

THERMAL AND MOISTURE CONTROL IN INSULATED ASSEMBLIES—FUNDAMENTALS

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PROPER DESIGN of space heating, air-conditioning, refrigeration, and other industrial systems requires knowledge of thermal insulations and thermal-moisture behavior of building structures. This chapter deals with heat and moisture transfer definitions, fundamentals and properties of thermal insulation materials, heat flow calculations, economic thickness of insulation, and the fundamentals of moisture as it relates to building components and systems.

TERMINOLOGY AND SYMBOLS

The following heat and moisture transfer definitions and symbols are commonly used in the building industry.

Thermal transmission, heat transfer, or rate of heat flow. The flow of heat energy induced by a temperature difference. Heat may be transferred by conduction, convection, radiation, and mass transfer. These can occur separately or in combinations, depending on specific circumstances.

Thermal conductivity, k . The time rate of heat flow through a unit area of 1 m thick homogeneous material in a direction perpendicular to isothermal planes, induced by a unit temperature gradient. (ASTM Standard C 168 defines homogeneity.) Units are W/(m·K). Thermal conductivity must be evaluated for a specific mean temperature and moisture content, because in most materials it varies with temperature and moisture content.

For porous materials, heat flows by a combination of modes and may depend on orientation, direction, or both. The measured property of such materials may be called **effective** or **apparent thermal conductivity**. The specific test conditions (i.e., sample thickness, orientation, environment, environmental pressure, surface temperature, mean temperature, temperature difference, and moisture content) should be reported with the values. With thermal conductivity, the symbol k_{app} is used to denote the lack of pure conduction or to indicate that all values reported are apparent.

Thermal resistivity, R_{μ} . The reciprocal of thermal conductivity. Units are m·K/W.

Thermal conductance, C-factor, C . The time rate of heat flow through a unit area of a body induced by a unit temperature difference between the body surfaces. Units are W/(m²·K).

When the two defined surfaces of mass-type (i.e., nonreflective) thermal insulation have unequal areas, as in the case of radial heat flow through a curved block or through a pipe covering (see [Table 2 in Chapter 3](#)), or through materials of nonuniform thickness, an appropriate mean area and mean thickness must be given. Heat flow formulas involving materials that are not uniform slabs must contain *shape factors* to account for the area variation involved.

When heat flow occurs by conduction alone, the thermal conductance of a material may be obtained by dividing the thermal conductivity of the material by its thickness. When several modes of heat transfer are involved, the **apparent** or **effective thermal conductance** may be obtained by dividing the apparent thermal conductivity by the thickness.

Where air circulates within or passes through insulation, as it may with low-density fibrous materials, the effective thermal conductance is affected.

Thermal conductances and resistances of the more common building materials and industrial insulations are tabulated in [Table 4 in Chapter 25](#).

Heat transfer film coefficient (or surface coefficient of heat transfer or surface film conductance), h or f . Heat transferred between a surface and a fluid per unit time per unit area driven by a unit temperature difference between the surface and the fluid in contact with it, in W/(m²·K).

Surface film resistance. The reciprocal of the heat transfer film coefficient, in m²·K/W. Subscripts *i* and *o* often denote inside and outside surface resistances and conductances, respectively.

The surrounding space must be air or other fluids for convection to take place. If the space is evacuated, the heat flow only occurs by radiation.

Thermal resistance R-value, R . Under steady-state conditions, the mean temperature difference between two defined surfaces of material or construction that induces unit heat flow through a unit area, in m²·K/W.

Thermal transmittance, U-factor, U . The rate of heat flow per unit area under steady-state conditions from the fluid on the warm side of a barrier to the fluid on the cold side, per unit temperature difference between the two fluids. It is determined by first evaluating the R-value, including the surface film resistances, and then computing its reciprocal, U , in W/(m²·K). The U-factor is sometimes called the **overall coefficient of heat transfer**. In building

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practice, the heat transfer fluid is air. The temperature of the fluid is obtained by averaging its temperature over a finite region near the surface involved.

Thermal emittance, ϵ . The ratio of the radiant flux emitted by a body to that emitted by a blackbody at the same temperature and under the same conditions.

Effective emittance of an air space, E . The combined effect of emittances from the boundary surfaces of an air space, where the boundaries are parallel and of a dimension much larger than the distance between them. [Table 2 in Chapter 25](#) lists values of E for various air spaces.

Surface reflectance, ρ . The fraction of the radiant flux falling on a surface that is reflected by it.

Water vapor permeance, M . The rate of water vapor transmission by diffusion per unit area of a body between two specified parallel surfaces, induced by unit vapor pressure difference between the two surfaces, $\text{ng}/(\text{s} \cdot \text{m}^2 \cdot \text{Pa})$.

Water vapor permeability, μ . The rate of water vapor transmission by diffusion per unit area of flat material of unit thickness induced by unit vapor pressure difference between two surfaces, under specified temperature and humidity conditions. When permeability varies with psychrometric conditions, the spot or specific permeability defines the property at a specific condition in $\text{ng}/(\text{s} \cdot \text{m} \cdot \text{Pa})$, where the vapor pressure difference is in pascals.

Water vapor resistance, Z . The reciprocal of permeance—signifies a resistance to moisture flow, $\text{TPa} \cdot \text{m}^2 \cdot \text{s}/\text{kg}$.

THERMAL INSULATION

Thermal insulations are materials or combinations of materials that, when properly applied, retard the rate of heat transfer by conductive, convective, and/or radiative modes. Thermal insulations can be fibrous, particulate, film or sheet, block or monolithic, open-cell or closed-cell, or composites of these materials that can be chemically or mechanically bound or supported.

By retarding heat flow, thermal insulations can serve one or more of the following functions:

- Conserve energy by reducing heat loss or gain of piping, ducts, vessels, equipment, and structures
- Control surface temperatures of equipment and structures for personnel protection and comfort
- Help control the temperature of a chemical process, a piece of equipment, or a structure
- Prevent vapor condensation on surfaces. However, thermal insulation may promote moisture condensation and subsequent damage in a building envelope, if the insulation application is improperly installed or poorly designed
- Reduce temperature fluctuations within an enclosure when heating or cooling is not needed or available
- Reduce temperature variations within a conditioned space for increased personal comfort
- Provide fire protection

Thermal insulation can serve additional functions, although such secondary functions should be consistent with its capabilities and primary purpose. Under certain conditions, insulations may

- Add structural strength to a wall, ceiling, or floor section
- Provide support for a surface finish
- Impede water vapor transmission and air infiltration
- Prevent or reduce damage to equipment and structures from exposure to fire and freezing conditions
- Reduce noise and vibration
- Reduce growth of mold and mildew

Thermal insulation is used to control heat flow at all temperatures, the limiting value being its survival temperature.

BASIC MATERIALS

Thermal insulations normally consist of the following basic materials and composites:

- Inorganic, fibrous, or cellular materials such as glass, rock, or slag wool; and calcium silicate, bonded perlite, vermiculite, and ceramic products. In the past, asbestos insulations was applied. But, because asbestos has been shown to be a carcinogen, extreme caution must be used if it is encountered.
- Organic fibrous materials such as cellulose, cotton, animal hair, wood, pulp, cane, or synthetic fibers; and organic cellular materials such as cork, foamed rubber, polystyrene, polyurethane, and other polymers.
- Metallic or metallized organic reflective membranes. These surfaces must face an air-filled, gas-filled, or evacuated space to be effective.

PHYSICAL STRUCTURE AND FORM

Mass-type insulation can be cellular, granular, or fibrous solid material. Reflective insulation consists of smooth-surfaced sheets of metal foil or foil-surfaced material separated by air spaces.

The physical forms of industrial and building insulations include the following:

Loose-fill insulations consist of fibers, powders, granules, or nodules. They are usually poured or blown into walls or other spaces.

Insulating cement is a loose material that is mixed with water or a suitable binder to obtain plasticity and adhesion. It is troweled or blown wet on a surface and dried in place. Both loose-fill and insulating cement are suited for covering irregular spaces.

Flexible and semirigid insulations consist of organic and inorganic materials with and without binders and with varying degrees of compressibility and flexibility. These insulations are generally available as blanket, batt, or felt insulation, and in either sheets or rolls. Coverings and facings may be fastened to one or both sides and serve as reinforcing, air or vapor retarders or both, reflective surfaces, or surface finishes. These coverings include combinations of laminated foil, glass, cloth or plastics and paper, wire mesh, or metal lath. Although standard sizes are generally used, thickness and shape of insulation can be any dimension handled conveniently.

Rigid materials are available in rectangular blocks, boards, or sheets, which are preformed during manufacture to standard lengths, widths, and thicknesses. Insulation for pipes and curved surfaces is supplied in sections or segments, with radii of curvature available to suit all standard sizes of pipe and tubing.

Reflective materials are available in sheets and rolls of single layer or multilayer construction and in preformed shapes with integral air spaces.

Formed-in-place insulations are available as liquid components or expandable pellets that can be poured, frothed, or sprayed in place to form rigid or semirigid foam insulation. Fibrous materials mixed with liquid binders can also be sprayed in place, and in some products, the binder is also a foam.

Accessory materials for thermal insulation include mechanical and adhesive fasteners, exterior and interior finishes, vapor and air retarder coatings, jackets and weather coatings, sealants, lagging adhesives, membranes, and flashing compounds. ASTM *Standard C 168* defines terms related to thermal insulating materials.

PROPERTIES

In addition to low thermal conductivity, the selection of thermal insulation may involve secondary criteria. Characteristics such as

resiliency or rigidity, acoustical energy absorption, water vapor permeability, airflow resistance, fire hazard and fire resistance, ease of application, applied cost, health and safety aspects, or other parameters may influence the choice among materials that have almost equal thermal performance values.

Thermal Properties

Thermal resistance is a measure of the effectiveness of thermal insulation to retard heat flow. A material with a high thermal resistance (low thermal conductance) is an effective insulator.

Heat flows through most thermal insulations by a combination of gas and solid conduction, radiation, and convection. Heat transfer through materials or systems is controlled by factors such as length of heat flow paths, temperature, temperature difference characteristics of the system, and environmental conditions.

Although heat transmission characteristics are usually determined by measuring thermal conductivity, this property does not strictly apply to thermal insulation. A particular sample of a material has a unique value of thermal conductivity for a particular set of conditions. This value may not be representative of the material at other conditions and should be called **apparent thermal conductivity**. For details, refer to ASTM *Standards* C 168, C 177, C 236, C 335, C 518, C 976, and C 1045.

Reflective insulations impede radiant heat transfer because the surfaces have high reflectance and low emittance values. ([Table 1](#) and [Table 2 in Chapter 25](#) give typical design values.) To be effective, the reflective face of both single and multiple layer reflective insulations must face an air or evacuated space. Multiple layers of reflective materials and smooth and parallel sealed air spaces increase overall thermal resistance. Air exchange and movement must be inhibited.

Mass-type insulation can be combined with reflective surfaces and air spaces to obtain a higher thermal resistance. However, each design must be evaluated because maximum thermal performance depends on such factors as condition of the insulation, shape and form of the construction, the means to avoid air leakage and movement, and the condition of the installed reflective surfaces and their aging characteristics.

Design values of effective or apparent thermal conductivity, thermal conductance, and thermal resistance for the most common insulations are listed in [Table 4 in Chapter 25](#). These values have been selected as typical and useful for engineering calculations. The manufacturer or test results of the insulation under appropriate conditions can give values for a particular insulation.

Other thermal properties that can be important are specific heat, heat capacity, thermal diffusivity, the coefficient of thermal expansion, and the maximum temperature limit. **Heat capacity** is the product of specific heat and mass. Because the rate of temperature change within an insulation is proportional to its thermal diffusivity for a given thickness, **thermal diffusivity** becomes important for applications where temperature varies with time. [Chapter 3](#) covers symbols, definitions, and methods of calculation in steady-state heat transfer.

Mechanical Properties

Some insulations have sufficient structural strength for load bearing. They are used occasionally to support load-bearing roofs and floors, form self-supporting partitions, or stiffen structural panels. For such applications, one or more of the following properties of an insulation may be important: strength in compression, tension, shear, impact, flexure, and resistance to vibration. These mechanical properties vary with basic composition, density, cell size, fiber diameter and orientation, type and amount of binder (if any), and temperature and environmental conditioning.

Health and Safety

Most thermal insulations have good resistance to fire, vermin, rot, objectionable odors, and vapors; some are a potential risk to health and safety. These risks can result from direct exposure to these materials and accessories while they are being stored or transported, during or after installation, or as a result of intervening or indirect actions or events, such as aging, fire, or physical disturbance. The potential health and safety effects of thermal insulation can be considered in two categories: (1) those related to storage, handling, and installation operations and (2) those that occur after installation (such as aging). Potential hazards during manufacture are not discussed here. Correct handling, installation, and precautionary measures can reduce or eliminate these problems.

Potential health effects range from temporary irritation to serious changes in body functions. The principal concerns are with insulation containing asbestos. Questions have also been raised about man-made fibers. To date, research is inconclusive as to their potential hazard; however, they can be very annoying in installation, and the use of proper safeguards is desirable. Potential traumatic injury can occur from direct contact with materials that are sharp, rough, have protrusions or abrasive surfaces, permit overheating, or transmit electrical energy.

Combustion of insulation materials and accessories may release heat, hazardous gases, fibers, and particulates. Manufacturers' recommendations and applicable government codes and standards (ASTM *Standard* C 930) have more details.

Acoustics

Some thermal insulations are used as acoustical control materials, whether or not thermal performance is a design requirement. Acoustical efficiency depends on the physical structure of the material. Materials with open, porous surfaces have sound absorption capability. Those with high density and resilient characteristics can act as vibration insulators; either alone or in combination with other materials, some are effective barriers to sound transmission. Insulations for sound conditioning include flexible and semirigid, formed-in-place fibrous materials, and rigid fibrous insulation.

Sound absorption insulations are normally installed on interior surfaces or used as interior surfacing materials. Rigid insulations are fabricated into tile or blocks, edge-treated to facilitate mechanical or adhesive application, and prefinished during manufacture. Some insulation units have a natural porous surface, and others include mechanical perforations to facilitate the entry of sound waves. Still others have a diaphragm or decorative film surfacing attached only to the edges of the units, which allows the sound waves to reach the fibrous backing by diaphragm action.

Flexible, semirigid, and formed-in-place fibrous materials used for sound absorption are available in a variety of thicknesses and densities that determine their sound absorption characteristics.

When density is increased by reducing the thickness of the material, sound absorption is generally reduced; however, as thickness increases, the influence of density decreases.

Thermal insulations improve sound transmission loss when installed in **discontinuous construction**. A wall of staggered-stud construction that uses resilient clips or channels on one side of the stud or resilient insulation boards of special manufacture to prevent acoustical coupling mechanically between the surfaces reduces sound transmission. A sound absorption thermal insulation blanket in a wall cavity reduces sound transmission, depending on the type of construction.

In floor construction, resilient channels or separate floor and ceiling joists form a discontinuous construction. Sound-absorbing thermal insulation placed within this construction further reduces sound transmission. Sound-deadening boards underlying finish

flooring absorb impact sounds and improve the airtightness of the construction, thus reducing airborne sound transmission.

Thermal insulation boards can be placed under mechanical equipment to isolate vibration. The imposed loading and natural resonant frequency of materials are critical for proper design. Because material must deflect properly under load to provide isolation, the system should be neither overloaded nor underloaded.

For further information on sound and vibration control, refer to [Chapter 47 of the ASHRAE Handbook—Applications](#).

Other Properties

Other properties of insulating materials that can be important, depending on the application, include density, resilience, resistance to settling, permanence, reuse or salvage value, ease of handling, dimensional uniformity and stability, resistance to chemical action and chemical change, resistance to moisture penetration, ease in fabrication, application of finishes, and sizes and thicknesses obtainable.

HEAT FLOW

FACTORS AFFECTING THERMAL PERFORMANCE

A wide variety of physical, environmental, application, and, in some cases, aging factors affect the thermal performance of insulations.

Thermal conductivity k is a property of a homogeneous material. Building materials, such as lumber, brick, and stone, are usually considered homogeneous. Most thermal insulation and many other building materials are porous and consist of combinations of solid matter with small voids.

For many materials, conduction is not the only mode of heat transfer. Consequently, the term **apparent thermal conductivity** describes the heat flow properties of materials. Some materials with low thermal conductivities are almost purely conductive (silica opacified aerogel, corkboard, etc.).

The apparent thermal conductivity of insulation varies with form and physical structure, environment, and application conditions. Form and physical structure vary with the basic material and manufacturing process. Typical variations include density, cell size, diameter and arrangement of fibers or particles, degree and extent of bonding materials, transparency to thermal radiation, and the type and pressure of gas within the insulation.

Environment and application conditions include mean temperature, temperature gradient, moisture content, air infiltration, orientation, and direction of heat flow. Thermal performance values for insulation materials and systems are usually obtained by standard methods listed in Volume 04.06 of the *Annual Book of ASTM Standards*. The methods apply mainly to laboratory measurements on dried or conditioned samples at specific mean temperatures and temperature gradient conditions. Although the fundamental heat transmission characteristics of a material or system can be determined accurately, actual performance in a structure may vary from that indicated in the laboratory. The design of the envelope, its construction, and the materials used may all affect the test procedure. These factors are detailed in ASTM STP 544, STP 660, STP 718, STP 789, STP 879, STP 885, STP 922, STP 1030, and STP 1116.

The effective thermal conductivity of some thermal insulation materials varies with density. [Figure 1](#) illustrates this variation at one mean temperature for a number of materials currently used to insulate building envelopes. For most mass-type insulations, there is a minimum in the respective apparent thermal conductivity versus density. This minimum depends on the type and form of material, temperature, and direction of heat flow. For fibrous materials, the values of density at which the minimum value occurs increase as both the fiber diameter or cell size and the mean temperature

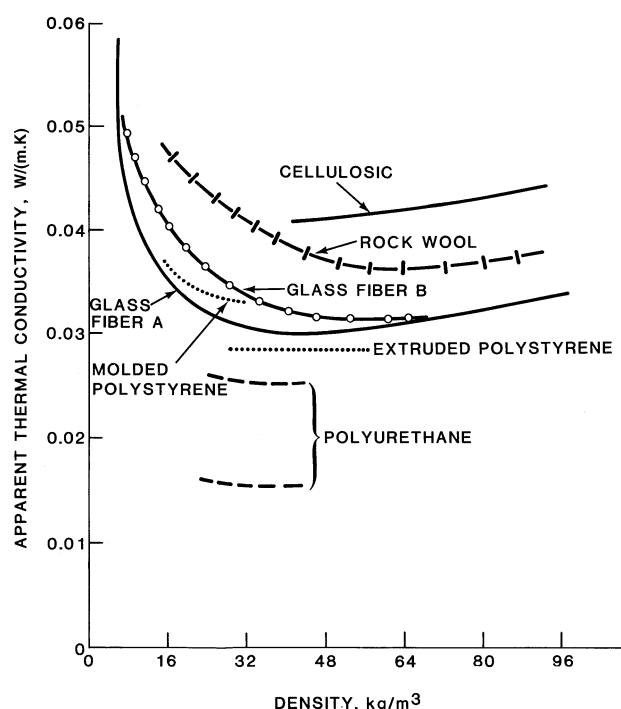


Fig. 1 Apparent Thermal Conductivity Versus Density of Several Thermal Insulations Used as Building Insulations

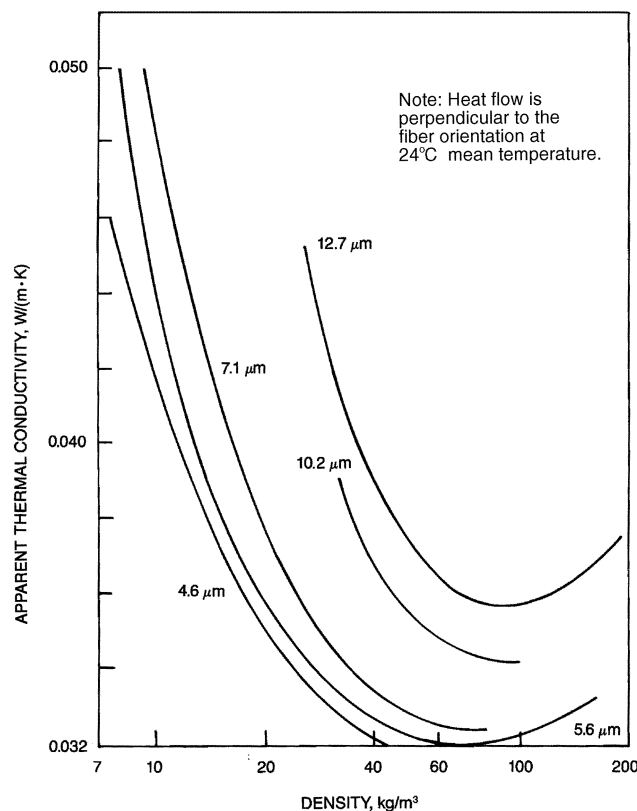


Fig. 2 Typical Variation of Apparent Thermal Conductivity with Fiber Diameter and Density

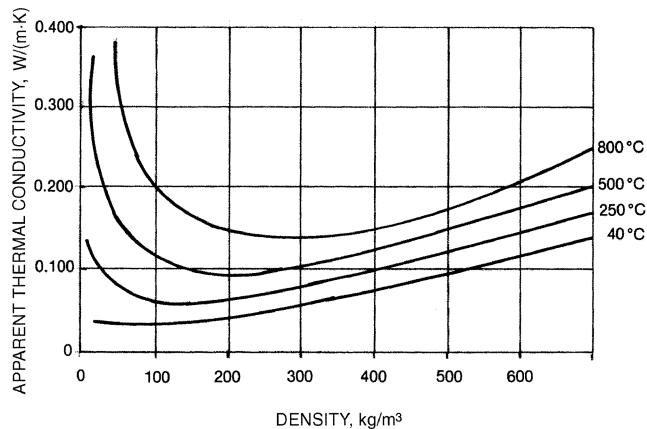


Fig. 3 Typical Variation of Apparent Thermal Conductivity with Mean Temperature and Density for Fibrous Insulations

increase. These effects are shown in [Figure 2](#) (Lotz 1969) and [Figure 3](#), respectively.

Other factors that affect thermal performance include compaction and settling of insulation, air permeability, type and amount of binder used, additives that may influence the bond or contact between fibers or particles, and the type and form of radiation transfer inhibitor, if used. In cellular materials, the factors that influence thermal performance and strength properties are the same as those that control the thermal conductivity of the basic structured material: size and shape of the cells, thickness of the cell walls, gas contained in the cells, orientation of the cells, and radiation characteristics of the cell surfaces.

A change in density caused by the degree of compaction of insulation powders affects their effective thermal conductivity. Insulating concretes made from lightweight aggregates can be produced in a wide range of densities, with corresponding thermal conductances.

Fibrous insulations reach a minimum conductivity when fibers are uniformly spaced and perpendicular to the direction of heat flow. Generally, a decrease in the diameter of the fiber lowers the conductivity for the same density ([Figure 2](#)). For cellular insulation, a specific combination of cell size, density, and gas composition produces optimum thermal conductivity.

At temperatures below 200 to 300°C, a large portion of heat transfer across most insulations occurs by conduction through the air or other gas in the insulations (Rowley et al. 1952, Lander 1955, Simons 1955, Verschoor and Greebler 1952). The overall heat transfer can be closely approximated by supposition of gas conduction with other mechanisms of heat transfer, each determined separately. If the gas in the insulation is replaced by another gas with a different thermal conductivity, the apparent thermal conductivity of the insulation is changed by an amount approximately equal to the difference in conductivity of the two gases. For example, replacing air with a fluorinated hydrocarbon gas can lower the apparent thermal conductivity of the insulation by as much as 50%.

Fluorocarbon-expanded cellular plastic foams with a high proportion (greater than 90%) of closed cells retain the fluorocarbon within the cells for extended periods. As these products are initially produced, they have apparent thermal conductivities of approximately 0.016 W/(m·K) at 24°C when the gas contained has a mean-free-path greater than the dimensions within the cells. However, this value increases with time as atmospheric gases diffuse into the cells and, over a long period of time, the fluorocarbon gas dissolves in the polymer or diffuses out.

The rates of diffusion and increase in apparent thermal conductivity depend on several factors, including permeance of the cell

walls to the gases involved, age of the foam, temperature, geometry of the insulation (thickness), and integrity of the surface protection provided. The significance of the surface protection is apparent when foams are encased in gas-impermeable membranes or some water vapor retarders (Brandreth 1986, Tye 1987). For estimating the long-term change in thermal resistance of unfaced rigid closed-cell plastic foams, a test method (ASTM *Standard C 1303*) has been developed that involves slicing and scaling under controlled laboratory conditions. Christian et al. (1995) provides an example of an application of this accelerated aging test method.

Brandreth (1986) and Tye (1988) show that the aging process of polyurethane and polyisocyanurate materials is reasonably well understood analytically and confirmed experimentally. The dominant parameters for minimum aging are as follows:

- Closed-cell content > 90%, preferably > 95%
- Small uniform cell diameter << 1 mm, with a larger proportion of polymer in windows
- Small anisotropy in cell structure
- High density
- Increased thickness
- High initial pressure of fluorocarbon blowing agent in cell
- Polymer highly resistant to gas diffusion and solubility
- Polymer distributed evenly in struts and windows of cells
- Low aging temperature

Aging may be further reduced, particularly for laminated and spray-applied products, with higher density polymer skins, or by well-adhered facings and coverings with low gas and moisture permeance characteristics. An oxygen diffusion rate of less than 3.5 mm³/(m²·day) for 25 µm thickness of barrier is one criterion used by some industry organizations manufacturing laminated products. The adhesion of any facing must be continuous, and every effort must be made in the manufacturing process to eliminate or minimize the shear plane layer at the foam/substrate interface (Ostrogorsky and Glicksman 1986).

Closed-cell phenolic-type materials and products, which are blown with similar gases, age differently and much more slowly. The reasons for this are believed to be higher material density, smaller more uniform cell size with a larger proportion of polymer in windows, and a basic polymer more resistant to gas diffusion.

The average distance, or **mean free path**, that an enclosed gas molecule travels before striking another gas molecule increases as pressure within an insulation decreases. When the mean free path equals the average distance a gas molecule travels before striking a solid part of the insulation, the apparent thermal conductivity of the insulation decreases with decreasing pressure. Correspondingly, for materials such as silica gel and fine carbon black, which have an average pore size smaller than the mean free path of air at atmospheric pressure, it is possible to attain thermal conductivity values lower than those for still air (Verschoor and Greebler 1952).

For homogeneous, dense materials, the primary mode of heat transfer is conduction. However, as the temperature increases, the heat transmission by thermal radiation and possible convection becomes a greater part of the total heat transferred. The magnitude of radiation and convection transfer depends on temperature difference, direction of heat flow, the nature of materials involved, and geometric considerations.

Because heat is transferred partly by radiation in low-density insulation, measured apparent thermal conductivity depends on test thickness. The thickness effect increases the apparent thermal conductivity measured at installed thickness over that commonly determined at 25 mm (Pelanne 1979). From a thermal resistance standpoint, the effect is small, typically less than 10% even for thin (e.g., 25 mm) low-density (e.g., 5.5 kg/m³) insulation. The effect becomes negligible for typical building applications (e.g., 150 mm insulation with a density of 11 kg/m³).

Environmental and Application Conditions

The apparent conductivity of insulating materials generally increases with increasing temperature. Figure 4 shows typical variations with mean temperature. However, some materials, such as fluorocarbon-expanded, closed-cell urethanes, have an inflection in the curve over the temperature range where there is a change of phase of the fluorocarbon from gas to liquid (see Table 10 in Chapter 25).

The apparent thermal conductivity of a sample at one mean temperature (average of the two surface temperatures) only applies to the material at the particular thickness tested. Further testing is required to obtain values suitable for all thicknesses. The rate of change of apparent thermal conductivity with temperature and environmental conditions varies with the type and density of material.

Insulating materials that permit a large percentage of heat transfer by radiation, such as low-density fibrous and cellular products, show the greatest change in apparent thermal conductivity with changes of temperature and surrounding surface emittance. The ASTM Standard Test Methods recognize the importance of radiation in heat transmission and require that the surfaces of all test apparatus plates be painted or otherwise treated to have a total emittance greater than 0.8 at operating temperature.

The effect of temperature alone on structural integrity is not ordinarily important for most materials in low-temperature insulation applications. Decomposition, excessive linear shrinkage, softening, or some other effects of temperature alone limit the maximum temperature for which a material is suited. At extreme temperatures, selecting materials for a specific service becomes more critical and

must be based on experience and actual performance data (see Table 4 and Table 10 in Chapter 25).

Convection and air infiltration in or through some insulation systems may increase heat transfer across them. Low-density, loose-fill, large open-cell and fibrous insulations, and poorly designed or installed reflective systems are most susceptible to increased heat transfer by air filtration and convection. The temperature difference across an insulation, as well as the height, thickness, or width of the insulated space, influences the amount of convection. In some cases, natural convection may be inherent in the systems (Wilkes and Rucker 1983, Wilkes and Childs 1992). However, in many cases, the effect of convection in or through insulation can be minimized by careful design of an insulated structure (Donnelly et al. 1976).

Gaps between both board- and batt-type insulation can lower the effectiveness. Board-type insulation may not be perfectly square, may be installed improperly, and may be applied to uneven surfaces. For example, a 4% void area around batt insulation can produce a 50% loss in effective thermal resistance of ceiling application with $R = 3.4 \text{ m}^2 \cdot \text{K/W}$ (Verschoor 1977). Similar results have been obtained with different test conditions and for wall configurations (Lewis 1979, Hedlin 1985, Tye et al. 1981). Preformed joints in board-type insulation allow it to fit together without air gaps. Boards and batts can be installed in two layers, with joints between layers offset and staggered to eliminate gaps. Chapter 24 has further details on these effects.

The presence of moisture may decrease the thermal performance of the installed insulation. The apparent thermal conductivity of construction materials increases with moisture content. If moisture condenses in the insulation, it may further reduce thermal resistance, and, perhaps physically damage the system. The reduction in thermal resistance depends on the material, the moisture content, and its distribution.

More information on the effects of moisture is provided in the section on Effect of Moisture on Heat Flow. Section A3 of the CIBSE Guide (1986) and Chapter 24 cover the thermal properties of building structures affected by moisture.

THERMAL TRANSMITTANCE

The method of calculating an overall coefficient of heat transmission requires knowledge of (1) the apparent thermal conductivity and thickness of homogeneous components, (2) thermal conductance of nonhomogeneous components, (3) surface conductances of both sides of the construction, and (4) conductance of air spaces in the construction. Procedures for calculating thermal conductance and resistance, and definitions of heat transfer terms and symbols are included in this chapter and in Chapter 3. In some construction, multidimensional heat flow effects are significant. Parallel heat flow paths of different resistances occur in wood frame house construction, for example. In such cases, the hot box method (ASTM Standard C 1363) or a multi-dimensional computer model may be used to determine overall thermal transmittance.

Surface Conductance

Surface conductance is the heat transfer to or from the surface by the combined effects of radiation, convection, and conduction. Each of these transport modes can vary independently. Heat transfer by radiation between two surfaces is controlled by the character of the surfaces (emittance and reflectivity), the temperature difference between them, and the solid angle through which they see each other. Heat transfer by convection and conduction is controlled by surface roughness, air movement, and temperature difference between the air and surface. Table 1 illustrates the importance of the effect of temperature of surrounding surfaces on surface heat flux caused by radiation.

In many cases, because the thermal resistance (reciprocal of conductance) of the internal parts of the wall is high compared

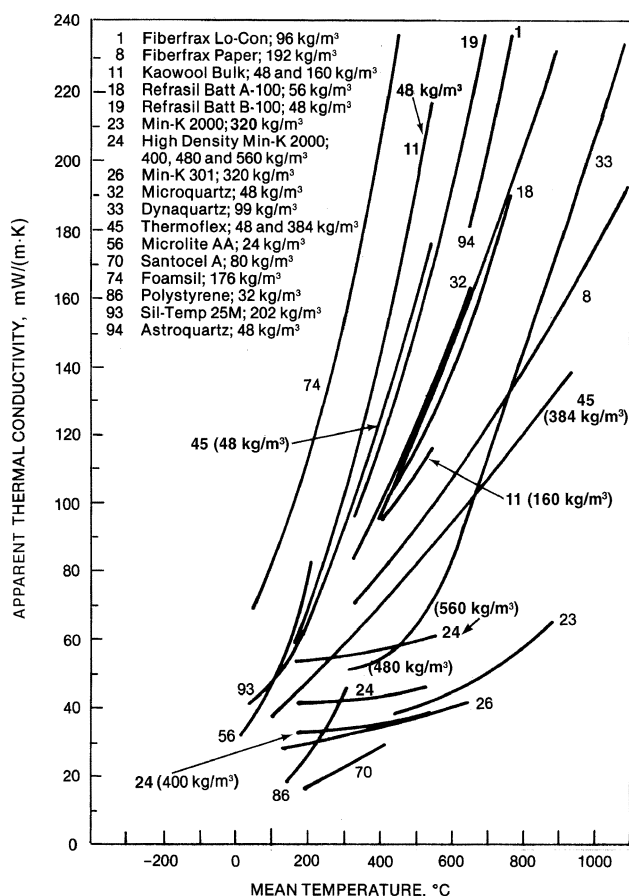


Fig. 4 Apparent Thermal Conductivity Versus Mean Temperature for Various Materials (in Air at Atmospheric Pressure)
(Glaser et al. 1967, Pelanne 1977)

Table 1 Variation in Surface Heat Flux for Vertical Surfaces at 26.7°C with Different Temperatures of Surrounding Surface (21.1°C Ambient Still Air; 0.83 Emittance)

Surrounding Surface Temperature, °C	Surface Heat Flux, W/m ²				
	23.9	21.1	18.3	15.6	10
Convection	20.8	20.8	20.8	20.8	20.8
Radiation	13.9	27.1	40.4	53.6	78.6
Total	34.7	47.9	61.2	74.4	99.4

with the surface resistance, the surface factors are of minor importance. However, surface resistances on a window with a single pane of glass constitute almost the entire resistance and are very important. Raber and Hutchinson (1945) analyzed the factors affecting surface conductance and the difference between surface and air temperatures.

The convective part of the surface conductance is markedly affected by the nature of the air movement on the surface, illustrated by [Figure 1 in Chapter 25](#). On smooth surfaces, surface length (Parmelee and Huebscher 1947) also affects the convection part of conductance; the average value decreases as the surface length increases. Moreover, Parmelee and Aubele (1950) observed that only under certain conditions can outdoors be treated as a blackbody radiating at an effective air temperature. Therefore, selection of surface conductance coefficients for a building becomes a matter of judgment. Surface conductances in [Table 1 in Chapter 25](#) are applicable to ordinary building materials. In special cases, where surface conductances become important factors in the overall rates of heat transfer, more accurate coefficients may be required. Principles and data given in [Chapter 3](#) can be applied in such cases.

FACTORS AFFECTING HEAT TRANSFER ACROSS AIR SPACES

Heat transfer across an air space is affected by the nature of the boundary surfaces, the intervening air space, the orientation of the air space, the distance between boundary surfaces, and the direction of heat flow. Air space conductance coefficients represent the total conductance from one surface bounding the air space to the other. The total conductance is the sum of a radiation component and a convection and conduction component. In all cases, the spaces are considered airtight with no through air leakage.

The radiation portion of the coefficient is affected by the temperature of the two boundary surfaces and by their respective surface properties. For surfaces that can be considered ideal graybodies, the surface properties can be characterized by emissivity. The combined effect of the emittances of the boundary surfaces of an air space is expressed by the effective emittance E of the air space. The radiation component is practically not affected by the thickness of the space, its orientation, the direction of heat flow, or the order of emittance (hot or cold surface). In contrast the heat transfer by convection and conduction combined is affected markedly by orientation of the air space and the direction of heat flow, by the temperature difference across the space, and, in some cases, by the thickness of the space. It is also slightly affected by the mean temperature of its surfaces. For air spaces in building construction, the radiation and convection-conduction components can vary independently of each other.

[Table 3 in Chapter 25](#) lists the thermal resistance values of sealed air spaces of uniform thickness and moderately smooth, plane, parallel surfaces. These data are based on experimental measurements (Robinson et al. 1954). Resistance values for systems with air spaces can be estimated from these results if emis-

sivity values are corrected for field conditions. However, the resistance value of some common composite building insulation systems involving mass-type insulation with a reflective surface in conjunction with an air space may be appreciably lower than the estimated value (Palfey 1980). This is true particularly if the air space is not sealed or of uniform thickness. The thermal resistance values for plane air spaces in [Table 3 in Chapter 25](#) represent typical values; for critical applications, the effectiveness of a particular design should be confirmed by actual test data undertaken by using ASTM hot box methods (ASTM *Standards* C 236 and C 976). This test is especially necessary for constructions combining reflective and nonreflective thermal insulation.

For narrow air spaces, defined as those for which the product of the temperature difference (in kelvins) and the cube of the space thickness (in millimetres) is less than 27 000 for heat flow horizontally or downward, or less than 9000 for heat flow upward, convection is practically suppressed. The conductance for these spaces is the sum of the radiative heat transfer coefficient and that for heat conduction alone through air. The radiation and conduction component can be computed by the method shown in the footnote to [Table 3 in Chapter 25](#). Effects of different mean temperatures, temperature differences, and effective emittances may be found in this table.

To obtain high thermal resistance with reflective insulation, a series of multiple air layers bounded by reflective surfaces is needed. The total resistance equals the sum of the resistance values across each air space. All air layers or spaces must be sealed because air moving between the layers can increase the heat flow. Depending on the type of reflective insulation, one or both sides may have highly reflective surfaces. Except for thick horizontal air spaces with heat flow down, little is gained thermally by the addition of a second highly reflective surface to the same air space. If an air space has only one reflective surface, and conditions are completely dry, the side on which the reflective surface is placed makes no appreciable difference in the rate of heat transfer. In typical building situations moisture is present and the reflective facing should always be placed on the warm side of the air space, else trace condensation will at times increase the emittance and reduce the insulation value (see [Chapter 25, Table 2](#)). A reflective surface placed on the warm side of an air space may also act as a water vapor retarder if the material and its joints have sufficiently low permeance (see the section on Vapor Retarder Functions and Properties).

The emittance of a surface is the measure of its ability to emit radiant energy and, for the same temperature and wavelength, is equal to its absorptance (ratio of the radiant energy absorbed by a surface to the total radiant energy falling on it). The ratio of the energy reflected by the surface to that falling on it is the reflectance. For an opaque surface, reflectance is equal to one minus the emittance. This emittance varies with surface type and condition and radiation wavelength.

For reflective insulation used with heating, air-conditioning, and refrigeration applications, the emittance value for long-wavelength (infrared) radiation is important, not the value for the shorter wavelengths of the visible spectrum. Visible brightness is not a true measure of the reflectance for thermal radiation because the reflectance for light and for long-wavelength radiation is unrelated. [Table 2 in Chapter 25](#) lists typical emittance values for reflective surfaces and building materials, and the corresponding emittance factors for air spaces.

Chemical action, dust or oil accumulation, or the presence of condensation or frost can change a reflective surface enough to reduce its reflectance and increase its emittance. Chemical changes include oxidation, corrosion, or tarnishing caused by air, moisture, wet plaster, or the chemical treatment of wood spacing strips or other adjoining structural members. Surface emittance values should be obtained by tests.

CALCULATING OVERALL THERMAL RESISTANCE

Using the principles of heat flow presented in [Chapter 3](#), calculating heat flow by the overall thermal resistance method is preferred.

The total resistance to heat flow through a flat building construction composed of parallel layers such as a flat ceiling, floor, or wall (or curved surface if the curvature is small) is the numerical sum of the resistances (R-values) of all layers of the construction in series:

$$R = R_1 + R_2 + R_3 + R_4 + \dots + R_n \quad (1)$$

where

$R_1, R_2, \dots, R_n$ = individual resistances of the layers
 R = resistance of construction from inside surface to outside surface

However, in buildings, to obtain the overall resistance R_T , the film resistances R_i and R_o from [Table 1 in Chapter 25](#) must be added to R :

$$R_T = R_i + R + R_o \quad (2)$$

The U-factor (thermal transmittance) is the reciprocal of R_T , or

$$U = \frac{1}{R_T} \quad (3)$$

Thus, for a wall with air space construction, consisting of two homogeneous materials of conductivities k_1 and k_2 and thickness x_1 and x_2 , respectively, and separated by an air space of conductance C , the overall resistance is

$$R_T = \frac{1}{h_i} + \frac{x_1}{k_1} + \frac{1}{C} + \frac{x_2}{k_2} + \frac{1}{h_o} \quad (4)$$

where h_i and h_o are the heat transfer film coefficients.

Series and Parallel Heat Flow Paths

In many installations, components are arranged so that heat flows in parallel paths of different conductances. If no heat flows between lateral paths, heat flow in each path may be calculated using Equations (1) and (2). The average transmittance is then

$$U_{av} = aU_a + bU_b + \dots + nU_n \quad (5)$$

where $a, b, \dots, n$ are respective fractions of a typical basic area composed of several different paths with transmittances $U_a, U_b, \dots, U_n$.

If heat can flow laterally with little resistance in any continuous layer so that transverse isothermal planes result, total average resistance $R_{T(av)}$ is the sum of the resistance of the layers between such planes. Each layer is calculated by the appropriate Equation (1) or modification of Equation (4), using the resistance values. This is a series combination of layers, of which one (or more) provides parallel paths.

The calculated heat flow, assuming parallel heat flow only, is usually considerably lower than that calculated with the assumption of combined series-parallel heat flow. The actual heat flow is some value between the two calculated values. In the absence of test values for the combination, an intermediate value should be used. Examination of the construction usually reveals whether a value closer to the higher or lower calculated value should be used. Generally, if the construction contains any highly conductive layer in which lateral conduction is very high compared to heat flow through the wall, a value closer to the series-parallel calculation should be used. If, however, no layer has a high lateral conductance, a value closer to the parallel heat flow calculation should be used. In the case where the presence or absence of high lateral conductance is

unclear, use the arithmetic mean of the isothermal-planes and parallel-path methods. A more precise value of the thermal transmittance may be obtained by using an appropriate computer program for two- or three-dimensional heat flow.

CALCULATING INTERFACE TEMPERATURES

The temperature at any interface can be calculated, since the temperature drop through any component of the wall is proportional to its resistance. Thus, the temperature drop Δt_n through R_n in Equation (1) is

$$\Delta t_n = \frac{R_n(t_i - t_o)}{R_T} \quad (6)$$

where t_i and t_o are the indoor and outdoor temperatures, respectively. Hence, the temperature at the interface between R_n and R_{n+1} is

$$t_{n-n+1} = t_i - \sum_{m=1}^n \Delta t_m \quad (7)$$

For building materials having nonuniform or irregular sections such as hollow clay tile or concrete blocks, the R-value of the unit as manufactured should be used.

If the resistances of materials in a wall are highly dependent on temperature, the mean temperature must be known to assign the correct value. In such cases, it is perhaps most convenient to use a trial-and-error procedure for the calculation of the total resistance R_T . First, the mean operating temperature for each layer is estimated, and R-values for the particular materials are selected. The total resistance R_T is then calculated as in Equation (4), and the temperature at each interface is calculated using Equations (6) and (7). The mean temperature of each component (arithmetic mean of its surface temperatures) can then be used to obtain second generation R-values. This procedure can then be repeated until the R-values have been correctly selected for the resulting mean temperatures. Generally, this can be done in two or three trial calculations.

HEAT FLOW CALCULATIONS

Equation (8) is used to calculate heat flow through flat surfaces; Equation (9) is used for cylindrical surfaces ([Figure 5](#)).

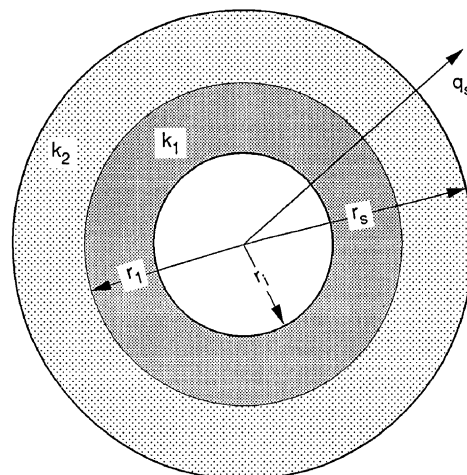


Fig. 5 Heat Flow Through Cylindrical Surfaces

$$q_s = \frac{t_{is} - t_{os}}{R} \quad (8)$$

$$q_s = \frac{t_{is} - t_{os}}{r_s \sum_{m=1}^N \ln(r_{o,n}/r_{i,n})/k_n} \quad (9)$$

where

q_s = rate of heat transfer per unit area of outer surface of insulation

R = surface-to-surface thermal resistance from Equation (1)

k_n = thermal conductivity of insulation layer n at calculated mean temperature

t_{is} = temperature of inner surface

t_{os} = temperature of outer surface

$r_{i,n}$ = inner radius of insulation layer n

$r_{o,n}$ = outer radius of insulation layer n

r_s = outer radius of outer insulation layer

N = total number of insulation layers

$\ln$ = natural or Napierian logarithm

Heat flow per unit length of pipe is the preferred unit. The terms that appear in the denominator of Equation (9) represent the resistances to heat flow based on logarithmic mean thickness. The thermal resistances for flat surfaces should not be confused with the thermal resistance of a cylindrical insulation where the surface areas involved are never equal.

INSULATION THICKNESS

ECONOMIC THICKNESS

Economics can be used (1) to select the optimum insulation thickness for a specific insulation, or (2) to evaluate two or more insulation materials for least cost for a given thermal performance. In either case, economics determine the most cost-effective solution for insulating over a specific period (FEA 1976). This solution can be reached by different techniques, but only one solution exists for a given set of economic variables.

Greater than optimum insulation thickness may also require a greater capital investment for the structure and piping. However, other concerns such as limited energy availability, sustainability, or comfort may alter the results of an economic analysis alone.

Life-cycle costing spreads the initial cost of the insulation over the number of years the insulation is expected to be in service. The life cycle selected affects the economic thickness of the insulation. Thinner insulation pays back on a short life cycle, and thicker insulation pays back over a longer cycle. An insulation system designed to pay for itself with energy savings in a short time, and that stays in service longer, does not necessarily produce the lowest total cost over the service period.

The annualized cost of the installed insulation must also be adjusted for the cost of money, which can be based on a desired rate of return on the insulation investment. Insulation system maintenance costs should also be included in the annual cost.

Because fuel cost is likely to change during the depreciation period (the life of the facility or payback period), the average cost should be estimated and this value used rather than current cost.

The total annual cost is the sum of the annual cost of insulation and the annual cost of lost energy. For each incremental increase in insulation thickness, the corresponding change in the total cost is $m_t = m_c + m_s$ where m_t is the incremental change in total annual costs, m_c is the incremental change in cost of insulation, and m_s is the incremental change in cost of lost energy plus any change in the cost of the mechanical equipment needed.

Initially, as insulation is applied, the total cost decreases because the incremental energy savings is greater than the incremental cost

of insulation. Additional insulation reduces this cost up to a thickness where the change in the total cost is equal to zero. At this point, $m_t = m_c + m_s = 0$, and no further reduction can be obtained. Beyond this thickness, the incremental insulation costs become greater than the additional energy savings derived by adding another increment of insulation. However, if total insulation costs then exceed total insulation benefits, the optimal level of insulation for a given component from a purely economics viewpoint is no insulation at all. This may occur if the startup costs are extremely high, as for installation of insulation in a sealed wall cavity.

ECONOMIC THICKNESS: MECHANICAL SYSTEMS

Determining the most profitable thickness of insulation for mechanical systems is difficult. The economics of each plant (including cost of producing energy, cost of insulating, discount rate or cost of capital, and potential for energy loss) indicate the preferred amount of insulation. Various types of equipment and piping also require different economic thicknesses. This analysis is further complicated because future energy cost and the life of the facility and insulation must also be considered. For every plant, these factors dictate different solutions to the economic analysis. Furthermore, additional insulation may lower heat loss or gain, possibly allowing for lower capacity equipment and thus for lower first costs.

Economic Analysis

The cost of installed insulation increases with thickness. This incremental cost is for both labor and material. Insulation is often applied in multiple layers (1) because materials are not manufactured in single layers of sufficient thickness and, (2) in many cases, to compensate for expansion and contraction. Figure 6 shows installed costs for a multilayer application. The average slope of the curves increases with the number of layers because labor and material costs increase at a more rapid rate as thickness increases.

Because the optimal economic thickness is the lowest total cost of lost energy and installed insulation over the life of the insulation, these two costs must be compared in similar terms. Either the annual

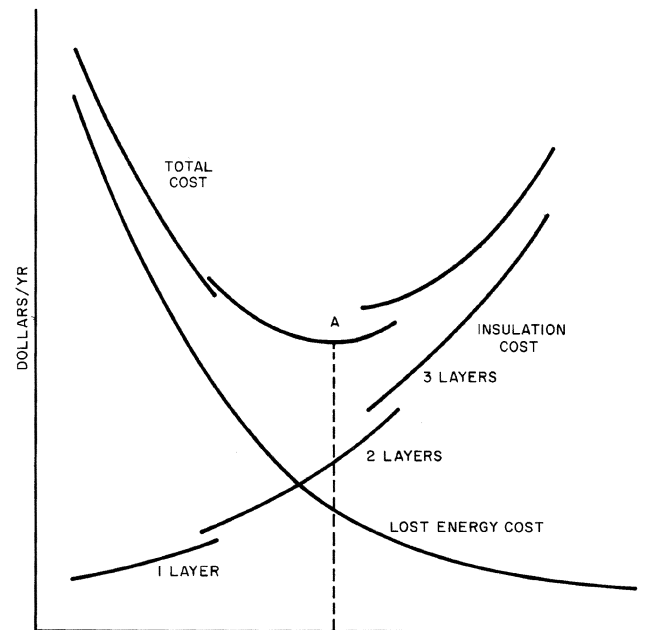


Fig. 6 Determination of Economic Thickness of Installed Insulation of Mechanical Equipment

cost of the insulation must be compared to the average annual cost of lost energy, or the cost of the energy lost each year must be expressed in present dollars and compared with the total cost of the insulation investment. The former method, annualizing the insulation cost and comparing this with the average annual cost of lost energy, is easier to compute.

Insulation reduces the size and capital costs of the heating and cooling equipment required for an installation because it lowers energy demand. This capital cost may be annualized by considering the plant depreciation period, cost of money, annual energy output for the plant, and operational expenses.

Figure 6 shows curves of total annual costs of operation, insulation costs, and lost energy costs. Point A on the total cost curve corresponds to the economic insulation thickness, which, in this example, is in the double-layer range. Viewing the calculated economic thickness as a minimum thickness provides a hedge against unforeseen fuel price increases and conserves energy.

ECONOMIC THICKNESS: BUILDING ENVELOPES

In buildings such as residences and warehouses, the internal energy gains are insignificant compared with the heat losses and gains through the envelope. For these buildings, the heating and cooling requirements are roughly proportional to the difference between the indoor and outdoor temperature. For commercial, industrial, and institutional buildings, internal heat loads can be significant, and the heating and cooling requirements are not as directly related to the indoor/outdoor temperature difference. In both types of buildings, solar heat can be an important factor and should be evaluated.

Dominant Heat Loss and Gain Through Envelope

Thermal insulation is generally installed in building envelope components (e.g., ceilings, walls, and floors) to reduce space heating and cooling costs on a long-term basis. Additional benefits may include increased occupant comfort, reduced heating and cooling system capacity, and elimination of condensation on wall surfaces in cold climates. When possible these benefits should be considered. The economically optimal insulation thickness (best measured in terms of thermal resistance) in an envelope component minimizes total life-cycle space heating and cooling costs attributable to it. Total life-cycle costs are the sum of present-value heating and cooling costs over the useful lifetime of the insulation plus the installed cost of the insulation and the installed cost of the heating and cooling equipment.

If the R-value of the insulation used is continuously variable (e.g., loose-fill insulation in attics), uniformly small increments of insulation can be used to determine appropriate optimal thicknesses; or calculus can be used to determine an exact optimum. If the insulation materials used are available only in discrete levels of thermal resistance ($R = 2$, $R = 3$, $R = 5$), the increment used in determining optimal thickness should be based on differences between those levels ($R = 2$ over $R = 0$, $R = 3$ over $R = 2$, $R = 5$ over $R = 3$). Where discrete increments of resistance are used, determining the resistance level for which incremental savings equal incremental costs may not be feasible. In such cases, the selection should be left to the judgment of the analyst based on the level of conservation desired. In addition, an increase in insulation may make it possible to reduce the size of the heating and cooling equipment, which becomes a discrete reduction in equipment cost.

If a building envelope component requires structural modifications to accommodate increased insulation thickness, this cost must be included in the installed cost of the additional insulation. Generally, such modifications should only be considered when they are less costly than the use of more efficient (i.e., lower thermal

conductivity) but more expensive insulation materials than those ordinarily used.

Typically, the incremental energy savings and insulation costs differ for each building envelope component; therefore, the optimal insulation level differs for each component in the same building. Less efficient heating plants and higher costs of heating energy necessitate higher optimal insulation levels in each building envelope component. Conversely, more efficient heating equipment reduces the optimal insulation level. The effects of climate, cooling energy costs, and cooling equipment efficiency on optimal insulation levels are less clear and differ widely, depending on overall building design and operational profile.

Dominant Internal Heat Loads

In buildings with dominant internal loads, the energy requirements vary so widely that no generalizations can be made regarding insulation. This contrasts with envelope-dominated structures, in which more insulation reduces energy consumption (Hart 1981).

In internal-load-dominated buildings with both annual heating and cooling loads, higher thermal resistance increases cooling energy consumption while reducing heating energy consumption. Therefore, the calculation of economically optimum resistance becomes quite complex and involves multiple measure or hourly methods described in Chapter 31. Spielvogel (1974), Burch and Hunt (1978), and Rudoy (1975) give more details.

Figure 7 shows the results of these calculations for a building in Columbus, Ohio, with 26 W/m^2 of internal heat gains that operates 24 h per day (Spielvogel 1974). This solution is not the only one possible, but illustrates problems faced by the designer. In this case, thermal resistance increases, the U-factor decreases, annual heating energy decreases, and annual cooling energy increases. The energy optimum exists at Point Y in Figure 7, where the total heating and cooling energy is at a minimum. Because the cost of cooling energy differs from the cost of heating energy, the economic optimum will not be the same as the energy optimum.

These results occur in some localities where there are far more hours per year with outdoor temperatures between 10 and 24°C than

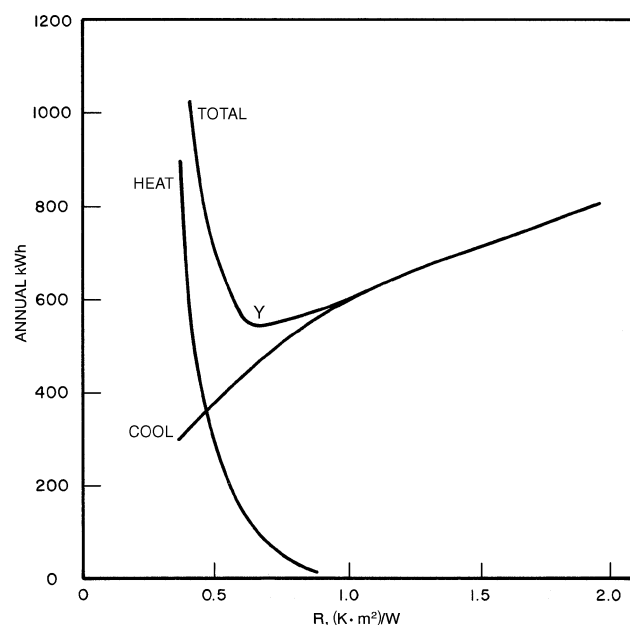


Fig. 7 Example of Optimal Thermal Resistance for Building with Internal Heat Gains
(Adapted from Spielvogel 1974)

between 24 and 38°C. At temperatures between 24 and 38°C, low U-factors result in less energy consumption for cooling. However, for temperatures between 10 and 24°C, low U-factors inhibit the flow of internal heat from the building, thereby creating higher cooling loads and higher energy requirements than those in buildings with higher U-factors. What might be saved at outdoor temperatures over 24°C can be more than spent in additional cooling energy at temperatures below 24°C. Economizer cycles could offset these excess internal gains with ventilation air, however.

Where the hours of use or the quantity of internal heat gains vary from room to room, the optimum thermal resistance also varies. For example, in a cold climate, a hotel kitchen requires little or no insulation, because the internal heat is sufficient to heat the space almost all year. In a meeting room adjacent to the kitchen, substantially more insulation is justified. Thus, the economic thermal resistance of any envelope element, such as a roof, will not be the same throughout the entire building.

This type of analysis must include the level and duration of internal gains and the nature of the energy consumption of the heating and cooling systems. Most buildings need evaluation of walls, roofs, and floors on a room-by-room basis. Computer programs make these more complex analyses possible. Due to the wide diversity of building types, internal gains, system types, and operating conditions, no simple rules can establish U-factors for minimum energy consumption.

Effectiveness of Added Insulation

The effectiveness of added insulation varies with many factors, including climate, original insulation level, preparation costs, and predicted life, based on payback calculations. Building codes generally balance life-cycle costs between construction, financing, and energy expenditures. Figure 8 shows typical relationships between life-cycle costs and energy consumption. Individual points on the curve represent different combinations of ceiling, wall, and floor insulation in R-values and glazing types (single, double, or triple). Because life-cycle costs vary not only with construction and energy costs but also with climatic factors, the profiles of this curve vary according to locality. In Figure 8, the optimal condition for this example is attained with $R = 5.3 \text{ m}^2 \cdot \text{K}/\text{W}$ attic insulation, $R = 3.4$ wall insulation, $R = 2$ floor insulation, and double glazing. However, the effectiveness of added insulation can be determined only by analyzing actual conditions.

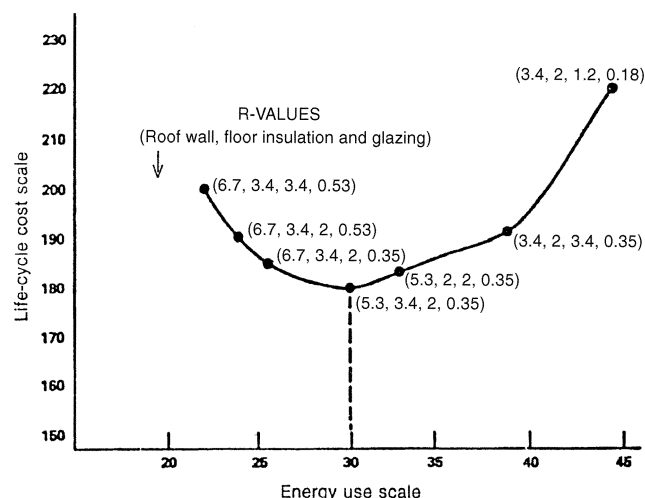


Fig. 8 Typical Relationship of Life-Cycle Cost to Energy Use

MOISTURE IN BUILDINGS

MOISTURE PROBLEMS IN BUILDINGS

Moisture control is necessary to avoid moisture-related problems with building energy performance, building maintenance and durability, and human comfort and health. Moisture degradation is the largest factor limiting the useful life of a building and can be visible or invisible. Invisible degradation includes degradation of the thermal resistance of building materials and decrease in the strength and stiffness of some materials. Visible moisture degradation may be in the form of (1) mold and mildew, (2) the decay of wood-based materials, (3) spalling of masonry and concrete caused by freeze-thaw cycles, (4) hydration of plastic materials, (5) corrosion of metals, (6) damage due to expansion of materials (e.g., buckling of wood floors), and (7) a decline in visual appearance (e.g., buckling of wood siding or efflorescence of masonry materials, which is the formation of a salt crust from the leaching of free alkalis). In addition, high moisture levels can lead to odors and mold spores in indoor air, which can seriously affect occupant health and comfort. Short summaries of such moisture conditions and related performance and health issues follow.

Mold, Mildew, Dust Mites, and Human Health

Mold and mildew in buildings are offensive, and the spores can cause respiratory problems and other allergic reactions in humans. Mold and mildew will grow on most surfaces if the relative humidity at the surface is above a critical value and the surface temperature is conducive to growth. The longer the relative humidity remains above the critical value, the more likely is visible mold growth; and the higher the humidity or temperature, the shorter is the time needed for germination. The surface relative humidity is a complex function of material moisture content, material properties, and local temperature and humidity conditions. In addition, mold growth depends on the type of surface. Fully recognizing the complexity of the issue, the International Energy Agency Annex 14 (1990) nevertheless established a surface humidity criterion for design purposes: The monthly average surface relative humidity should remain below 80%. Others have proposed more stringent criteria, the most stringent requiring that surface relative humidity remain below 70% *at all times*. Although there still is no agreement on which criterion is most appropriate, mold and mildew can usually be avoided by limiting surface moisture conditions over 80% to short time periods. These criteria should only be relaxed for nonporous surfaces that are regularly cleaned. Hukka and Viitanen (1999) developed a mathematical model for the prediction of a mold growth index. This model was successfully implemented and linked to a hygrothermal model by Karagiozis and Salonvaara (1998). Most molds grow at temperatures above approximately 5°C. Moisture accumulation below 5°C may not cause mold and mildew if the material is allowed to dry below the critical moisture content before the temperature rises above 5°C.

Dust mites can trigger allergies and asthma (Burge et al. 1994). Dust mites thrive at high relative humidities (over 70%) at room temperature, but will not survive sustained relative humidities below 50% (Burge et al. 1994). These relative humidities relate to local conditions in typical places that mites tend to inhabit such as mattresses, carpets, soft furniture, etc.

Paint Failure and Other Appearance Problems

Moisture trapped behind paint films may cause failure of the paint. Water or condensation may also cause streaking or staining. Excessive swings in the moisture content of wood-based panels or boards may cause buckling or warping. Excessive moisture in masonry and concrete may cause efflorescence, a white powdery area or lines, or, when combined with low temperatures, may cause freeze-thaw damage and spalling (chipping).

Structural Failures

Structural failures due to decay of wood are rare but have occurred (e.g., Merrill and TenWolde 1989). Decay generally requires wood moisture content at fiber saturation (usually about 30%) or higher and temperatures between 10 and 40°C. Wood moisture contents above fiber saturation are only possible in green lumber or by absorption of liquid water from condensation, leaks, ground water, or other saturated materials in contact with the wood. To maintain a safety margin, 20% moisture content is sometimes used during field inspections as the maximum allowable moisture level. Because wood moisture content can vary widely with sample location, a local moisture content of 20% or higher may indicate fiber saturation elsewhere. Once established, decay fungi produce water that enables them to maintain moisture conditions conducive to their own growth.

Rusting or corrosion of nails, nail plates, or other metal building components is also a potential cause of structural failure. Corrosion may occur at high relative humidities near the metal surface or as a result of liquid water from elsewhere. Wood moisture content over 20% encourages corrosion of steel fasteners in wood, especially if the wood is treated with preservatives. In buildings, metal fasteners are often the coldest surfaces, encouraging condensation on and corrosion of the fasteners.

Effect of Moisture on Heat Flow

Moisture in the building envelope can significantly degrade the thermal performance of most insulation materials. Bomberg and Shirliffe (1978), Epstein and Putnam (1977), Hedlin (1977, 1983, 1987, 1988a, 1988b), Jespersen (1960), Joy (1957), Knab et al. (1980), Kumaran (1989), Kyle and Desjarlais (1994), Langlais et al. (1983), Paljack (1973), Pedersen (1990), Pedersen et al. (1991), Shapiro and Motakef (1990), Thomas et al. (1983), Tobiasson and Richard (1979), Tobiasson (1987, 1991), and Tye (1987) investigated the effect of moisture content on heat flow and showed that the effect depends on the type of insulation material, the moisture content, the temperature of the insulation material, the insulation material's thermal history, and the building envelope's interior and exterior environments. The reported relationships between the thermal performance of the insulation material and heat flow can vary significantly; the variations are more pronounced in open-cell and fibrous insulations. Rapid vapor transfer through vapor-permeable insulations during testing accounts for these variations. Variations can also be due to the location of water in the insulation layer. Kyle and Desjarlais (1994) estimated that water distribution can account for a difference of up to 25% in heat flow in certain cases.

Moisture can contribute to both sensible and latent heat flow, as well as through mass transfer by diffusion or convection. Evaporation on the warm side of the insulation and condensation or adsorption on the cold side add a latent heat component to the heat flow.

Under steady-state conditions, the effect of moisture on thermal resistance may be small. Verschoor (1985) showed that an insulated residential-type stud wall panel with a poor vapor retarder on the warm side accumulated 1.5 kg of moisture per square metre when exposed to conditions continuously below freezing (steady-state) for 31 days. All of the accumulated moisture was located in the 13 mm layer of mineral fiber insulation immediately adjacent to the cold-side sheathing and at the interface between the insulation and the sheathing. In a continuation of the test program, to a total exposure period of 60 days, the rate of moisture gain remained constant during the entire period. Subsequently, the same test wall was subjected to diurnal outside temperature cycles through the freezing point. With this exposure, most of the accumulated moisture was found in the sheathing and the bottom of the test wall rather than in the coldest insulation layer. Except for the sheathing, there was negligible change in the overall thermal performance of the wall.

The behavior may be different for closed-cell plastic foam insulations. Field observations of low-temperature insulated tanks have

shown that when no air space exists between the cold surface and the insulation, the expected accumulation of condensed moisture did not occur.

Degradation of thermal resistance is more pronounced when daily reversals in temperature across the insulation drive moisture back and forth through the insulation layer and is exacerbated when the insulation material has a high water vapor permeance. A wetted compact low-slope roof is a good example of these phenomena. During the nighttime, moisture migrates upward through the insulation layer and can condense in the upper part of the insulation layer on the underside of the membrane. The following day, the increase in ambient temperature coupled with solar radiation heats the membrane and reverses the vapor pressure difference, evaporating some or all of the condensed water and driving it downward into the roofing system, transporting heat in the process. If sufficient water vapor can be driven downward, it may condense somewhere in the lower portion of the insulation layer, releasing its heat of condensation.

Hedlin (1988b) and Shuman (1980) experimentally showed that, for building envelopes containing permeable fibrous insulations that underwent temperature reversals, the rate of energy transfer increased sharply as the moisture content (MC) increased to approximately 1% by volume. The rate of increase in energy transfer diminished rapidly with further increases in moisture content. Energy transfer for permeable insulation with 1% MC by volume was roughly double that of dry insulation. Pedersen et al. (1991) analytically reproduced Hedlin's results; he demonstrated the high mobility of moisture in a permeable insulation and showed that latent effects are appreciable for a wide variety of North American climates. The latent effects typically add to the energy load and can increase peak energy demand. The extra load is added to the building load in the warm afternoon, and nearly the same amount of heat is removed in the cool evening.

Certain organic insulations such as wood fiberboard and perlite are hygroscopic and can contain 1% MC by volume if installed at equilibrium conditions; water leakage into the building envelope component is *not* a prerequisite for significant increases in heat flow.

In studies of hourly temperature and moisture content variations in wood frame wall cavities, Duff (1971) showed measurable levels of daily moisture migration across the cavity. Pedersen et al. (1991) demonstrated the same phenomenon in compact low-slope roofs.

The building envelope is exposed to ever-changing exterior conditions; fluctuations in the outdoor air temperature and the amount of solar radiation affect the temperature profile through the building envelope. These temperature changes affect the magnitude and the direction of the vapor pressure gradients. Water vapor transfer rates and direction are constantly changing, adjusting not only to the thermal changes but to changes in moisture concentration. However, conditions may exist where the *average* vapor pressure drive is in one direction, for example, upward in a low-slope roof during winter. In this situation, moisture accumulates in the insulation just below the impermeable roof membrane, and, assuming these conditions can be maintained for a reasonable length of time, water accumulates or frost forms unless the top layer of the insulation has adequate moisture absorption capacity (e.g., perlite or wood fiberboard). Under similar conditions in the summer, moisture is driven down to the vapor retarder or deck (if the deck is less permeable than the insulation layer). If there are no layers in the system that are less permeable than the insulation, the water vapor simply diffuses into the building interior.

Under conditions where the vapor pressure changes slowly or where the insulation layer has an extremely low water vapor permeance, little water vapor is transported. Moisture still affects the sensible heat transfer in the building envelope component. Epstein and Putnam (1977) and Larsson et al. (1977) showed a nearly linear increase in sensible energy transfer of approximately 3 to 5% for each volume percent increase in moisture content in cellular plastic insulations. For example, an insulation material with a 5% MC by

volume has 15 to 25% greater energy transfer than the dry insulation material. Other field studies by Dechow and Epstein (1978) and Ovstaas et al. (1983) have shown similar results for insulations installed in below-grade applications such as foundation walls.

Moisture Effect on Heat Storage

Moisture also affects the thermal storage capacity of certain hygroscopic building materials. At 10% MC, nearly 30% of the heat storage capacity of wood is in the water held in the cell walls. Since the specific heat of wood is a function of its temperature and moisture content (but almost independent of density and species), heat storage calculations must include an estimate of the equilibrium in-service moisture content of wood building components.

PROPERTIES OF WATER VAPOR IN AIR

Chapter 6 describes the properties of moist air and defines the various terms associated with water vapor in air, such as dew-point temperature, dry-bulb and wet-bulb temperatures, and relative humidity. Chapter 6 also explains the use of the psychrometric chart, as well as the physics of heating and cooling moist air.

MOISTURE IN BUILDING MATERIALS

Many common building materials are porous. The pores provide a large internal surface area, which generally has an affinity for water. In some materials, such as wood, moisture may also be adsorbed in the cell wall itself. The amount of water in these **hygroscopic** (water-attracting) materials is related to the relative humidity (rh) of the surrounding atmosphere. When relative humidity of the surrounding air rises, hygroscopic materials gain moisture (**adsorption**), and when the relative humidity drops these materials lose moisture (**desorption**). The relationship between relative humidity and the moisture content (MC) at a particular temperature can be represented in a graph called a sorption isotherm. Often isotherms obtained by adsorption are not identical to isotherms obtained by desorption, because the material tends to retain moisture when it is

drying. This difference between desorption and adsorption isotherms is called **hysteresis**. At high relative humidity, small pores become entirely filled with water. The maximum moisture content is reached when all pores are filled with water. But experimentally this can only be achieved in a vacuum, by boiling the material or by keeping the material in contact with water for an extremely long time (i.e., many years). In practice, the maximum moisture content of porous materials is lower. This lower maximum moisture content is sometimes referred to as the **capillary saturation moisture content**. Figure 9 shows typical sorption curves, giving the **equilibrium moisture content** (EMC) as a function of relative humidity. The EMC increases with relative humidity, especially above 80% rh. The EMC decreases slightly with increasing temperature.

Chapter 22 describes hygroscopic substances and their use as dehumidifying agents. Table 2 in Chapter 12 of the *ASHRAE Handbook—Applications* has data on the moisture content of various common materials in equilibrium with the atmosphere at various relative humidities.

Wood and many other hygroscopic materials change dimensions with variations in moisture content. The moisture content at which cell walls of wood are saturated but no free water exists in cell cavities is the **fiber saturation point**. It represents the upper limit for moisture gain from the air as water vapor. It is also the upper limit of swelling; although more water can be absorbed in cell cavities, additional swelling does not occur. Wood moisture content is expressed as a percentage of its oven-dry mass. The average fiber saturation point for most species is about 30%. The average EMC at 20°C and 45% rh (heating season indoor conditions) is about 8.5%. At 24°C and 70% rh (summer conditions), the EMC is about 13%.

The resulting dimensional changes in wood are proportional to the change in moisture content, but vary with species and direction of grain. For white oak, which is representative of interior trim material, 4.5% MC variation causes 2.5% volumetric shrinkage or swelling. Longitudinal dimensional change in straight-grained wood is insignificant, but it increases with crossgrain and other irregularities.

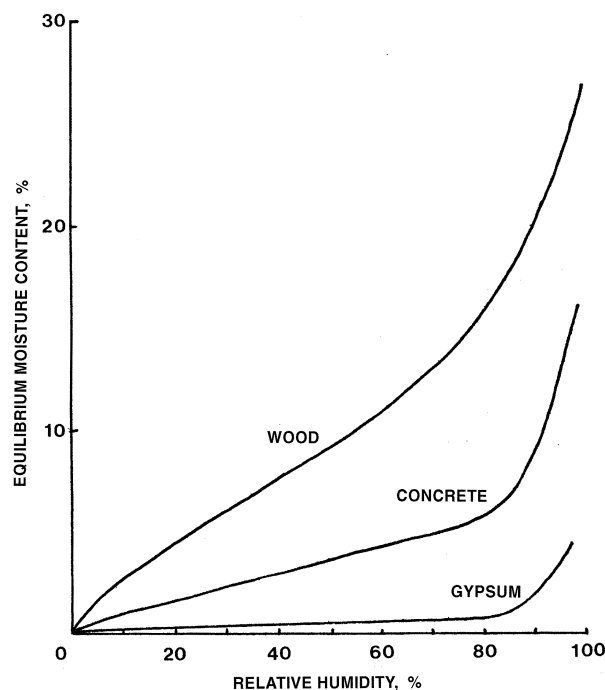


Fig. 9 Typical Sorption Isotherms for Wood, Concrete, and Gypsum (Hysteresis Is Ignored)

Table 2 Linear and Volumetric Shrinkage Values of Wood, from Green to Oven Dry Moisture Content

Wood Species	Radial %	Tangential %	Volumetric %
<i>Hardwoods</i>			
Birch			
Yellow	7.3	9.5	16.8
Oak			
Northern red	4.0	8.6	13.7
Southern red	4.7	11.3	16.1
White	5.6	10.5	16.3
<i>Softwoods</i>			
Cedar			
Northern white	2.2	4.9	7.2
Western red cedar	2.4	5.0	6.8
Douglas fir			
Coast	4.8	7.6	12.4
Fir			
White	3.3	7.0	9.8
Hemlock			
Western	4.2	7.8	12.4
Pine			
Eastern white	2.1	6.1	8.2
Longleaf	5.1	7.5	12.2
Ponderosa	3.9	6.2	9.7
Redwood			
Young growth	2.2	4.9	7.0
<i>Imported wood</i>			
Lauan	3.8	8.0	—

Note: Values expressed as a percentage of the green dimension (FPL 1999).

Accordingly, residential wood trusses with top and bottom chords exposed to different temperature and moisture regimes can show measurable seasonal vertical movements (Plewes 1976).

Thermal expansion of wood is usually outweighed by shrinkage or swelling due to moisture content changes. The linear thermal expansion coefficient for wood across the grain ranges from about 12.6×10^{-6} per kelvin for light wood species to about 45×10^{-6} per kelvin for dense wood species, which is small compared to that of many other materials. The thermal expansion coefficient parallel to the grain is between 3.1×10^{-6} and 4.5×10^{-6} per kelvin.

Most plant and animal fibers undergo dimensional changes similar to those noted in wood. Typical values for wood can be found in Table 2; the *Wood Handbook* (FPL 1999) gives more detailed information. Related changes in other materials are not as well documented. However, different expansion rates caused by temperature and moisture changes in different materials used in composite constructions should be considered (Baker 1964, BRS 1974).

Porous materials also absorb water in liquid form when in contact with it. Liquid water may be present because of leaks, rain penetration, flooding, or surface condensation. Wetting may be so complete that the material reaches the capillary saturation moisture content.

MOISTURE MIGRATION

Liquid water and water vapor migrate by a variety of moisture transport mechanisms. The following are some of the most important mechanisms:

- Liquid flow by gravity or air pressure differences
- Capillary suction of liquid water in porous building materials
- Movement of water vapor by air movement
- Water vapor diffusion by vapor pressure differences

Although in the past many moisture control strategies focused on control of vapor diffusion through the installation of vapor (diffusion) retarders, the other mechanisms, when present, can move far greater amounts of moisture. Therefore, liquid flow, capillary suction, and air movement should be controlled first.

Liquid flow by gravity and air pressure difference is not discussed here, but a short description of the other mechanisms follows. A more comprehensive treatment of moisture transport and storage may be found in Kumaran et al. (1994) and Kuenzel (1998).

Capillary Suction

Within small pores of diameter less than approximately $0.1 \mu\text{m}$, molecular attraction between the surface of the capillary and the water molecules causes a capillary suction defined by

$$s = \frac{2\sigma \cos \theta}{r} \quad (10)$$

where

- s = capillary suction
- σ = surface tension of water
- r = radius of the capillary
- θ = contact wetting angle

The **contact wetting angle** is the angle between the water meniscus and the capillary surface. The smaller this angle is, the larger the capillary suction. In **hydrophilic** (water-attracting) materials, the contact wetting angle is less than 90° , and in **hydrophobic** (water-repelling) materials, the angle is between 90° and 180° . Capillary suction is greater in smaller capillaries, so capillary suction moves moisture from larger to smaller capillaries. Although surface tension is a function of temperature (the higher the temperature, the lower the surface tension), this effect is very small.

Isothermal and nonisothermal movement may occur in the liquid phase, or in the vapor phase if the capillaries are not completely

filled. The transfer in the vapor phase is by vapor diffusion and is caused by a difference in vapor saturation pressure in the capillaries. **Thompson's law** states that the saturation vapor pressure in equilibrium with the water in a capillary is given by

$$p'' = p' \exp\left(\frac{s}{\rho RT}\right) = p' \exp\left(\frac{2\sigma \cos \theta}{r \rho RT}\right) \quad (11)$$

where

- p'' = saturation vapor pressure in capillary
- p' = saturation vapor pressure in ambient air at same temperature as p''
- ρ = density of water
- R = gas constant
- T = absolute temperature

Equation (11) shows that the saturation vapor pressure is lower in smaller capillaries than in larger capillaries, which causes vapor diffusion from larger water-filled capillaries to smaller capillaries. Saturation vapor pressure in the capillaries is lower at lower temperatures, which causes diffusion from higher to lower temperatures.

If the vapor pressure in the ambient air is in equilibrium with the saturation vapor pressure in the capillaries, Equation (11) can be rewritten as

$$s = \rho RT \ln \phi \quad (12)$$

where ϕ is the relative humidity of the ambient air.

Capillary flow of water can be expressed as a function of suction pressure gradients follows:

$$w_m = -k_m \frac{ds}{dx} \quad (13)$$

where

- w_m = water flux
- k_m = water permeability coefficient

Air Movement

Water vapor movement by air can be represented by

$$w = W\rho v \quad (14)$$

where

- w = water vapor flux (flow per unit area)
- W = humidity ratio of source air
- ρ = density of air
- v = airflow velocity

Even small airflows can carry large amounts of water vapor when compared to vapor diffusion. Airflow retarders are designed to inhibit the flow of air and thereby the transport of water vapor into the construction.

Water Vapor Diffusion

Water vapor also migrates by diffusion through air and building materials. Although moisture diffusion through air is relatively rapid, distribution of vapor in air is dominated by convection. This results in minimal vapor pressure differentials between connected spaces and rapid flow to condensing surfaces, such as cold glass or dehumidifier coils. Although movement by air convection usually dominates, when present, vapor diffusion can be an important mode of transportation in industrial applications such as cold storage facilities or built-in refrigerators. The control of diffusion also becomes more important with increasingly airtight construction.

The equation used to calculate water vapor diffusion flux through materials is based on a form of Fick's law:

$$w = -\mu \frac{dp}{dx} \quad (15)$$

where

w = water vapor flux (flow rate per unit area)
 p = water vapor pressure
 x = distance along flow path
 μ = water vapor permeability

According to Equation (15), water vapor flow by diffusion is proportional to the water vapor pressure gradient and closely parallels Fourier's equation for heat flow. The actual diffusion of vapor through a material is complex. The apparent water vapor permeability is a function of relative humidity and temperature and may vary spatially due to variations in material properties.

ASTM *Standard* E 96 describes test methods for the measurement of water vapor permeability. The rate of moisture transfer through a material is determined gravimetrically while maintaining a steady temperature and vapor pressure differential across the specimen. The standard identifies two tests: a dry cup (0% to 50% rh) and a wet cup (50% to 100% rh). In the wet-cup tests, liquid water movement may occur and the resulting water vapor transport coefficients should be treated with care (Kuenzel 1995).

Permeance is usually expressed in $\text{ng}/(\text{s} \cdot \text{m}^2 \cdot \text{Pa})$, and permeability in $\text{ng}/(\text{s} \cdot \text{m} \cdot \text{Pa})$. Whereas permeability refers to water vapor flux per unit thickness, the term permeance is used in reference to a material of a specific thickness. For example, a material that is 50 mm thick generally is assumed to have half the permeance of 25 mm thick material, even though permeance of many materials often is not strictly proportional to thickness. In many cases, this assumption ignores the effect of moisture content variations within the material, and the effect of cracks or holes in the surface. It is inappropriate to use the term permeability in reference to inhomogeneous or composite materials, such as plywood or gypsum board with paper facings. Whenever a building product is made of two dissimilar materials, only water vapor permeance is meaningful for characterizing vapor transfer through that product.

Methods have been developed that allow measurement of water vapor transport with temperature gradients across the specimen (Douglas et al. 1992, Krus 1996, Galbraith et al. 1998). These test methods promise more accurate data on isothermal vapor transfer through materials and will eventually allow better distinction between various transport modes.

Combined Liquid and Vapor Flow

It is nearly impossible to experimentally distinguish between liquid flows and vapor flows in hygroscopic materials. To distinguish the moisture flow in each phase, nonisothermal tests may be performed. In most practical applications in moisture analysis both vapor and liquid flow may be treated as parallel processes. Therefore, moisture flow is often expressed as the sum of two transport equations—one using vapor pressure as a driving potential for vapor flow and the other using either capillary suction or relative humidity as driving potentials for liquid moisture flow. These conservation equations may be written as follows:

$$\frac{\partial m}{\partial t} = -\nabla(w_v + w_w) + S_w \quad (16)$$

where

m = moisture content of the building material
 w_v = vapor diffusion flux
 w_w = liquid transport flux
 S_w = moisture source or sink

The symbol ∇ represents the nabla operator, which denotes divergence, or the gradients along the three spatial coordinates. The vapor and liquid transport flux densities may be given by

$$w_v = -\mu \nabla p \quad \text{or} \quad w_v = -\mu \nabla(\phi p_{sat}) \quad (17)$$

$$w_w = -D_p \nabla s \quad \text{or} \quad w_w = -D_\phi \nabla \phi \quad (18)$$

where

μ = water vapor permeability of building materials
 s = capillary suction pressure
 p_{sat} = water vapor saturation pressure
 D_p = liquid transport coefficient related to capillary suction
 D_ϕ = liquid transport coefficient related to relative humidity
 ϕ = relative humidity

Previous methods of calculation used moisture content and temperature as driving potentials for combined vapor and liquid movement. This approach has the disadvantage that moisture content is discontinuous at interfaces between different materials and, therefore, cannot be used as a moisture flow potential at those interfaces. Equation (17) and Equation (18) provide the advantage of continuity at material interfaces and maintain physically meaningful material parameters.

WATER VAPOR RETARDERS AND AIRFLOW RETARDERS

Water vapor retarders and airflow retarders combine to control the movement of moisture and air. Although their functions are different, a single component may serve both functions. The designer assesses the needs for moisture and air movement control in the building envelope and provides a system that combines the required vapor retarder and airflow retarder properties.

Airflow Retarder Functions and Properties

In addition to a vapor retarder, control of moisture requires an effective airflow retarder (also referred to as an air barrier or air infiltration barrier). Without effective control of airflow, vapor retarders are completely ineffective. However, airflow may accelerate the drying of a wet building component, as described by Karagiozis and Salonvaara (1999a,b).

A vapor retarder may also be an airflow retarder, that is, an air/vapor retarder. In the past, many designs were based on this, and measures were taken to ensure that the vapor retarder was continuous in order to control airflow through it. This remains a valid approach. Some recent designs treat airflow retarders and vapor retarders as separate entities, but an airflow retarder should not be placed in a location where it can cause moisture to condense if it also has vapor retarder properties. For example, an airflow retarder placed on the cold side of a building envelope may cause condensation, particularly if the vapor retarder is ineffective and the airflow retarder is impermeable to moisture.

However, a cold-side air/vapor retarder that also has sufficient insulation may result in a lower potential for condensation by raising the temperature of the surface of the air/vapor retarder, but this requires careful installation and sealing of joints.

Air leakage characteristics of airflow retarders can be determined with ASTM *Standard* E 283 or ASTM *Standard* E 1424. Di Lenardo et al. (1995) discuss specific air leakage criteria for airflow retarders in cold climates. These specifications call for maximum permissible air leakage rates between 0.05 and 0.2 L/s per square metre (as measured with an air pressure difference of 75 Pa), depending on the water vapor permeance of the outermost layer of the building envelope. The highest permissible air leakage rate of the airflow retarder applies if the permeance of the outermost layer is greater than 570 $\text{ng}/(\text{s} \cdot \text{m}^2 \cdot \text{Pa})$, and the lowest rate applies if the permeance is less than 60 $\text{ng}/(\text{s} \cdot \text{m}^2 \cdot \text{Pa})$. Intermediate values are provided as well. The recommendations apply only to heating climates.

The effectiveness of an airflow retarder can be greatly reduced if openings, even small ones, exist in it. Such openings can be

caused by poor design, poor workmanship during application, poorly sealed joints and edges, insufficient coating thickness, improper caulking and flashing, uncompensated thermal expansion, mechanical forces, aging, and other forms of degradation. Common faults or leaks occur at electrical boxes, plumbing penetrations, telephone and television wiring, and other unsealed openings in the structure.

A ceiling airflow retarder needs to be continuous at chases for plumbing, ducts, flues, and electrical wiring. In flat roofing, mechanical fasteners are sometimes used to adhere the system to the deck. These often penetrate the airflow retarder, and the resulting hole may allow air and accompanying moisture leakage into the roof.

Because it resists airflow, an airflow retarder must withstand pressures exerted by chimney (stack) effects, wind effects, or both, during construction and over the life of the building. The magnitude of the pressure varies, depending on the type of building and the sequence of construction. At one extreme, single-family dwellings may be built with the exterior cladding partly or entirely installed and insulation in place before the airflow retarder is added. Chimney effects in such buildings are small even in cold weather, so stresses on the airflow retarder during construction are small.

At the other extreme, in tall buildings, wind and chimney-effect forces are much greater than they are in single-family or other low-rise buildings. A fragile, unprotected sheet material should not be used as an airflow retarder (or vapor retarder) in a tall building because it will probably be torn by the wind before construction is completed.

In summary, an airflow retarder must

- Meet air permeability requirements
- Be continuous, i.e.,
 - Tight joints in the airflow retarder must be constructible
 - Effective bonds in the airflow retarder must be made at intersections (e.g., wall/roof)
 - Dimensional changes due to temperature changes or shrinkage must be accommodated without damage to joints or the retarder material
- Be strong enough to support the stresses applied to it, i.e.,
 - It must not be ruptured or excessively deformed by air pressures due to wind and stack effects
 - Where an adhesive is used to complete a joint, it must be designed to withstand forces that might gradually peel it away

A small penetration across an airflow retarder may seriously affect its performance. A penetration concentrates the air/vapor flow in such a way that large local deposits of water and ice are possible. In this situation calculations of moisture flow and accumulation using permeance values are useless when airflow is involved.

In addition, the following properties of an airflow retarder may be important, depending on the application:

- Elasticity
- Thermal stability
- Fire and flammability resistance
- Inertness to deteriorating elements
- Ease of installation

More information on air leakage in buildings may be found in [Chapter 26](#).

Vapor Retarder Functions and Properties

A vapor retarder retards water vapor diffusion but does not totally prevent its transmission. The requirements for buildings are entirely different than those for pipes and equipment. Conditions on the inside and outside of buildings vary continually, and air movement and ventilation can provide wetting as well as drying at various times. Moisture entering one side of a wall cavity can be stored and released at a later time, or transmitted immediately out of the cavity

through the other side. Requirements for vapor retarders in building components are therefore not extremely stringent.

In contrast, moisture that enters the insulation of cold storage facilities, cold pipes, or equipment is unlikely to escape, except during periods when the facilities, pipes, or equipment are not in use and are allowed to warm up. Vapor retarders for cold pipe or equipment applications must therefore have an extremely low permeance [e.g., less than $3 \text{ ng}/(\text{s} \cdot \text{m}^2 \cdot \text{Pa})$, or lower for severe conditions]. However, Korsgaard (1993) demonstrated that water condensing on an insulated cold pipe can be removed continuously by wicking action with a specially designed and installed wick system, as long as pipe temperatures are above freezing.

In HVAC applications, vapor retarders are applied to thermal insulation on tanks, cold pipes, ducts, refrigerated enclosures, and buildings. If conditions are conducive to condensation, water vapor retarders help (1) keep the insulation dry, thereby reducing the cooling load; (2) prevent structural damage by rot, corrosion, or the expansion of freezing water; and (3) reduce paint problems on exterior wall construction (ASTM *Standard C 755*).

In addition to vapor permeance, the following properties of vapor retarders are important, depending on the application:

- Mechanical strength in tension, shear, impact, and flexure
- Adhesion
- Elasticity
- Thermal stability
- Fire and flammability resistance
- Inertness to other deteriorating elements
- Ease of fabrication, application, and joint sealing

Any vapor retarder's effectiveness depends on its vapor permeance, installation, and location within the insulated section. The vapor retarder is usually located at or near the surface exposed to the higher water vapor pressure. For residences in heating climates, this is usually the winter-warm side of the insulation.

Under conditions of reversible water vapor flow that can occur during temperature cycling of industrial insulations or of special-purpose buildings, the selection and location of water vapor retarders require special study and treatment (Stachelek 1955).

Vapor retarder material is usually a thin sheet or coating. However, a construction of several materials, some perhaps of substantial thickness, could also constitute a vapor retarder system.

Water vapor permeances and permeabilities of some vapor retarders and other building materials are given in [Table 9 in Chapter 25](#).

Vapor retarders that allow substantial summer drying while functioning as effective vapor retarders during the heating season are sometimes called "smart" vapor retarders. One type of smart vapor retarder has a low permeance to vapor but is permeable to liquid water, allowing the drying of condensed moisture. Korsgaard and Pedersen (1989, 1992) describe such a vapor retarder composed of a synthetic fabric sandwiched between staggered strips of plastic film. The fabric wicks free water from the building envelope, while the plastic film retards vapor flow into it.

Another smart vapor retarder provides low vapor permeance at low relative humidities but much higher permeance at high relative humidity. During the heating season, indoor humidity usually is below 50%, and the permeance of the smart vapor retarder is low. In the summer and even during winter days with high solar heat gains, when the temperature gradient is reversed, moisture moving from the exterior of the wall or roof raises the relative humidity at the vapor retarder. This leads to a higher vapor permeance of the vapor retarder and the potential for the wall or roof to dry out. One such vapor retarder, a nylon film, is described by Kuenzel (1998). Below 50% rh, the permeance of the film is less than $60 \text{ ng}/(\text{s} \cdot \text{m}^2 \cdot \text{Pa})$, but it becomes more permeable at above 60% rh, reaching $2070 \text{ ng}/(\text{s} \cdot \text{m}^2 \cdot \text{Pa})$ at 90% rh.

Vapor retarder material for pipes is usually sheet metal with soldered seams; heavy foil with wide, sealed overlaps; plastic pipe; or other very low permeance systems.

Classification of Vapor Retarders

Historically, a material or system with a permeance of 60 ng/(s·m²·Pa) or less qualifies as a vapor retarder. More recently, further classification of vapor retarders has been proposed. For example, the Canadian General Standards Board (CGSB) has specified Type I vapor retarders as retarders with a permeance of 15 ng/(s·m²·Pa) or less, and Type II as retarders with a permeance of 45 ng/(s·m²·Pa) or less before aging and 60 ng/(s·m²·Pa) or less after aging.

Water vapor retarders are classified as rigid, flexible, or coating materials. Rigid retarders include reinforced plastics, aluminum, and stainless steel. These retarders usually are mechanically fastened in place and are vapor-sealed at the joints.

Flexible retarders include metal foils, laminated foil and treated papers, coated felts and papers, and plastic films or sheets. Such retarders are supplied in roll form or as an integral part of a building material (e.g., insulation). Accessory materials are required for sealing joints.

Coating retarders may be semifluid or mastic; paint (arbitrarily called surface coatings); or hot melt, including thermofusible sheet materials. Their basic composition may be asphaltic, resinous, or polymeric, with or without pigments and solvents, as required to meet design conditions. They can be applied by spray, brush, trowel, roller, dip or mop, or in sheet form, depending on the type of coating and surface to which it is applied. Potentially, each of these materials is an airflow retarder; however, to meet airflow retarder specifications, it must satisfy the requirements for strength, continuity, and air permeance.

Designers have many options. For example, the conditions for control of airflow and moisture movement might be achieved using an interior finish, such as drywall, to provide strength and stiffness, along with a low-permeability coating, such as a vapor retarder paint, to provide the required low level of permeance. In this case, edge sealing is needed to establish continuity with adjacent airflow retarder/vapor retarder components.

Other designs may use more than one component. However, (1) any component that qualifies as a vapor retarder usually also impedes airflow, and is thus subject to pressure differences that it must resist, and (2) any component that impedes airflow often also retards vapor movement and may promote condensation or frost formation.

Additional information regarding the control of moisture and airflow through the use of vapor retarders and airflow retarders may be found in [Chapters 24 and 26](#) and in Construction Specifications Canada (1990).

Several studies found a significant increase in the apparent permeance of vapor retarders as a result of small holes in the vapor retarder. For example, Seiffert (1970) reports a 100-fold increase in the permeance of aluminum foil when it is 0.014% perforated, and a 4000-fold increase when 0.22% of the surface is perforated. In general, penetrations particularly degrade a vapor retarder's effectiveness if the vapor retarder has a very low permeance (e.g., polyethylene or aluminum foil). In addition, perforations may lead to additional air leakage, which further erodes the effectiveness of the vapor retarder.

STEADY-STATE DESIGN TOOLS

Traditional methods for moisture design of the exterior building envelope all have severe limitations, and the results are sometimes difficult to interpret. However, these methods are used by design professionals and form the basis for current codes dealing with moisture control and vapor retarders.

The three best-known manual steady-state design tools for evaluating the probability of condensation within exterior envelopes (exterior walls, roofs, or ceilings) are (1) the dew-point method, (2) the Glaser diagram, and (3) the Kieper diagram. All three methods compare the vapor pressures within the envelope, as calculated by simple vapor diffusion equations, with the saturation pressures, which are based on the calculated temperatures within the envelope. If the calculated vapor pressure is above the saturation pressure at any point within the envelope, condensation is indicated.

The **dew-point method**, used in North America, and the **Glaser diagram**, commonly used in Europe and elsewhere, are almost identical. They differ slightly in the formulation of the vapor diffusion equation for flow through a building material and in definition of terms; the main difference lies in the graphical procedures. These methods are often misused, especially when condensation is present.

The **Kieper diagram**, a variant of the previous two methods, was introduced by Kieper et al. (1976) and described in greater detail by Trethewen (1979) and TenWolde (1983, 1994). 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 that (1) the same diagram can be used for different wall configurations, as long as indoor and outdoor conditions are not changed; and (2) the calculation does not need to be repeated if condensation is indicated.

Both the dew-point method and the Kieper diagram allow simple estimation of the effect of wall or roof cavity ventilation by representing the effect of ventilation on thermal and vapor transport through the addition of parallel thermal and vapor diffusion resistances (Trethewen 1979, TenWolde and Carll 1992). The parallel resistances account for the heat and vapor bypassing the exterior material layers with outside ventilation air. The magnitude of the parallel resistances may be determined from the following equations:

$$R_{t,par} = \frac{S}{\underline{Q} \rho c_p} \quad (19)$$

$$R_{v,par} = \frac{S}{\underline{Q} \rho c} \quad (20)$$

where

$R_{t,par}$ = parallel thermal resistance, m²·K/W

$R_{v,par}$ = parallel vapor flow resistance, Pa·m²·s/ng

S = surface area of the wall or ceiling, m²

$\underline{Q}$ = cavity ventilation airflow rate, m³/s

ρ = density of air, kg/m³

c = ratio of humidity ratio and vapor pressure, approximately 6.13 g/(kg·kPa)

c_p = specific heat, J/(kg·K)

Although this method of including ventilation only approximates the actual effects of ventilation, it can be a useful tool.

Many people advocate abandoning steady-state design tools because of their severe limitations. Perhaps the greatest limitation is that their focus is restricted to prevention of sustained interstitial condensation. Many building failures (such as mold and mildew, buckling of siding, and paint failure) are not necessarily related to surface condensation.

Conversely, limited condensation can often be tolerated, depending on the materials involved, the temperature conditions, and the speed at which the material dries out. Wetting and drying cycles cannot be accurately analyzed with steady-state tools because these tools neglect moisture storage in the building materials. Another weakness is that these methods exclude all moisture transfer mechanisms other than vapor diffusion. Results obtained with any of these methods should therefore be considered as approximations and be used with extreme care.

The validity and usefulness of any of these methods depend on the judicious selection of boundary conditions and material properties. Specifically, they should only be used to estimate seasonal mean conditions, rather than daily or even weekly mean conditions. Furthermore, permeances may vary with moisture content and the effect of rain splash, flashing imperfections, leaky or poorly formed joints, weather exposure, and sunshine can have overriding effects.

For those who want to use these simple tools, despite their shortcomings, a short description of the dew-point method is presented, with an example of its use. The Glaser diagram closely parallels the dew-point method. A comprehensive description of these methods can be found in TenWolde (1994).

Dew-Point Method

The dew-point method is based on a slight modification of diffusion Equation (15):

$$w = -\mu \frac{\Delta p}{d} \quad (21)$$

where

w = water vapor flux through a layer of material, $\text{ng/s} \cdot \text{m}^2$

μ = water vapor permeability of material, $\text{ng/(s} \cdot \text{m} \cdot \text{Pa)}$

Δp = vapor pressure difference across the layer, Pa

d = thickness of the layer, m

The term μ/d represents the permeance of the material. Water vapor resistance Z is defined as the inverse of the permeance. Then Equation (21) can be written as

$$w = -\frac{\Delta p}{Z} \quad (22)$$

Example 1. The dew-point method is explained and demonstrated for the frame wall construction and materials described in Table 3. Assume 21°C, 40% rh indoors, and -6.7°C, 50% rh outdoors.

Solution:

Step 1. Calculate the temperature drop across each material. The temperature drop is proportional to the R-value as follows:

$$\frac{\Delta T_{\text{material}}}{\Delta T_{\text{wall}}} = \frac{R_{\text{material}}}{R_{\text{wall}}}$$

Table 4 lists the resulting temperature drops and resulting temperatures at each surface.

Step 2. Find the saturation vapor pressures corresponding to the surface temperatures (Table 4). These values can be found in Table 2 in Chapter 6, or in other psychrometric tables or charts.

Step 3. Calculate the vapor pressure drops across each material. These are calculated in much the same way as the temperature drops in step 1.

$$\frac{\Delta p_{\text{material}}}{\Delta p_{\text{wall}}} = \frac{Z_{\text{material}}}{Z_{\text{wall}}}$$

where

p = vapor pressure, Pa

Z = vapor diffusion resistance, $\text{Pa} \cdot \text{m}^2 \cdot \text{s/ng}$

From Table 3, the total resistance of the wall with the vapor retarder is

$$\begin{aligned} Z_{\text{wall}} &= 1/9200 + 1/290 + 1/1724 + 1/29 + 1/2010 + 1/57000 \\ &= 0.0391 \text{ Pa} \cdot \text{m}^2 \cdot \text{s/ng} \end{aligned}$$

The vapor pressure drop across the wall is calculated from indoor and outdoor relative humidities and the indoor and outdoor saturation vapor pressures (see Table 4).

$$\begin{aligned} \Delta p_{\text{wall}} &= p_{\text{indoor}} - p_{\text{outdoor}} \\ &= (40/100) 2.496 - (50/100) 0.3701 = 0.8134 \text{ kPa} \end{aligned}$$

Table 3 Approximate Thermal and Vapor Diffusion Properties of Wall in Example 1

Air Film or Material	Thermal Resistance R , $\text{m}^2 \cdot \text{K/W}$	Permeance M , $\text{ng/(s} \cdot \text{m}^2 \cdot \text{Pa)}$	Diffusion Resistance Z , $\text{Pa} \cdot \text{m}^2 \cdot \text{s/ng}$
Air film (still)	0.12	9200 ^a	0.00011 ^a
Gypsum board, painted	0.079	290	0.0035
Insulation	1.9	1700	0.00058
Plywood sheathing	0.11	29	0.0345
Wood siding	0.18 ^b	2010 ^b	0.0005 ^b
Air film (wind)	0.03	57000 ^a	0.000017 ^a
Total	2.42	Not applicable	0.0392

^aApproximate values; permeances of surface air films are very large compared to those of other materials and do not affect results of calculations.

^bApproximate values; permeance reflects limited ventilation of back of siding.

Table 4 Calculated Temperature Drops, Surface Temperatures, and Saturation Vapor Pressures in Example 1

Air Film or Material or Surface	Temperature Drop, °C	Surface Temperature, °C	Saturation Vapor Pressure at Surface, kPa
Indoor air	—	21	2.496
Surface air film	1.3	—	—
Interior wall surface	—	19.7	2.299
Gypsum board	0.9	—	—
Gypsum board/Insulation	—	18.8	2.168
Insulation	21.9	—	—
Insulation/Sheathing	—	-3.1	0.4843
Plywood sheathing	1.2	—	—
Sheathing/Siding	—	-4.3	0.442
Wood siding	2.0	—	—
Exterior wall surface	—	-6.3	0.3796
Surface air film	0.3	—	—
Outdoor air	—	-6.6	0.3701

Table 5 Initial and Final Calculations of Vapor Pressure Drops and Surface Vapor Pressures in Example 1

Air Film or Material or Surface	Saturation Vapor Pressure, kPa	Initial Calculation Vapor Pressure, kPa		Final Calculation Vapor Pressure, kPa	
		Drop	At Surface	Drop	At Surface
Indoor air (40% rh)	2.496	—	0.9986	—	0.9986
Surface air film	—	0.0024	—	0.0135	—
Interior wall surface	2.299	—	0.9962	—	0.9851
Gypsum board	—	0.0716	—	0.4292	—
Gyp. board/Insulation	2.168	—	0.9246	—	0.5559
Insulation	—	0.0122	—	0.0716	—
Insulation/Sheathing	0.4843	—	0.9124	—	0.4843
Plywood sheathing	—	0.7169	—	0.2951	—
Sheathing/Siding	0.442	—	0.1955	—	0.1892
Wood siding	—	0.0101	—	0.0040	—
Exterior wall surface	0.3796	—	0.1854	—	0.1852
Surface air film	—	0.0003	—	0.00014	—
Outdoor air (50% rh)	0.3701	—	0.1851	—	0.1851

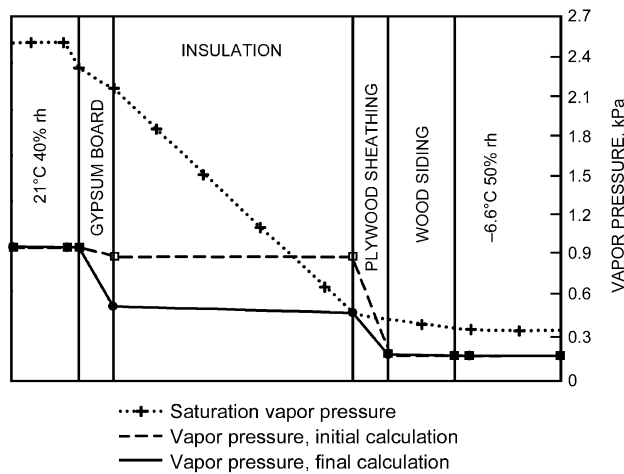


Fig. 10 Dew-Point Calculation in Example 1

As with temperatures, the vapor pressures at the surfaces of each material can easily be determined from the vapor pressure drops. Table 5 lists the results for the example wall in the initial calculation column.

Step 4. Figure 10 shows the saturation and calculated vapor pressures. Comparison with saturation pressures reveals that the calculated vapor pressure on the interior surface of the sheathing (0.9125 kPa) is well above the saturation pressure at that location (0.4843 kPa). This indicates condensation, probably on the surface of the sheathing. *It does not indicate condensation within the insulation.*

If the location of the condensation or the condensation rate is of interest, additional calculations (steps 5 and 6) are necessary.

Step 5. Figure 10 shows that the calculated vapor pressure exceeds the saturation vapor pressure by the greatest amount at the interior surface of the plywood sheathing. Therefore, this is the most likely location for condensation to occur. With condensation at that surface, the vapor pressure should equal the saturation vapor pressure at that location (see the final calculation column in Table 5).

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 the calculation in step 3, but the wall is now divided into two parts: one part on the interior of the condensation plane (i.e., gypsum board and insulation) and the other part on the exterior (plywood sheathing and wood siding). The vapor pressure drop over the first part of the wall is

$$\Delta p_1 = 0.9986 - 0.4843 = 0.5143 \text{ kPa}$$

and that over the second part is

$$\Delta p_2 = 0.4843 - 0.1851 = 0.2992 \text{ kPa}$$

The vapor diffusion resistances of both parts of the wall are

$$Z_1 = 1/9200 + 1/290 + 1/1724 = 0.0041 \text{ Pa} \cdot \text{m}^2 \cdot \text{s/ng}$$

$$Z_2 = 1/29 + 1/2010 + 1/5700 = 0.035 \text{ Pa} \cdot \text{m}^2 \cdot \text{s/ng}$$

The vapor pressure drops across each material can now be calculated from

$$\frac{\Delta p_{\text{material}}}{\Delta p_i} = \frac{Z_{\text{material}}}{Z_i} \quad \text{for } i = 1, 2$$

Final calculations of vapor pressure are shown in Table 5. The vapor pressure no longer exceeds the saturation vapor pressure, which means that the condensation plane was chosen correctly. Figure 10 shows the vapor pressure profile (labeled as Vapor pressure, final calculation).

Vapor flow is no longer the same throughout the wall—vapor flow into the wall from the indoor air increases as a result of the lower vapor pressure at the plywood surface, while flow from the wall to the outside decreases. The difference between the two flows is the rate of moisture accumulation:

$$w_c = \Delta p_1/Z_1 - \Delta p_2/Z_2 = 0.5143/0.0041 - 0.2992/0.035 = 117 \mu\text{g}/(\text{s} \cdot \text{m}^2)$$

This amounts to about 10 g/day·m². In our example, the plywood surface is below freezing, and this moisture would probably accumulate as frost. The moisture content of the plywood would be increased by 1% after about a week of condensation at this rate.

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 whether the saturation pressure is above the 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, the following steps may be followed:

1. Select the condensation surface. In most cases it is the surface where the difference between the calculated vapor pressure and the saturation vapor pressure is the highest. Vapor pressure at this surface should be set equal to the saturation vapor pressure.
2. Recalculate the vapor pressures; if any vapor pressures are above saturation, steps 5 and 6 should be repeated with a different choice for the condensation surface.
3. If needed, calculate the rate of condensation.

MATHEMATICAL MODELS

The rapid advance in computer technology has made it possible to develop computer models capable of analyzing and predicting the thermal and moisture behavior of building components. A small number are extensions of the steady-state analysis methods described before, but with the **transient models** it is possible to predict hourly drying and wetting of building components in a variety of conditions, climates, and design configurations. The information in this section is largely based on a review of the state of the art of heat and moisture transport modeling for buildings, which identified 37 different models of various complexity (Hens 1996). Some of those models do not include moisture transport and are therefore not included here. Most of the models are research tools that are not readily available, but some are available either commercially, free of charge, or through a consultant. Karagiozis (2001) describes the more sophisticated design tools, indicating both the capabilities and the limitations. ASTM *Manual 40* covers available design tools and approaches to investigate the performance of building envelope systems in terms of heat and moisture transport.

For many applications, the actual behavior of an assembly under transient climatic conditions must be simulated in order to account for short-term processes like driving rain absorption, summer condensations, and phase changes. Understanding the application limits of each model is an important part of applying mathematical models to develop design guidelines.

The features of a complete moisture analysis model include:

1. Transient heat, air, and moisture transport formulation, incorporating physics of
 - Vapor transport
 - Liquid transport
 - Airflow
 - Heat and moisture storage/capacity
 - Condensation and evaporation
 - Freezing and thawing
2. One- or two-dimensional spatial formulation
3. Material properties as functions of moisture content, relative humidity, or temperature
 - Thermal properties (density, heat capacity, thermal conductivity)
 - Moisture properties (porosity, sorption, water retention, vapor permeability, liquid diffusivity)
 - Airflow properties (air permeability)

4. Boundary conditions (generally on an hourly basis)
 - Incident solar radiation and sky radiation (depending on inclination and orientation)
 - Wind-driven rain at exterior surfaces (depending on location, and aerodynamics)
 - Wind speed, orientation, and pressure
 - Interior and exterior temperature and relative humidity
 - Interior moisture sources and stratification
5. Surface conditions
 - Convective heat transfer coefficients
 - Mass transfer coefficients
 - Short wave absorptivity
 - Long wave emissivity
 - Precipitation absorptivity
6. Building systems and subsystem effects
 - Water penetration rates through subsystems (joints, cracks, etc)
 - Air leakage (cracks, joints, e.g., around a window)
 - Additional sources of moisture

While not all these features are required for every analysis, additional features may be required in some applications, such as moisture flow through unintentional cracks and intentional openings. To accurately model these cracks and openings, supplementary experiments may be used to define their performance under various loads. In Feature 6, additional laboratory-controlled tests provide performance data specific to each subsystem (e.g., water entry through a crack) (Straube and Burnett 1997). In most cases, field measurement of system and subsystem effects is preferred.

The validation, verification, and benchmarking of hygrothermal models is a formidable task. Little internationally accepted experimental data exist to benchmark hygrothermal models. The main difficulty lies in the fact that it is difficult to measure moisture flows and moisture transport potentials even in laboratory-controlled conditions. Even a validated model should be verified for each new application. Two-dimensional and three-dimensional hygrothermal models are extremely complex and mostly require the direct expertise of the authors.

In most hygrothermal models, moisture content, temperature, relative humidity, and related fluxes are common outputs of simulations. Results have to be checked for consistency, accuracy, grid independency, and sensitivity to parameter changes. The results may be used to determine the moisture tolerance of an envelope subjected to various interior and exterior loads. The heat fluxes may be used to determine the thermal performance under the influence of moisture and airflow. Furthermore, the transient output data may be used to assess durability and indoor air quality. Post-processing tools concerning durability (e.g., corrosion, mold growth, freezing and thawing, hygrothermal dilation, and indoor air humidity) are currently being developed. For instance, Karagiozis and Kuenzel (1999) developed a model to estimate the rate of mold growth and corrosion. It is expected that hygrothermal models will be incorporated in whole-building simulation tools (Karagiozis and Salonvaara 1999b).

Transient models enable an hour-by-hour analysis of moisture conditions in building components and a much more realistic calculation than steady-state diffusion models. However, many are not easy to use and require judgment and expertise on the part of the user. Existing moisture transport models are one- or two-dimensional, which requires the user to devise a realistic representation of a three-dimensional building component. Users need to be aware of which transport phenomena and types of boundary conditions are included and which are not. For instance, some models are not able to handle rain wetting of the exterior.

Results from an analysis tend to be very sensitive to the choice of indoor and outdoor conditions, but exact conditions are seldom known. Indoor and outdoor conditions to be used for the purpose of

building design have not yet been established, although standards are being developed. Accurate data for all the materials in a component is difficult to find. Finally, interpretation of the results is not easy; accurate data on what moisture and temperature conditions materials can tolerate are not often available.

PREVENTING SURFACE CONDENSATION

Surface condensation occurs when water vapor comes in contact with a surface that has a temperature lower than the dew point of that vapor. The insulation should be sufficiently thick to ensure that the insulation surface temperature always exceeds the dew-point temperature to prevent surface condensation from occurring on the warm side of insulated rooms, pipes, ducts, and equipment.

The concept of a **temperature index coefficient** τ , also called the condensation resistance factor, is useful for calculating the surface temperature:

$$\tau = \frac{t_s - t_c}{t_a - t_c} \quad (23)$$

where

t_s = surface temperature on warm side of insulation

t_c = temperature on cold side of insulation

t_a = ambient temperature on warm side of insulation

The minimum temperature index coefficient to avoid surface condensation is

$$\tau_{min} = \frac{t_d - t_c}{t_a - t_c} \quad (24)$$

where t_d is the dew point of ambient air.

For flat surfaces and insulation, the temperature index coefficient can be stated as

$$\tau = \frac{L/k}{L/k + 1/h_i} \quad (25)$$

where

L = thickness of the insulation

k = thermal conductivity of the insulation

h_i = surface heat transfer coefficient

The minimum insulation thickness to avoid surface condensation on a flat surface can be calculated from

$$L_{min} = \frac{\tau_{min} k}{1 - \tau_{min} h_i} \quad (26)$$

The minimum insulation thickness for pipe insulation is given by

$$r_{s,min} \ln \left(\frac{r_{s,min}}{r_i} \right) = \frac{\tau_{min} k}{1 - \tau_{min} h_i} \quad (27)$$

where

$r_{s,min}$ = minimum outer radius of the insulation

r_i = inner radius of the insulation

The term to the left of the equal sign in Equation (27) is called equivalent thickness. **Equivalent thickness** is the thickness of insulation on a flat surface required to give the same rate of heat transmission per unit area of outer surface of insulation as on a cylinder or pipe. Figure 11 provides a convenient way to convert equivalent thickness to actual thickness.

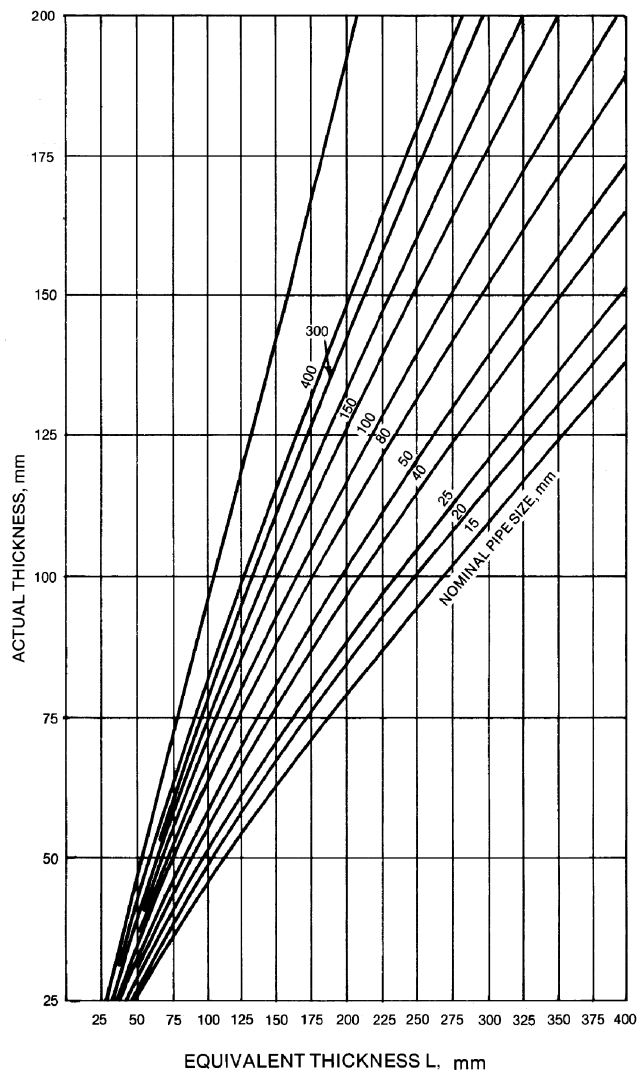


Fig. 11 Conversion of Equivalent Thickness to Actual Thickness for Pipe Insulation

STANDARDS

- ASTM. 1997. Standard terminology relating to thermal insulating materials. *Standard C 168-97*.
- ASTM. 1997. Standard test method for steady-state heat flux measurements and thermal transmission properties by means of the guarded-hot-plate apparatus. *Standard C 177-97*.
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