] Grasberger, S., and Meschke, G., "Numerical Simulation of Coupled Thermo-Hygro-Mechanical Processes Within Concrete," *6th International Conference on Creep, Shrinkage and Durability of Concrete and other Quasi-Brittle Materials* (*Concreep 6*), Cambridge, USA, 2001.

[71] Lewis, R. W., and Schrefler, B. A., *The Finite Element Method in the Static and Dynamic Deformation and Consolidation of Porous Media*, John Wiley & Sons, Chichester, 1998.

[72] Coussy, O., Ulm, F.-J., and Mainguy, M., "A Short Course on Environmental Mechanics of Concrete," Lecture notes, Udine, 1999.

[73] Ulm, F.-J., Torrenti, J.-M., and Adenot, F., "Chemoporoplasticity of Calcium Leaching in Concrete, *J. Engineering Mech.* Vol. 125, 1999, pp. 1200–1211.

[74] Carmeliet, J., Delerue, J. F., Vandersteen, K., and Roels, S., "Three-dimensional Liquid Transport in Concrete Cracks," *Int. J. Numer. Analyt. Meth. Geomech.* Vol. 28, 2004, pp. 671–687.

[75] Therrien, R., and Sudicky, E. A., "Three-dimensional Analysis of Variably-saturated Flow and Solute Transport in Discretely-fractured Porous Media," *J. Contam. Hydrol.* Vol. 23, 1996, pp. 1–44.

[76] Roels, S., de Proft, K., and Carmeliet, J., "A Coupled Discrete Approach to Simulate Moisture Effects on Damage Processes in Porous Materials," submitted for publication in *Comput. Methods Appl. Mech. Eng.* 2004.

[77] de Proft, K., "A Combined Experimental Computational Study to Discrete Fracture of Brittle Materials," Ph.D. Thesis, Vrije Universiteit Brussel, 2003.

[78] Roels, S., Vandersteen, K., and Carmeliet, J., "Measuring and Simulating Moisture Uptake in a Fractured Porous Medium," *Adv. Water Resour.* Vol. 26, 2003, pp. 237–246.

[79] IEA-Annex 41, "Whole Building Heat, Air and Moisture Response," International Energy Agency (IEA), Energy Conservation in Buildings and Community Systems (ECBCS), http://www.kuleuven.be/bwf/projects/annex41/index.htm, 2005.

Subject Index

A

B

C

D

E

F

G

H

I

J

K

L

M

N

O

P

Q

R

S

T

U

V

W

Heinz R. Trechsel has been consulting on moisture problems in buildings for over 25 years, has managed design contracts for the Naval Facilities Engineering Command (USN), managed the Energy Conservation research program for NBS (now the National Institute for Standards and Technology), and developed innovative building products and systems for the steel industry.

Trechsel is a graduate architect of the Swiss Federal Institute of Technology in Zürich and a registered architect in the State of New York.

As a member of ASTM since 1961 he is currently active in Committees C16 on Thermal Insulation and E06 on Performance of Buildings and has been chairman of several subcommittees. He received the ASTM Award of Merit in 1986. Trechsel also is a member of the National Institute of Building Sciences (NIBS) and was chairman of its Building Enclosure Technology and Environment Council (BETEC).

Trechsel has published extensively on moisture control and on energy conservation in buildings. He was editor of the first edition of MNL18, *Moisture Control in Buildings*, published in 1994; Manual 40, *Moisture Analysis and Condensation Control in Building Envelopes;* Co-editor of ASTM STP 719, *Building Air Change Rate and Infiltration Measurements*; STP 779, *Moisture Migration in Buildings*; STP 904, *Measured Air Leakage of Buildings*; and STP 1039, *Water Vapor Transmission through Building Materials and Systems* (with Dr. Mark Bomberg).

Mark T. Bomberg obtained the title of Technology Doctor at the Lund University for research on moisture transport in building materials and has been involved in the field of building physics for over 35 years (25 years at the National Research Council of Canada and 10 years in academia). Bomberg also earned Doctor of Science (Engineering) from Warsaw Technical University, Poland where he previously graduated in civil engineering.

He currently leads the hygrothermal program at Syracuse University, Syracuse, New York. An ASTM member since 1976, he is active in Committees C16 on Thermal Insulation and E06 on Performance of Buildings, he is also the recipient of the 2009 C16 David L. McElroy Award. He is a co-leader in the field of heat, air and moisture in the Building Enclosure Technology and Environment Council (BETEC) at the National Institute of Building Science and one of the organizers of the BEST conferences (www.thebestconference.org) where he chairs the energy efficiency track.

Bomberg has more than 200 research papers and several book chapters in the area of building physics; he co-edited with Heinz Trechsel ASTM STP 1039, *Water Vapor Transmission through Building Materials and Systems*. Worth mentioning is M.T. Bomberg and J.W. Lstiburek, *Spray Foam in External Envelopes of Buildings*, published in 1998 by Technomic Publication Corporation; the third edition was reprinted by CRC Press in 2006.

www.astm.org

ISBN: 978-0-8031-7004-9
Stock #: MNL18-2nd