

THERMAL AND MOISTURE CONTROL IN INSULATED ASSEMBLIES—APPLICATIONS

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IN THE ORIGINAL planning phase of buildings, the thermal and moisture design and long-term performance must be considered. Installation of adequate insulation and moisture control assemblies during construction can be much more economical than installation later. Proper selection of thermal insulation and moisture control assemblies must be based on

- Thermal and moisture properties of the materials
- Other properties required by the location of the materials
- Space availability
- Compatibility of the materials with adjacent materials
- Interior and exterior climate
- Performance expectations

Types of thermal insulation, their properties, economic thickness, and principles of moisture control and moisture transport are discussed in [Chapters 23 and 25](#). Insulation in various assemblies that can be used interchangeably for a given construction, as well as specific moisture control options for various climatic regions, are discussed in this chapter. For specific industrial applications of insulated assemblies see the appropriate chapter in other ASHRAE Handbooks. In the *ASHRAE Handbook—Refrigeration*, for refrigerators and freezers, see [Chapters 47, 48, and 49](#); for insulation systems for refrigerant piping, see [Chapter 32](#) and this chapter; for refrigerated facility design, see [Chapters 13 and 39](#); for trucks, trailers, and containers, see [Chapter 29](#); for marine refrigeration, see [Chapter 30](#); and for environmental test facilities, see [Chapter 37](#).

GENERAL BUILDING INSULATION PRACTICE

WOOD FRAME CONSTRUCTION

Wood framing members and structural panels such as plywood, particleboard, and fiberboard only provide limited resistance to heat flow; therefore, wood frame construction is well suited to application of both cavity insulation and surface-applied insulation. The most common materials for cavity insulation are glass fiber, mineral fiber, cellulose, and spray-applied foams. For surface applications, a wide variety of sheathing insulations exists.

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Roof decks of wood, metal, or preformed units may be insulated on top of or below the deck.

Attic construction with conventional rafters and ceiling joists or roof trusses can be insulated between framing members with batt, blanket, or loose-fill insulation. In warm climates, radiant barriers, low emissivity surfaces, and reflective insulations further reduce cooling loads. The Radiant Barrier Attic Fact Sheet (DOE 1991) provides information on climatic areas best suited for radiant barrier applications. This document also provides comparative information on the relative performance of these products versus conventional fibrous insulations.

The cavities of **cathedral ceiling construction** (in which the ceiling insulation and interior finish are parallel to the roof plane) can be insulated using glass fiber, cellulose, rigid foam, or spray-applied insulation. The surface above cathedral ceiling framing may be insulated with insulating panels or structural insulated panels (SIPs). The placement of insulation directly beneath a sloped roof deck in standard flat-ceiling construction, with or without ventilation, has been called “cathedralized” construction.

The **wall cavities** of wood frame construction can be insulated with batt, blanket, and loose-fill or spray-applied insulation. When using insulation materials in wall applications, extra care must be taken during the installation to eliminate voids within the wall cavity. When installing loose-fill insulation during retrofit of existing construction, all cavities should be checked prior to installation for obstructions such as fire stop headers and wiring that could prevent complete filling of the cavity. In addition, the material must be installed at the manufacturer’s recommended density to ensure the desired thermal performance.

In addition to being properly insulated, the **exterior envelope** of a building should be constructed to minimize airflow into or through the building envelope. Airflow may degrade the thermal performance of insulation and cause excessive moisture accumulation in the building envelope. The use and function of airflow retarders are discussed in both in [Chapter 23](#) and in this chapter.

COLD-FORMED STEEL FRAME CONSTRUCTION

Conventional light frame construction with cold-formed steel framing has many characteristics in common with light frame wood construction. The greatest differences are the increased thermal conductivity and the dimension and shape characteristics of steel framing members. Barbour et al. (1994) and Tuluca and Gorthala (1999) found that the conductivity and framing member spacing

have the most significant roles in determining overall R-value (U-factor). They determined that the thickness of cold-formed steel does not play a significant role in the R-value (U-factor). The parallel path method overestimates the R-values for building assemblies containing cold-formed steel framing, and the isothermal planes calculation methods underestimates the R-value. For methods to calculate heat flow in framing assemblies using cold-formed steel, see [Chapter 25](#).

The most common cavity insulation materials are glass fiber, mineral fiber, cellulose, and spray-applied foams. Cavity insulation should be full width to cover between the steel framing members; it should not be a nominal width such as used for wood stud construction. Surface applications of continuous insulation sheathing, such as rigid foam board (i.e., extruded or expanded polyisocyanurate or polystyrene), may be applied to the exterior or interior of the assembly framing to provide a thermal break. Rigid board insulation applied as a sheathing does not provide structural lateral bracing.

Thermal bridging may be more severe with cold-formed steel-framed trusses than with conventional joist and rafter framing. Roof trusses have chords and web members that extend through the insulation into an unconditioned attic space and act as a thermal bridge to the bottom chord. A continuous insulating sheathing on the exterior or interior of the roof framing provides a thermal break.

HEAVY STEEL FRAME CONSTRUCTION

Buildings and structures with heavy, steel framing supports and exterior metal cladding are usually insulated between the frame and cladding with faced blanket or spray insulation. In heating climates, the facing may serve as a combination vapor retarder and interior finish, which must be protected against physical damage. Other types of insulation can be used by adding framing or furring to the inside of frame or exterior siding. Insulation securements that compress batt and blanket insulations reduce thermal resistance. This reduction, plus the thermal bridging caused by the screw or bolt penetrating the insulation, may cause condensation during cold weather.

The exterior cladding of structural steel-framed buildings may be (1) custom walls for specific projects, where most construction components are developed on a one-time basis; (2) commercial walls, where standard components are adapted to a particular building design; and (3) industrial-type walls, where standard metal sheets are fluted or ribbed to form field-assembled sandwiches to meet job conditions.

The cladding may consist of prefabricated panels or sections that may be classified as one of the following general types:

1. To withstand the elements, **single-thickness facings** are usually inserted in subframing with the windows to form a veneer over separate backup walls. Thermal insulation is integral with, or added to, the exterior of the backup wall and covers the edge of the floor slab or spandrel beam. In heating climates, this method reduces heat loss and keeps floors warm at their exterior edge. Insulating the exterior of the framing reduces thermal movement of the building structure.
2. **Sandwich construction** or adhesive-bonded panels are generally three-ply: exterior skin, core materials, and interior skin. This type of panel, when manufactured with concrete faces and an insulation core, comes in large sizes and can be attached directly to the exterior of the building frame. When using metal facings, the width of the panels is usually restricted to match that of the standard formed sheet. These panels are installed on the exterior of the building framing. The thermal performance required for a particular installation (including the interfaces between walls, floors, ceiling, doors, and windows) should be checked carefully because adding insulation later is difficult.
3. **Mechanically fastened panels** generally have a hollow box shape, with the exterior facing nesting over the interior facing.

The cavity can be filled with flexible or semirigid insulation. The edges should vent to the exterior of the building to allow the panel to serve as a rain screen. The panels are normally installed in a subframing system.

4. **Industrial metal panels** have an exterior facing of standard ribbed, corrugated V-beam materials and an interior facing of proprietary metal pans or standard corrugated or ribbed sheeting. Insulation varies from semirigid to rigid, depending on the design of the inner surfacing materials. It provides good thermal and moisture control when installed with tight inner surface construction.

All curtain wall panels with insulation in the cavity, or as a core, should be sufficiently tight at their edges to prevent the entrance of free water or moisture. However, because some moisture may enter the wall from the inside or outside, the wall should be capable of drying out. Panel edges should not be hermetically sealed. For cold climates, the subframing members or wall mullions should be of noncontinuous construction. The exterior to interior path should have a thermal break or insulated mullion cover on the interior or exterior to reduce the hazard of condensation.

MASONRY AND CONCRETE CONSTRUCTION

Because concrete masonry unit walls and masonry cavity walls have hollow vertical cavities, insulating materials can be placed within the wall itself. Loose-fill insulation, such as water-repellent perlite and vermiculite, as well as foam inserts and foamed-in-place insulations, are used. This insulation method is more effective with low-density masonry units. Rigid insulation can be placed between the wythes in a cavity wall or veneered construction, and furring on the inside of the wall is still used in many areas.

The thickness and density of concrete masonry wall construction coupled with its interior air cavities moderate the heat transmission. The thermal mass or inertia of such heavy construction causes a time lag in heat migration, which may lower the peak gains or losses. Insulation placed on the outside of a concrete masonry wall enhances this time lag effect and helps protect the structure from expansion and contraction caused by temperature extremes.

Precast or poured-in-place solid concrete walls are insulated similarly to solid masonry construction. The design and method of fabricating the panels dictates the type of insulation selected.

Insulating concrete forms are manufactured from foam plastic. Generally they are made in units that resemble concrete masonry units, although they are typically somewhat larger. The individual units, which have interlocking edges, are stacked to the desired height to create a form for the concrete for a wall. Where openings for doors and windows are desired, units are omitted. The top, bottom, and sides of the opening are formed and braced with framing lumber to retain the concrete in the same way that an opening would be formed in a conventionally formed concrete wall.

Steel reinforcing and anchor bolts, if required, are placed, the forms are plumbed and braced, and concrete is placed in the form. To this point, construction of the concrete wall proceeds in much the same way as it would for a conventionally formed concrete wall. However, the foam plastic forming material is left in place to serve as building insulation and to reduce sound transmission through the wall after the concrete has hardened.

Although the concrete contributes to the R-value of the wall, the primary insulation value is obtained from the foam plastic forms. The R-value for the walls depends on the thickness and type of foam plastic, but the typical R-value for an approximately 200 mm thick wall ranges from 3.5 to 5.3 m²·K/W. The method used to tie the foam plastic panels together to create the form also affects the R-value. Ties to connect the outside panels are usually made of plastic or metal, but some manufactured forms use continuous foam plastic across the width of the wall.

FOUNDATION AND FLOOR SYSTEMS

Perimeter foundation insulation may be applied on the outside or inside of foundation walls. Rigid mineral fiber or cellular plastic insulation is commonly used as perimeter exterior insulation. Exterior insulation may be applied below grade vertically or may extend as skirting down and outward from the building. These two profiles have comparable heat loss. Insulation applied on the exterior, especially skirting, should resist compressive forces from the soil and from the backfilling process. The thermal performance of vertically applied insulation may be degraded if it remains wet, so drainage at the base of the foundation may be required by manufacturers of some perimeter insulations. Some insulation products are designed to facilitate vertical drainage.

Perimeter insulation usually needs protection from physical damage and ultraviolet radiation if it extends above grade level. The exposed section of a foundation that extends from grade up to the top of the foundation can be a source of considerable heat loss. However, in buildings subject to termite infestation, the exposed foundation at grade should remain uncovered to facilitate inspection.

Exterior insulation that extends as skirting from a **shallow foundation** can prevent frost heave of the slab without a perimeter footing down to frost depth. The insulation thickness is selected so that even during the coldest weather, the soil beneath the insulation remains above freezing.

A **slab foundation** may be insulated by vertical and horizontal insulation, usually of rigid foam. Insulation at the perimeter of the building provides more resistance to heat loss than beneath the slab inside the building. Perimeter insulation usually includes vertical (installed either inside or outside the stem wall) and horizontal panels. The horizontal panels may extend from the foundation wall inward for a distance of 600 mm or more, or outward as skirting.

In **crawl space construction**, insulation may be applied either to the perimeter walls or to the floor framing. Rigid foam panels are often installed at the inside of the crawl space walls. The cavities at the band joist may be insulated with batts or custom fitted panels of rigid insulation. In vented crawl space construction, the floor framing may be insulated—commonly with batt or blanket insulation. The facing is stapled to the underside of the floor framing and the exposed batt faces down. Unless additional measures are taken to keep the insulation in place, such as wire strapping, rigid insulation panels, or a reinforced plastic membrane (like the “belly paper” used in manufactured housing), it may fall down.

Another floor insulation method uses double-sided, perforated aluminum foil draped and stapled over floor joists (BRANZ 1983). For a sag depth of about 100 mm, laboratory R-values had a mean of $1.2 \text{ m}^2 \cdot \text{K/W}$ and ranged from 1.0 to $2.5 \text{ m}^2 \cdot \text{K/W}$, depending on the humidity above the floor space. Field measurements have shown R-values up to $2.5 \text{ m}^2 \cdot \text{K/W}$ for carpeted floors over good installations with a sag of 100 mm.

Basement insulation may be applied at the interior as well as the exterior. Insulation should not be placed on the interior of a basement unless extra measures have been taken to ensure proper drainage. Insulating concrete forms (see above) are often used for basement wall construction. Control of pests around below-grade insulation, especially termites and insects, is a continuing concern.

Details on foundation insulation may be found in the *Building Foundation Design Handbook* (Labs et al. 1988).

LOW-SLOPE ROOF DECK CONSTRUCTION

Almost all low-slope structural roof deck construction requires thermal insulation to economically maintain the design indoor environment. For low-slope roofs, insulation should be placed on top of the deck, on the outside of the structure. This location moderates the deck temperature, which reduces thermal movement of the deck and the potential for underdeck condensation. Traditionally, the insulation is placed under the roof membrane so that it functions as a base

for the built-up roof (BUR) or single-ply membrane. For a stable base, a good bond must be established between the insulation and the roof deck, and between the insulation and the BUR. Ineffective bonds that allow the BUR to move in reaction to stresses from temperature changes often cause the roof to fail. Single-ply membrane roofs are frequently installed with ballasted, mechanically fastened or fully adhered systems.

Insulation can also be placed above the membrane in a protected or inverted roof system. With this approach, the roof membrane is installed on the deck, where it functions as a waterproofing membrane and vapor retarder. Insulation can be placed above and below membranes to function both as the base and protector for the membrane. Some insulation can be wetted and then successfully dried; however, while wet, it has a greatly reduced insulation value.

INSULATION FIELD PERFORMANCE CHARACTERISTICS

Convection and air infiltration in some insulation systems may increase the 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 caused by natural and forced convection (air infiltration). A temperature differential across the insulation, as well as the height, thickness, or width of the insulated space, influences the amount of convection. When a membrane with low air permeance is applied to one surface or when the cavity is filled with insulation, natural convection is reduced significantly and apparent thermal conductivities measured by standard test methods apply. The heat loss due to air convection may not be significant for many types of insulation products, such as batts and higher density loose-fill insulations. Convective heat loss potentials should be obtained from insulation manufacturers.

The effectiveness of thermal insulation is seriously impaired when it is installed incorrectly. For example, a 4% void area in wall insulation with an R-value of $1.9 \text{ m}^2 \cdot \text{K/W}$ increases heat loss by 15%. A 4% void area in ceiling insulation with an R-value of $3.3 \text{ m}^2 \cdot \text{K/W}$ causes a 50% increase in heat loss. Verschoor (1977) found that air interchange around thin wall insulation installed vertically with air spaces on both sides increases heat loss by 60%. Lecompte (1990) found significant losses (up to 300%) as a function of the size and distribution of openings around insulation materials. Other factors, including vibration, temperature cycling, and other mechanical forces, can affect thermal performance by causing settling or other dimensional changes. [Chapter 23](#) gives more information on the effect of moisture on thermal properties of building structures.

MOISTURE CONTROL IN BUILDINGS

Not all moisture problems can be avoided at all times. Proper design can help reduce the risk and make a building more tolerant to moisture. The recommendations in this chapter are intended to provide guidance.

Strategies to control moisture accumulation fall into two general categories: (1) minimizing moisture entry into the building envelope and (2) removing moisture from the building envelope. Once basic moisture transport mechanisms and specific moisture control practices are understood, roof, wall, and foundation constructions for various climates can be reviewed to determine whether each significant moisture transport mechanism is controlled. Because it is not possible to prevent moisture migration completely, construction should include drainage, ventilation, removal by capillary suction, or other provisions to carry away unwanted water.

CONTROL OF LIQUID WATER ENTRY

Moisture problems in buildings are frequently caused by liquid water entering through leaking roofs or the foundation, or through

the walls due to wind-driven rain or rain splashing. Poor flashing details are often a major cause of water entry into walls and roofs. Rainwater should be carried away from the foundation through gutters, downspouts, and positive grading. A rain screen can minimize penetration of walls due to raindrop momentum, capillarity, gravity, and air pressure difference. The rain screen wall is designed so that the air pressure difference across the exterior rain screen is nearly zero at all times. A rain screen wall contains three components: an airflow retarder system, a pressure-equalization chamber, and a rain screen. The airflow retarder must be able to resist pressures from wind, the stack effect, and mechanical ventilation. The pressure-equalization chamber separates the rain screen and the air flow retarder system. It may be an air cavity or may be filled with a self-draining material to prevent water that penetrates the rain screen from reaching the airflow retarder system. The chamber should consist of separate compartments to avoid lateral airflow, especially around corners of the building. Each chamber compartment is vented to the outside through the rain screen to provide pressure equalization and must be flashed to the outside to drain water that has penetrated the rain screen. The rain screen must contain sufficient vents to provide pressure equalization; that is, the airflow resistance of the rain screen must be much lower than that of the airflow retarder.

CONTROL OF WATER VAPOR MIGRATION

Water vapor entry into the building envelope can be limited by airflow retarders and water vapor retarders. As described in [Chapter 23](#), airflow retarders are intended to restrict airflow, and thereby water vapor flow, whereas water vapor retarders are designed to restrict vapor flow by diffusion.

Air Leakage Control

Past research demonstrated that air movement is more effective than water vapor diffusion for transporting water vapor within the building envelope. In order to minimize moisture penetration by air leakage, the building envelope should be as airtight as possible. The airflow retarder must also be sufficiently strong and well supported to resist wind loads.

In the past, air leakage in residential buildings provided sufficient ventilation, and the air leakage paths rarely led to interstitial condensation. However, in airtight buildings mechanical ventilation must be provided to ensure acceptable air quality and prevent moisture and health problems caused by excessive indoor humidity. Ventilation or drainage must go to the outside of the airtight layer of construction or it will increase air leakage of the building. To avoid condensation on the airtight layer, either the temperature of the layer must be kept above the dew point by locating it on the warm side of the insulation, or the permeance of the layer must be adequate to permit vapor transmission.

As described in the section on Leakage Distribution in Residential Buildings in [Chapter 26](#), air leakage through the building envelope is not confined to doors and windows. Although 6 to 22% of the air leakage occurs at windows and doors, 18 to 50% typically takes place through walls, and 3 to 30% through the ceiling. Leakage often occurs between the sill plate and the foundation, through interior walls, electrical outlets, plumbing penetrations, and cracks at the top and bottom of the exterior walls. More detailed information can be found in [Chapter 26](#).

Not all cracks and openings can be sealed in existing buildings, nor can absolutely tight construction be achieved in new buildings. However, an effort should be made to provide as tight an enclosure as possible to reduce leakage and minimize potential condensation within the envelope. Such measures also reduce energy loss.

Moisture accumulation in the building envelope can also be minimized by controlling the dominant direction of airflow. This can be accomplished by operating the building at a small negative or

positive air pressure, depending on climate. In cooling climates, the pressure should be positive to prevent the entry of humid outside air into the envelope. In heating climates, the building pressure should be neither strongly negative, which could risk drawing soil gas or combustion products to the indoors, nor strongly positive, which could risk driving moisture into building envelope cavities.

MOISTURE CONTROL OPTIONS

Options for moisture control under heating conditions often differ from those under cooling conditions, even though the physical principles of moisture movement are the same. Therefore, the selection of moisture control options depends on whether the local climate is predominantly a heating or cooling climate. The *Moisture Control Handbook* (Lstiburek and Carmody 1991) recommends a three-step procedure for designing energy-efficient roofs, walls, and foundations with inherent moisture control capabilities:

1. Identify the climate: heating, cooling, or mixed
2. Determine the potential moisture transport mechanisms in each part of the exterior envelope: liquid flow, capillary suction, air movement, and vapor diffusion
3. Select the moisture control strategies: control moisture entry, control liquid moisture accumulation (condensation), or remove moisture by draining, venting, or diffusion

The definitions of climate zones are somewhat arbitrary. Lstiburek and Carmody (1991) recommend that heating climates be defined as climates with 2200 heating kelvin-days (base 18.3°C) or more. Cooling climates are defined as warm, humid climates where one or both of the following conditions occur: (1) a 19.5°C or higher wet-bulb temperature for 3000 or more hours during the warmest six consecutive months of the year; (2) a 23°C or higher wet-bulb temperature for 1750 or more hours during the warmest six consecutive months of the year.

Mixed climates are all climates that do not fall under the definitions of heating or cooling. Regions with heating climates in North America generally include the northern half of the United States, Alaska, and all of Canada. The climate in southeastern coastal regions of the United States generally can be characterized as cooling. However, the local climate should be evaluated to determine whether to design for heating, cooling, or mixed-climate conditions.

MOISTURE CONTROL OPTIONS FOR HEATING CLIMATES

Surface Condensation

Heating climates are defined as climates with 2200 heating kelvin-days (base 18.3°C) or more. In such climates, occasional window condensation is common in buildings during winter and fall.

Lowering indoor humidity to minimize surface condensation on windows is one approach, but increasing the interior surface temperature of the window using multiple glazing, low-emittance glazing, low-conductivity spacers, appropriate selection of window frame, or gas-filled glazing may be more effective. Higher thermal resistance in windows has the added advantages of saving energy, improving occupant comfort, and reducing the possibility of condensate damage to the interior adjacent to the window (e.g., staining of the wall, rotting of the window sill, and mold growth).

Windows should remain clear most of the time. Some condensation may appear around the window perimeter, but should disappear with a warming trend. This criterion should be used to decide which glazing should be installed to maintain the desired humidity, or whether to reduce the humidity to avoid condensation during the coldest periods.

Local condensation and mildew growth on walls and ceilings is often the result of low inside surface temperatures due to insufficient or faulty insulation. Increasing the thermal insulation or eliminating

the voids in the insulation is the obvious remedy. If the problem is due to infiltration of cold air, an attempt should be made to eliminate the air leakage. However, in existing buildings these measures are often difficult or too expensive. In these cases, the only alternatives are lowering the indoor humidity, raising the indoor temperature, or increasing the air circulation near the surface.

Indoor Humidity Control

A common cause of moisture problems during the heating season is excessive indoor humidity. This is caused by an improper balance between moisture generation and moisture removal. This balance can be changed by reducing the sources of moisture or by increasing the removal rate, usually by ventilation or dehumidification. However, it is important to avoid lowering the relative humidity too far below the lower comfort limit, which is generally about 25 to 30% rh.

Because water vapor is introduced into the building from various sources, the moisture content of the air in an occupied building without dehumidification is always higher than that of the outdoor air. Christian (1994) provides a detailed discussion of various individual moisture sources, primarily in residences. The section on Internal Moisture Gains in [Chapter 20 of the ASHRAE Handbook—Systems and Equipment](#) states that a family of four produces an average of 320 g/h of moisture. TenWolde (1988, 1994) reports production rates between 135 and 330 g/h for one to two adults, with an average of 230 g/h. European sources report rates between 270 and 540 g/h for families without children, and rates between 210 and 950 g/h for families with one to three children (Christian 1994). These numbers demonstrate that moisture production rates in residences can vary widely. Moisture production rates for various kinds of livestock and plants can be found in [Chapter 10](#).

A residential crawl space or basement can contribute significant amounts of additional water vapor. Trethowen (1994) reported an average moisture release of 0.40 kg/m²·day from moist or wet crawl spaces. Moisture released from building materials that are drying (construction moisture) in a new building can add large amounts of water vapor. Exposed soil surfaces in crawl spaces or cellars should be covered with vapor retarder membranes (see the section on Crawl Spaces).

If indoor humidity is excessive, and source reduction is impossible, increasing the ventilation rate should be considered. Ventilation may be natural or mechanical, and mechanical ventilation may be exhaust, inlet, or balanced. An air-to-air heat recovery device can be included to reduce the heating energy penalty from an exhaust fan. Other approaches include the use of mechanical dehumidifiers and insulated vent stacks that extend from the living space through the roof.

Short-term ventilation procedures such as occasionally opening a window or door may lower humidity momentarily, but it will rise to its original level soon after the window or door has been closed. This is due to the evaporation of stored moisture into the indoor air. When water vapor is released from showers or cooking, much of it is adsorbed by hygroscopic materials (paper, wood, fabrics, etc.) in the building. Some temporary storage in the form of surface condensation may also occur. This moisture is released more slowly at a later time. Moisture storage effectively dampens the effect of short-term (hourly or daily) changes in moisture release or weather conditions on indoor humidity. Stored moisture also slows the effect of ventilation and dehumidification because this moisture needs to be released and removed before the indoor humidity can be lowered permanently. The evaporation of moisture stored during the summer's periods of high relative humidities is the cause of high relative humidity and window condensation in early fall.

In cold or cool winter climates, house ventilation can be an effective method for moisture removal. In these climates, a ventilation level of 0.35 air changes per hour (ACH) (as recommended in ASHRAE *Standard* 62) is generally sufficient to prevent excessive

indoor humidity and most window condensation (TenWolde 1994). Ventilation is primarily required to ensure acceptable indoor air quality. If the recommended minimum ventilation levels are achieved, additional ventilation is probably unnecessary and ineffective for humidity control. In mild, humid climates, ventilation rates greater than 0.35 ACH may be needed for humidity control, but in such climates other means of moisture removal, such as dehumidifiers, should be considered.

Some suggest that high indoor humidity is caused by vapor retarders that lock in moisture. However, only a small fraction of the total moisture generated can be removed by vapor diffusion through the building envelope. Most high indoor humidity is due to inadequate ventilation, inadequate dehumidification and air conditioning, or an unusually large moisture source in the building.

Vapor Retarders and Airflow Retarders

Vapor retarders are recommended and often mandated in heating climates, and should be placed on the interior (warm) side of the insulation. Airflow retarders are also necessary, but their placement in the wall or ceiling assembly is probably less critical and still subject to debate. Vapor retarder and airflow retarder functions may be combined in one material. Airflow retarder placement on the exterior prevents cold air from penetrating the insulation (wind washing) and therefore improves thermal performance of the building envelope. However, in heating climates, airflow retarders on the exterior should have a high water vapor permeance. Special airflow retarder materials for exterior use with sufficiently high water vapor permeance are commonly available. Exterior airflow retarders do not prevent penetration and circulation of warm indoor air inside the wall or ceiling/roof cavity. Conversely, interior airflow retarders do not prevent wind washing. Interior airflow retarders do not need to have a high water vapor permeance. For additional general guidance on the placement and properties of airflow retarders, see [Chapter 23](#).

The use of vapor retarders in compact low-slope roofing systems has been a long-standing issue for the roofing industry. Unlike other portions of the building envelope, water intrusion into a low-slope roof due to membrane failure is inevitable. Wet insulation performs below thermal performance levels specified during design. A survey by Kyle and Desjarlais (1994) has indicated that the average energy efficiency of the entire roofing inventory in the United States is reduced by approximately 40% due to moisture contamination.

Powell and Robinson (1971) studied these problems and stated that the “most practical and economical solution to the problem of moisture in insulated flat-roof constructions (is) to provide a design that would have in-service self-drying characteristics.” A self-drying roof uses the local meteorological conditions to create a vapor drive into the building interior. Desjarlais (1995) demonstrated that climates with up to 5000 heating kelvin-days create annually averaged downward vapor drives. In a self-drying roof, any leakage into the roofing system is passively driven into the building interior; if the leak is repaired, the roof system will dry.

A vapor retarder prevents including the self-drying characteristics in the roofing design by placing an impermeable layer between the roof insulation and the building interior. A vapor retarder should only be placed in a roofing system when the amount of wintertime water uptake that the roofing system experiences exceeds the moisture limit of the insulation material in the roof. Desjarlais (1995) offers guidelines on how to determine these limits.

Penetrations through the airflow retarder (such as electrical outlets, light fixtures, or plumbing stacks) should be minimized. Any penetration should be sealed carefully. Special airtight electrical boxes are available. Limited or minor penetrations of the vapor retarder are not of great concern, if an effective airflow retarder is placed elsewhere in the wall or ceiling.

Attics and Cathedral Ceilings

Attics and cathedral ceilings are protected from interior moisture in heating climates first by limiting the entry of moisture into roof cavities, and second by ventilating the cavities to minimize accumulation of moisture. Entry of interior moisture is limited by designing and constructing effective airflow and vapor retarders between the interior space and roof cavities.

Attics. Ventilation is required in all United States and Canadian Model Building Codes. Studies on roof cavity and attic ventilation aimed at reducing paint peeling were conducted by Rowley et al. (1939), Britton (1948), and Jordan et al. (1948). These studies concluded with recommendations for venting of attics. Britton found that air movement from a wet foundation through chases and wall space could reach the attic and cause moisture damage to roof sheathing. Jordan et al. and later reports demonstrated the use of air barriers as the primary requirement for keeping moisture out of attics. Colder attics were found to require more ventilation to prevent frost. A review of the studies (Rose 1992) concluded that support for attic ventilation was at times contradictory and the specific requirement for 1 m² of vent area for 300 m² of floor space not resolved by the findings.

The four commonly cited reasons for attic ventilation are (1) preventing moisture damage, (2) enhancing the service life of temperature-sensitive roofing materials, (3) preventing ice dams, and (4) reducing the cooling load (TenWolde and Rose 1999). In some cases, venting may be inconsistent with the moisture control design approach. If the attic is vented, care should be taken to prevent entry of snow and to prevent airflow that might degrade the thermal performance of insulating materials (Hens and Janssens 1999).

Moisture. Vents have been shown to provide effective lowering of moisture levels in roof sheathing for attics constructed with a single unconditioned space, sloped roof, and a tight ceiling plane (Jordan 1948). It is relatively easy and inexpensive to install vents in such an attic without compromising the effectiveness of the ceiling insulation. In heating climates, attic ventilation usually provides a measure of protection from excessive moisture accumulation in the roof sheathing. If indoor humidity is high and humid indoor air leaks into the attic, attic vents by themselves may not prevent moisture accumulation.

Moisture control in attics in heating climates depends primarily on (1) maintaining lower indoor humidity levels during cold weather, (2) assuring maintainable airtightness and vapor resistance in the ceiling, and (3) attic ventilation (NRC 1963).

Temperature. A ventilated attic is cooler in the summer than an unventilated attic, and ventilation can reduce the temperature of shingles during daylight hours. Asphalt shingle manufacturers encourage ventilation as a prescriptive practice (ARMA 1997). In one study, the temperature difference due to power or turbine ventilation over soffit ventilation led to significant differences in maximum attic air temperatures, but was not shown to be an effective energy conservation method in moderately or heavily insulated ceilings (Burch and Treado 1978). It is not clear that attic air temperature reduction is a significant factor in extending the service life of shingles (TenWolde and Rose 1999), since the long term studies on the temperature effects on shingle service life are incomplete.

Ice Dams. Ventilation of roofs, coupled with additional insulation and reductions in air exfiltration, reduces ice dam damage during winter in cold regions (Buska et al. 1998). Where heat sources are located in the unconditioned attic space, large amounts of ventilation may be needed to prevent ice dams, necessitating mechanical attic ventilation (Tobiasson et al. 1994). Such heat sources may include furnaces, air handlers, or ductwork with conductive or convective heat losses.

Reducing heat loss into the attic by effective insulation, air leakage control, and avoidance of heat sources such as uninsulated or leaky heating ducts in the attic, possibly coupled with ventilation, is

a positive way of reducing ice dams and moisture damage (Fugler 1999). Damage due to ice damming in roof valleys and eaves can also be prevented by installing a waterproof underlayment of sufficient width beneath the shingles.

Other Considerations. Roofs with absorbent claddings, such as wood shingles or cement or clay tiles are subject to solar-driven moisture penetration (Cunningham et al. 1990). Moisture is driven into the roof when it is wetted by rain or dew and subsequently exposed to sunshine. When the moisture source is from the exterior, an impermeable membrane under the shingles or tiles can greatly reduce moisture transfer into the roof; but measures should be taken to prevent water accumulation on the underside of this membrane.

Leaks cause another moisture load on roofs. Roof leaks are properly addressed by repair rather than by ventilation.

Cathedral Ceilings. Cathedral ceiling construction is inherently prone to a wider range of conditions than attic construction because this type of construction has isolated air cavities in each rafter bay. Vented attics perform better than vented cathedral ceilings for the same framing type (Goldberg 1999). Although providing effective ventilation to attics with simple geometries is relatively easy and inexpensive, providing soffit and ridge ventilation to each individual cavity in a cathedral ceiling may be difficult or impractical. Improperly installed insulation can obstruct the area designed or intended to provide ventilation. (Tobiasson 1994). An airtight ceiling plane, a vapor retarder, and foam air chutes between the sheathing and the top of the insulation effectively control moisture in cathedral ceilings with fiberglass insulation (Rose 1995). Hens and Janssens (1999) pointed out that moisture control is assured only if airtightness is effective and can be maintained. They showed that the consequences of air entry and wind washing in insulated cathedral ceilings are detrimental, leading to degraded thermal performance, moisture response and overall durability. TenWolde and Carll (1992) showed that ventilation of roof cavities may cause increased air leakage, and that the net moisture effect depends on whether the principal source of makeup air is from indoors or outdoors.

Goldberg et al. (1999) noted that unvented attics and cathedral ceilings show a better retention of thermal resistance of the fibrous insulation than similar vented assemblies, though this benefit is smaller for attics than for cathedral ceilings. With careful attention to design for air- and vapor-tightness, unvented cathedral ceilings can be expected to perform satisfactorily in cold heating climates.

Operating Practices

Details of indoor humidity control are discussed in the section on Indoor Humidity Control. Buildings in heating climates should not be operated at substantial positive indoor air pressures, which drive moist air into the building envelope and increase the potential for moisture accumulation. Large negative pressures should also be avoided if any unsealed combustion equipment is operated in the building. Negative pressure in the basement or in slab-on-grade buildings should also be avoided when there is potential radon leakage from the soil into the building, unless a subslab depressurization system has been installed.

Other Considerations

In heating climates, it is important to design for excessive indoor humidity. If the anticipated indoor humidity will be high, then extra care must be taken in design and construction by using air barriers in conjunction with building pressure regulation.

In general, mechanical equipment should be kept within the conditioned space of the building. This approach reduces the number of openings through the building envelope and reduces the energy losses associated with exterior equipment and ductwork. Several design options permit installation of insulation below the roof plane, as in cathedralized construction (Rose 1995).

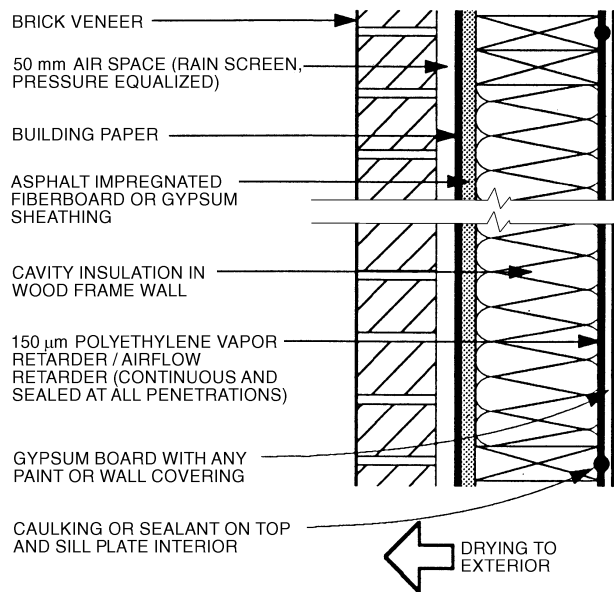


Fig. 1 Example of Residential Wall Construction for Heating Climates

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Example of Residential Wall Construction for Heating Climates

Figure 1 shows the cross section of a residential wall for heating climates. Moisture control is handled in the following ways:

- **Rain.** The brick veneer, an air space, and the building paper form an effective rain screen. The air space behind the brick veneer provides a capillary break for any rainwater absorbed by the brick and mortar. Mortar should not breach the air space and touch the building paper, as this would allow rainwater to bypass the capillary break. The building paper protects the fiberboard or gypsum from any water penetrating the rain screen.
- **Air movement.** The sheathing and building paper serve as an airflow retarder. Sufficient airtightness can be obtained by airtight installation of the sheathing (i.e., installed vertically with joints over the studs, with sealant or caulk used at the joints).
- **Vapor diffusion.** Vapor diffusion from the inside is inhibited by the polyethylene vapor retarder.

MOISTURE CONTROL OPTIONS FOR MIXED CLIMATES

Mixed or temperate climates fall neither under the definition of a heating climate, nor under the definition of a hot, humid climate. Mixed climates may be heating- or cooling-dominated. This zone includes areas with hot and dry climates (e.g., Arizona). Buildings in mixed climates may encounter high interior levels of humidity during winter and high exterior levels of humidity during summer.

Summer cooling or winter heating for comfort in mixed climates does not usually create serious vapor problems in exterior walls and ceilings. The summer outdoor dew point, especially during peak values, may exceed the design dew-point temperature in common use, but it seldom exceeds 24°C for a prolonged period. Condensation within exterior walls exposed to an indoor temperature of 24°C is seldom as serious as winter condensation.

In a study of a wood-sided house in Athens, Georgia, Duff (1956) showed that under summer cooling conditions, temperatures were lower outside than inside long enough to prevent moisture buildup from damaging the structure. This was true regardless of whether or

not a low-permeance material was placed near the inner surface. However, masonry or brick-veneered structures with a low-permeance vapor retarder (e.g., vinyl wallpaper or polyethylene) near inner surfaces do have a moisture buildup under summer cooling conditions.

Vapor Retarders and Airflow Retarders

Airtight construction is recommended in all climates. Airflow retarders provide protection from excessive moisture accumulation in the building envelope during cooling and heating, and may reduce energy consumption. In mixed climates, the need for low-permeance vapor retarders in most types of buildings is less pronounced than in heating climates or in warm, humid climates.

However, if a vapor retarder is deemed necessary in a mixed climate zone, its placement presents somewhat of a dilemma. Under cooling conditions, a vapor retarder would normally be located on the outside of the insulation. But under winter conditions, it would be located on the inner side. Use of vapor retarders at both locations is undesirable because it restricts moisture movement into the insulation as well as the escape of any moisture. In dwelling construction, the vapor retarder should be placed to protect against the more serious condensation (winter or summer). However, if indoor humidity is kept below 35% (at 21°C) during winter, a vapor retarder on the inside of the insulation is probably not necessary in mixed climates.

The choice and placement of a vapor retarder, airflow retarder, and other materials minimize the potential for condensation while allowing for some drying. For example, if a vapor retarder is installed on the interior, an exterior airflow retarder and/or sheathing should have sufficient permeance to allow drying. The corresponding situation in cold storage buildings, in which a more serious reversal of vapor flow conditions from winter to summer may occur, requires individual analysis.

Attics and Cathedral Ceilings

Venting of attics and cathedral ceilings during winter in a mixed climate has similar benefits and drawbacks as in a heating climate. Venting may provide benefits for moisture control in attics where effective vents can be installed relatively easily and cheaply, and where the ceiling is tightened against air leakage. Unvented cathedral ceilings can provide satisfactory moisture performance in mixed climates when the system (1) is designed to control moisture migration, and (2) contains an airflow retarder that is maintained. More detailed discussion of ventilation of attics and cathedral ceilings can be found in the sections on Attics and Cathedral Ceilings under Moisture Control Options for Heating Climates.

Both vented and unvented construction should be designed and constructed to exclude interior moisture from cathedral ceiling cavities. As in heating climates, vents in cathedral ceilings may be less effective and beneficial than vents in attics; therefore, vents should be considered a design option.

Ductwork should be kept in the conditioned space of the building in order to improve energy efficiency. In hot, dry climates, energy losses through ductwork located in unconditioned attics is greater than energy losses in attics using cathedral construction, in which the insulated envelope is located at the roof (Rudd 1998).

Example of Residential Wall Construction for Mixed Climates

Figure 2 shows an example of a residential wall detail for mixed climates, with rigid insulating sheathing serving as a vapor retarder and air retarder. Moisture control is handled in the following ways:

- **Rain.** The combination of siding and airtight foam sheathing serves as a screen system and controls rain penetration. The air cavities behind the siding should be sufficient to act as a capillary break. If the air space is insufficient, the siding may be installed

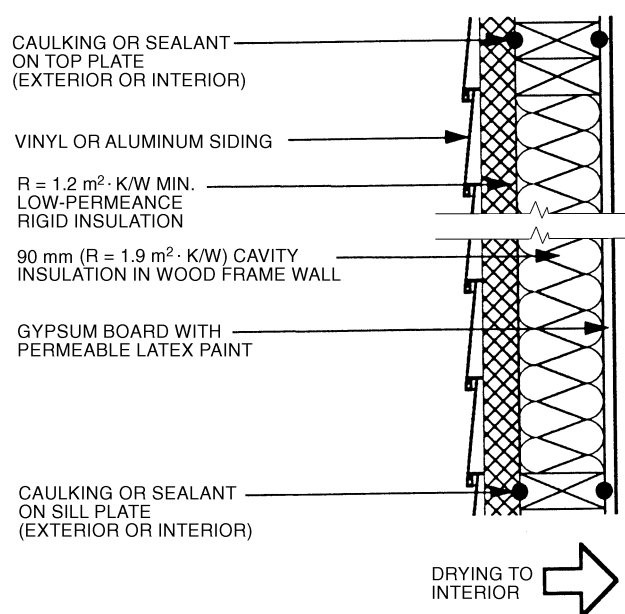


Fig. 2 Example of Residential Wall Construction for Mixed Climates

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on furring strips to provide the air space. With vinyl or aluminum siding, liquid absorption and capillary moisture transfer are not a concern.

- **Air movement.** The rigid insulating sheathing can be caulked at the top and bottom plates and at the joints to provide an exterior air flow retarder. Alternatively, caulking of the gypsum board can provide an interior airflow retarder.
- **Vapor diffusion.** The impermeable rigid insulation acts as a vapor retarder. During cooling periods, vapor diffusion from the outside is impeded at the exterior sheathing surface. During heating periods, vapor diffusion from the inside is inhibited at the interior surface of the foam sheathing. To keep moisture condensation to a minimum, this first condensing surface temperature should be elevated through the use of foam sheathing with a high R-value. For mixed climates, the thermal resistance of the insulating sheathing in this example should be $1.2 \text{ m}^2 \cdot \text{K/W}$ or greater, with $R = 2 \text{ m}^2 \cdot \text{K/W}$ in the cavity.

MOISTURE CONTROL OPTIONS FOR WARM, HUMID CLIMATES

Warm, humid cooling climates are defined as climates where one or both of the following conditions occur: (1) a 19.5°C or higher wet-bulb temperature for 3000 or more hours during the warmest six consecutive months of the year; (2) a 23°C or higher wet-bulb temperature for 1500 or more hours during the warmest six consecutive months of the year. Depending on local experience with moisture problems, humid climate design criteria may also be desirable in locations that do not quite meet the foregoing conditions.

In warm, humid climates dehumidification by air conditioning or other means is the most practical approach to moisture removal from the conditioned space. The overall latent-cooling load is composed of diffusion, ventilation, infiltration, and internally generated latent cooling loads. Because the latent-cooling load on an air conditioner in high-humidity climates frequently exceeds the sensible load, a system should be capable of handling the latent load without overcooling. In residential buildings, oversized air conditioners may not alleviate the problem of high humidity due to short cycling.

Approaches to solving this problem include proper sizing of the system, the use of reheat, or design for variable flow rates.

Airflow Retarders and Water Vapor Retarders

Construction should be airtight, as in all other climates. Many moisture and condensation problems in cooling climates have been found to be caused by excessive leakage of outside air into the building envelope. Airflow retarders in cooling climates are best placed on the exterior. Negative pressures of the indoor space should be avoided. Under high-humidity conditions, ambient water vapor diffuses through building materials from the outside into air-conditioned spaces. Exterior surfaces should have lower permeance than interior surfaces in high-humidity climates. Paints and finishes can provide the necessary permeance, with lower permeance at the outside surface and higher permeance toward the inside.

Low-permeance paints, vinyl wall paper, or any other similar low-permeance material should not be used on the inside of walls and ceilings in warm, humid cooling climates.

Vapor retarders, if used, should be on the outside of the insulation. Then, any water vapor that enters the construction can flow to the inside of the building, where it can be removed by the air conditioner instead of accumulating in the wall or roof. Note that this recommendation is the reverse of the recommended practice for cold climates.

Attics and Cathedral Ceilings

The commonly stated rules for attic and cathedral ceiling construction—ventilation and vapor retarder toward the inside—pertain to cold climates and not to warm, humid climates with indoor air conditioning. Common sense suggests that venting with relatively humid outdoor air means higher levels of moisture in the attic or cathedral ceiling. Higher moisture levels in vented attics in hot, humid climates do not lead to moisture damage in sheathing or framing. However, higher moisture levels in attic cavities may affect chilled surfaces of the ceiling and cold surfaces of mechanical equipment. When cooling ducts are located in the attic space, attic ventilation with humid outdoor air may increase the chance of condensation on the ducts.

As in all climates, airtight construction is desirable. In warm, humid climates, airtight construction usually reduces the latent load. Insulation and interior finishes should be selected and installed with an understanding that vapor diffusion is primarily inward.

As with other climates, a ventilated attic in a warm, humid climate is noticeably cooler in the summer than an unventilated attic. Beal and Chandra (1995) found that venting can greatly affect the temperature difference across the ceiling.

Other Considerations

To encourage drying, shaded exterior surfaces that do not benefit from the evaporative effects of sun and wind (such as inside corners) should be avoided or minimized. Building components that are prone to thermal bridging (such as exterior cantilevers, columns, foundations, or window and door frames) are of special concern. Although these solutions may not totally eliminate mold and mildew growth, they substantially reduce the potential.

Serious wetting within walls can occur in summer under certain conditions. The National Research Council of Canada tested the walls of huts of brick masonry finished inside with furring, insulation, a vapor retarder, and plasterboard. The walls were opened during a sunny period following rain. Extensive wetting was observed in the insulation, particularly on the back of the vapor retarder. The absorptive brick wall had accumulated substantial quantities of water during the rainfall. Subsequent heating by the sun had driven the moisture as vapor into the wall, where it condensed and caused

serious wetting. The construction had no protection in the form of parging or paper on the inside of the brick.

The study showed that walls with exterior coverings capable of absorbing and storing considerable quantities of water during a rain, and providing little resistance to vapor flow into the insulation from outdoors, may experience serious interior wetting by condensation. No wetting occurred in a similar construction when a saturated sheathing paper was placed between the insulation and the brick. Thus, a moderate vapor flow resistance, such as that provided by parging or a good sheathing paper on the outside of the insulation, can effectively stop vapor flow in such cases.

Operation and Maintenance

Because the potential for damage to a building and its contents is substantial in an air-conditioned building in humid climates, it is more important to properly operate and maintain the building and its air conditioning system in humid climates than it is in others. The chilled water supply temperature and flow should be reliable, and multiple chillers and pumps should be considered to ensure continuous uninterrupted dehumidification.

Raising the chilled water supply temperature to conserve energy should not be attempted under these conditions, as this would impair the dehumidification capacity of the air-conditioning system.

Lowering the cooling thermostat setting generally increases the chance for mold and condensation in exterior walls, especially in locations where the cooled air is blown directly towards the wall.

Example of Residential Wall Construction for Warm, Humid Climates

Figure 3 shows an example of a residential wall detail for warm, humid climates, with rigid insulation serving as a vapor retarder and airflow retarder. Moisture control is handled in the following ways:

- **Rain.** The combination of airtight foam sheathing and siding serves as a rain screen system and controls rain penetration. The air cavities behind the siding should be sufficient to act as a capillary break. If the air space is insufficient, the siding may be installed on furring strips to provide the air space. With vinyl or aluminum siding, liquid absorption and capillary moisture transfer are not a concern. Wood siding may be backprimed to prevent moisture absorption through the back, and installation of wedges and clips on wood lapped siding should be considered to minimize capillary transport between the boards.
- **Air movement.** The exterior sheathing is the best location for an air seal, using either an adhesive or caulk to fasten the sheathing to the framing members.
- **Vapor diffusion.** In warm, humid climates, the dominant source of moisture is the outside air, and moisture is typically driven toward the interior. This means that the best location for the vapor retarder is at or near the exterior wall surface. Vapor-permeable paint should be used on the interior gypsum wallboard.

MEMBRANE ROOF SYSTEMS

Because most membrane roof systems in commercial and institutional construction are highly resistant to vapor leakage, condensation must be prevented when insulation is placed between the heated interior and the roof membrane. Wet insulation in low-slope roof construction is difficult to dry. Drainage is likely to be so slow as to be ineffective. Ventilation to the outside is not effective for drying roof insulation, because forces acting to remove the moisture are small. The vents themselves may present a hazard to the insulation by admitting moisture and drifting snow. Also, water leaks can occur where the vents penetrate the roof unless they are properly installed. Finally, vents may allow chimney action to carry air upward through openings in the deck and ceiling. Then as air flows

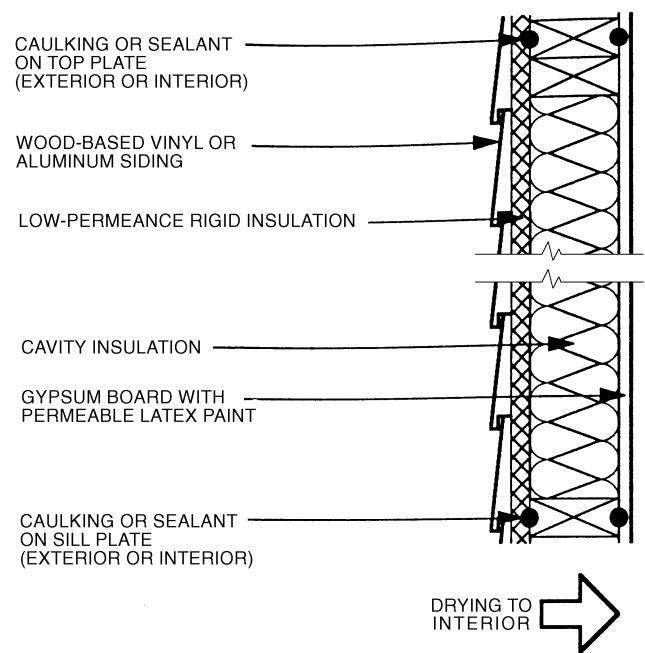


Fig. 3 Example of Residential Wall Construction for Warm, Humid Climates

Source: Lstiburek and Carmody (1991). Reprinted with permission.

to the outside, further moisture is drawn into the roof with the replacement air and may condense.

A vapor retarder in a conventional flat roof can trap moisture in the roof cavity. The decision whether to use a vapor retarder depends on interior humidity and climate. The absence of a vapor retarder allows vapor to enter a roof during the heating season, but it also facilitates the removal of moisture in warm weather. This may not be acceptable in buildings with high indoor humidity or in extremely cold climates, when a large accumulation of frost or liquid condensation results in dripping. Where humidities are lower, or the climate less severe, the roof system may successfully store moisture through the heating season without problems (Baker 1980). The success of this strategy, however, also depends on the airtightness of the roof assembly. More information on this can be found in the section on Self-Drying, Low-Slope Roof Systems.

Regular inspection of the membrane and flashings helps prevent water leakage into the roof. Infrared scanners or capacitance meters can help detect wet insulation, which can be removed or possibly dried out.

Inverted Roof Systems

The top layers in protected membrane or inverted roof systems are not waterproof; therefore, insulation is exposed to rainwater. To remain effective, it must be able to resist moisture penetration. Extruded polystyrene board has been used extensively. Insulation moisture content commonly ranges up to 4 or 5% by volume.

Some insulations are damaged by freezing and thawing, which fracture cell walls and allow water into an otherwise low-permeance material. When free moisture is available, the rate of entry increases rapidly as the temperature gradient increases (Hedlin 1977). Even when insulation is immersed in ponded water, moisture absorption through the edges is less than through the upper and lower surfaces, because the temperature gradient is normal to the roof surface.

Protective measures can reduce moisture gains. Roof slope performs much the same function for protected membrane roofs as it does for conventional ones. Covering the bottom surface of the insulation with a low-permeance layer inhibits moisture entry

there. The upper surface should be open to the atmosphere so that water can evaporate freely. If it is trapped against the upper surface (e.g., by paving stones), solar heating may drive the water into the insulation.

Where a high thermal resistance is required, roofs may combine conventional and protected membrane systems when they are applied in two separate lifts. The protected membrane system may be applied to existing conventional roofs to increase the thermal resistance, if the roof structure can support the added weight. This addition keeps the roof membrane warmer, so that the chance of moisture condensation on the underside of the roof membrane is significantly reduced.

Self-Drying, Low-Slope Roof Systems

A major cause of roof replacement is excessive accumulation of water in the roofing system. Historically, this accumulation has been minimized by delaying its ingress into the roofing system through the use of improved roofing membranes and periodic planned maintenance. Of course, most roofing systems eventually leak. Without periodic inspection, small leaks in a roofing system containing a vapor retarder or some other low-permeance layer (such as an asphalt mopping) can go undetected for long periods and lead to a major roof system failure. The self-drying roof facilitates the controlled out flow of water vapor into the building interior, preventing any long-term accumulation of water in the roof. Although they have not been optimized, the roofing industry has constructed self-drying roofs for many years. A roof installed without a vapor retarder or a low-permeance layer is effectively a self-drying roof.

A self-drying roof should be considered whenever the average yearly vapor drive is into the building interior. Tobiasson and Harrington (1985) have produced vapor drive maps for the continental United States. Desjarlais (1995) reported that this condition (vapor drive to the interior) is satisfied for climatic regions having less than 5000 heating kelvin-days (18.3°C base).

The self-drying roof system must be carefully designed and include special features. The deck system must be reasonably permeable to water vapor so that downward drying can be maximized. The water vapor permeance of the insulation materials must be selected so that the anticipated wintertime wetting is maintained at a level that the insulation materials can tolerate. Water vapor absorptive layer(s) should be included in the roof system so that a major leak into the roof can be controlled without leakage into the building interior. The self-drying roof must not contain a vapor retarder or any layers that are relatively impermeable. A suggested roof design procedure for self-drying roofs has been proposed by Kyle and Desjarlais (1994). The drying rate at the bottom depends on the airflow and the drying potential beneath the roof.

MOISTURE CONTROL IN FOUNDATIONS

Grading

Many of the problems related to moisture in foundations are due to the failure to discharge rainwater away from the building foundation.

Good construction practice generally requires exposed foundation between soil grade and the top of the foundation, as an inspection site for pest control. Traditionally the height of exposed foundation has been 200 mm, although recent codes have reduced this requirement to 150 mm. Because of the likelihood of heat loss through this exposed foundation, covering with an insulating material is desirable wherever pest inspections are not necessary.

The soil should slope away from the building at a 5% grade for the first 3 m around the building perimeter. That is, the fall from grade to a point 3 m away from the building should be a minimum of 150 mm. The soil should be covered with a cap of relatively impermeable soil, in order to maximize surface flow of water away

from the foundation. The soil backfill around the foundation is likely to settle in the first years after construction, requiring correction to achieve the proper grade. If the general slope of the soil on the site is toward the building, then swales or drains should be used to divert surface flow around the building.

Rainwater discharge from the downspouts should be managed to ensure that it does not contribute to saturation of any soil that is in contact with the foundation. The discharge may consist of extenders, splash blocks, or designed drainage systems to carry the roof runoff away from the building. On sloped lots, downspouts should discharge on the downhill side where possible.

Footing drains are traditionally installed to ensure against a rising water table; nevertheless, they may assist in draining water that may accumulate directly from surface rains. The footing drains should discharge water to an appropriate discharge site such as a storm sewer, a sump pump, or, if the site permits, daylight. Any footings for basements or crawl spaces, where the interior grade is below the exterior, should be provided with footing drains.

Gutters, downspouts, and below-grade drainage systems require maintenance. Below-grade drainage systems should be designed with cleanouts.

Floor Slab

Summer surface condensation may form on concrete floors on grade, especially during the first few years after construction. Carpeting tends to lower the interior slab surface temperature, increasing the condensation potential. Dehumidification and ventilation may be sufficient to avoid odors or floor cover bonding problems caused by moisture, which are generally more objectionable than actual damage to the floor covering.

Entry of ground moisture can be further reduced by isolating the slab with the placement of a low-permeability membrane over the soil beneath the slab and by using coarse gravel to break the capillary moisture rise. Application of a membrane is difficult, however, because it can be easily damaged during construction.

Sealing of floor slabs and basements against the entry of radon should also be considered. Although soil cover sheets are commonly referred to as vapor retarders, they can also act as a water-proofing membrane when exposed to liquid water.

Control of the slab surface temperature is important in order to minimize the need for mechanical dehumidification, particularly with solar-oriented designs that emphasize the effects of thermal mass. In localities with severe summer surface condensation problems, low-density concrete should be considered for floor slabs to increase their insulating value, or insulation should be added under the slab.

Crawl Spaces

Moisture problems generally occur when improper drainage or grading around the house leads to wet soil or even standing water in the crawl space. Evaporation of moisture then causes high humidity in the crawl space and often in the rest of the building. Sometimes the wet soil leads to high moisture content in wood framing members in the floor and in the band joist (header joist). Any source of subfloor warmth (heating ducts, furnaces) is likely to seriously increase the evaporation from wet subfloor soil (Trethowen and Middlemass 1988, Trethowen 1988). Providing proper drainage of water away from the foundation is critical for moisture control (ASHRAE 1994).

Dewatering techniques, including sump pumps, drain tiles, etc., should be used to keep the soil in the crawl space as dry as possible. Ground covers that restrict evaporation of water from the soil into the crawl space provide an effective way to prevent moisture and humidity problems. It is important to seal any ducts in the crawl space, to avoid venting clothes dryers into the crawl space, and to repair any leaking water pipes. A minimum clearance of 450 mm.

between the crawl space soil and the underside of any wood framing members is recommended and often required. Good access into and around the crawl space is very important.

Whether or not to ventilate a crawl space has been a controversial issue. Most building codes require installation of vents to provide ventilation with outside air, but a symposium on crawl space design concluded that there is no compelling technical basis for crawl space ventilation requirements (ASHRAE 1994). A distinction must be made between conditioned and unconditioned crawl spaces. Conditioned crawl spaces have insulated perimeter walls and may contain plumbing and heating runs. Conditioned crawl spaces should not be ventilated with outdoor air. If air circulation is desired, indoor air should be used. One way to accomplish this is by exhausting indoor air through the insulated crawl space, which may be done in conjunction with an air-to-air heat exchanger for energy efficiency (Samuelson 1994). Unconditioned crawl spaces have an insulated floor above the crawl space. Ventilation with outside air is permitted but not always necessary. Unvented crawl spaces must have a ground cover, which should cover 100% of the crawl space soil. Ground cover treatments for conditioned and unconditioned crawl spaces are similar.

The ground cover material should have a permeance of no more than $57 \text{ ng}/(\text{s}\cdot\text{m}^2\cdot\text{Pa})$ and must be rugged enough to withstand foot and knee traffic. The most commonly used material is 0.15 mm polyethylene. The membrane ground cover may be covered with a thin slab of concrete to prevent entry of rodents. Before laying the membrane, all debris must be removed and the soil leveled. Edges need only be lapped 100 to 150 mm, and no sealing is required. The membrane need not be carried up the face of the wall.

If control of entry of radon or other soil gases is desired, a minimum 0.15 mm polyethylene ground cover is recommended. Some have recommended that the ground cover should be weighted down and sealed at the perimeter and overlapped to retard radon entry, but others argue that weighting and sealing may lead to water ponding on top of the ground cover. If radon control is not of primary importance, the ground cover may be cut in several low spots to provide drainage should ponding occur. The primary function of the ground cover (i.e., moisture control or radon control) should govern the decision.

Example of Residential Foundation Construction Details

Figure 4 shows a cross section detail of a typical residential basement for mixed climates. Moisture control has been handled in the following ways:

- **Rain and groundwater.** Rain is carried away by gutters, downspouts, grading away from the building, and a cap of low-permeance backfill material. Subgrade drainage prevents water from reaching the foundation wall by use of a drain screen (gravel and footer drain connected to daylight, sump, or storm sewer).
- **Liquid moisture transport.** A dampproof coating is installed on the exterior of the foundation wall and over the top of the footing to control water entry. Capillary moisture movement into the slab is inhibited by a gravel pad 100 mm thick.
- **Air movement.** All air leakage openings (i.e., floor slab/wall intersection, rim joist area) are caulked and sealed.
- **Vapor diffusion.** Dampproofing on the wall and polyethylene under the slab inhibit vapor diffusion into the slab and foundation walls. During heating periods, vapor may diffuse from the interior into the rim joist framing, where it may accumulate. To reduce moisture accumulation, the temperature of the rim joist is raised through the installation of exterior insulation.

Figure 5 shows an example of a moisture-controlling residential slab-on-grade foundation detail for warm, humid climates, with insulation laid horizontally beneath the perimeter of the floor. Rigid insulation is also placed in the vertical joint between the wall and the slab. Because the rigid insulation can act as a conduit for insects

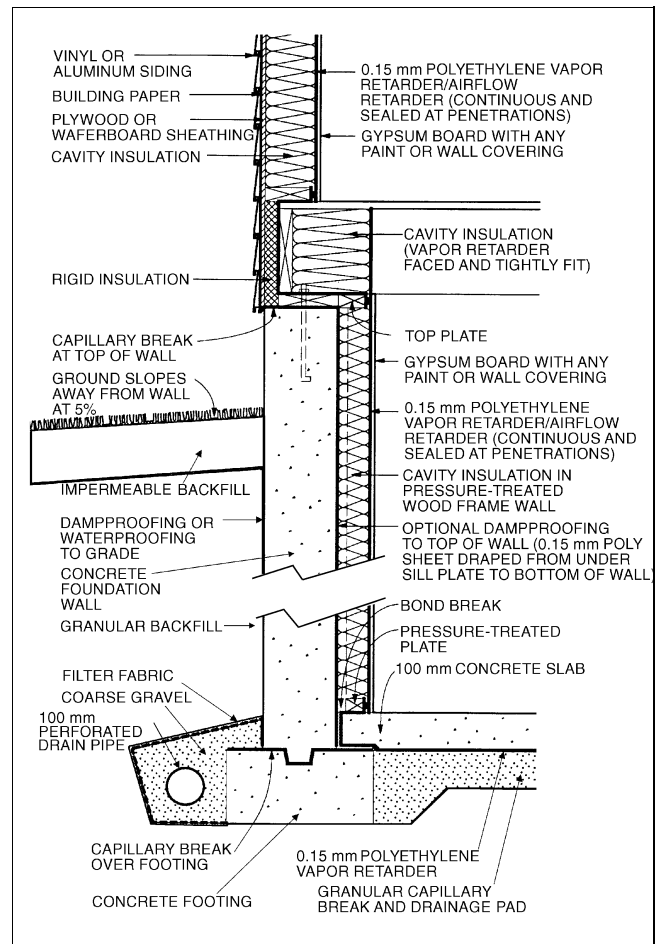


Fig. 4 Example of Residential Basement Construction for Mixed Climates

Source: Lstiburek and Carmody (1991). Reprinted with permission.

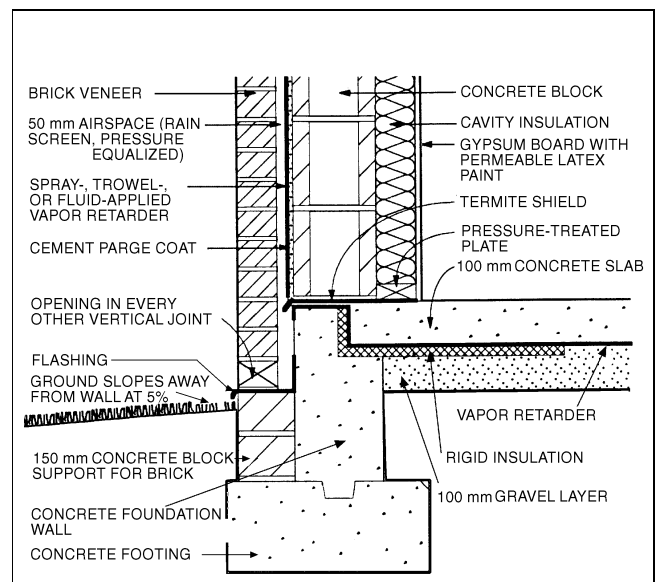


Fig. 5 Example of Residential Slab-on-Grade Construction in Warm, Humid Climates

Source: Lstiburek and Carmody (1991). Reprinted with permission.

into the building, additional protection such as metal flashings or other treatments may be necessary.

- **Rain and groundwater.** The bottom of the gravel layer is the grade level adjacent to the perimeter. The ground should be graded to direct water away from the building.
- **Liquid moisture transport.** The granular layer under the slab provides a capillary break between the soil and the slab. This pad can also be integrated into a subslab ventilation system to provide radon mitigation, if needed. Extension of the vapor diffusion

retarder over the top of the foundation wall and appropriate flashing for the brick facing serve as a capillary break protecting the above-grade wall from ground moisture.

- **Air movement and vapor diffusion.** The vapor retarder placed under the slab restricts both moist soil gas entry and vapor diffusion through the slab. Ductwork located in slabs increases the risk of ground source moisture entering the conditioned space if groundwater and soil gas are permitted to seep into the ducts.

ENVELOPE COMPONENT INTERSECTIONS

A moisture control strategy must consider not only envelope components, but also how these components come together. Component intersections are especially prone to air leakage and thermal bridging and therefore require special care.

Exterior Wall Corners. Mold and mildew often grow in exterior corners during heating periods due to cold surfaces caused by (1) thermal bridges, where structural members penetrate the insulation and provide a low-resistance heat flow path; (2) wind washing; (3) increased heat loss due to the fin effect; and (4) poor circulation of indoor air. [Figure 6](#) shows heat loss effects at building corners. Insulating sheathings and two-stud corners help prevent cold interior surfaces and corner moisture problems.

Wall/Window Intersections. Restricting air-transported moisture at all potential openings makes a major contribution to the overall building tightness. The airflow retarder must be continuous. [Figure 7](#) shows several details that help form a continuous airflow retarder at a window jamb.

Wall/Roof Intersections. Exterior wall/ceiling intersections are other common cool spots during the heating season caused by reduced attic insulation at the eaves and wind washing. High-heel trusses that allow installation of more insulation, wind baffles, and rigid insulation exterior sheathing all help control moisture at these locations. [Figure 8](#) shows the heat loss mechanisms at attic/wall intersections and how to minimize the risk of moisture problems.

Wall/Floor Intersections. Air leakage at rim joist assemblies is avoided by making sure the airflow retarder is continuous. Caulking and sealing are necessary at all polyethylene seams, as shown in [Figure 4](#). Floor structural members penetrating the insulation can cause thermal bridging, but the use of insulating sheathing helps minimize this (see [Figure 4](#)).

Wall/Foundation Intersections. Concrete footings are frequently poured directly in contact with the ground, which occasionally becomes damp or wet. Concrete used for most residential foundations has the right degree of porosity to provide capillary suction, which draws water into the footings and then into the foundation wall. This water usually evaporates into the inside space undetected. However, the moisture occasionally manifests itself as a ring of dampness visible at the bottom interior surface of a basement or crawl space wall. Gravel and capillary breaks installed between the footing and the foundation wall are effective moisture control strategies in these below-grade envelope intersections. Several techniques to control capillary moisture below grade are shown in [Figure 4](#) and [Figure 5](#).

MOISTURE CONTROL IN COMMERCIAL AND INSTITUTIONAL BUILDINGS

Moisture control in commercial and institutional buildings often requires approaches different from those in residential buildings. Indoor humidity conditions can vary greatly from one building to the next, depending on the use and requirements. The building envelope should be designed to perform well with these indoor conditions. Special thought should be given to the moisture control features of the HVAC equipment and the building envelope for certain buildings with special indoor humidity conditions or requirements, such as swimming pools, hospitals, and museums.

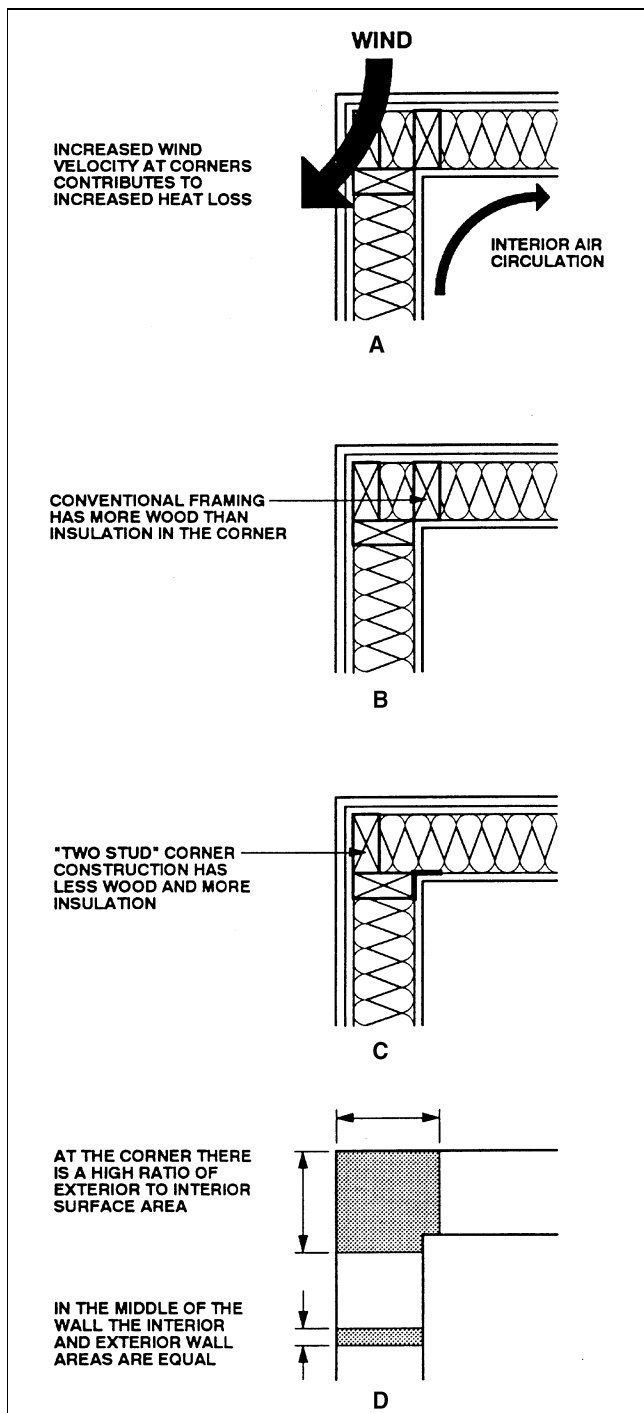


Fig. 6 Heat Loss at Building Corners

Source: Lstiburek and Carmody (1991). Reprinted with permission.

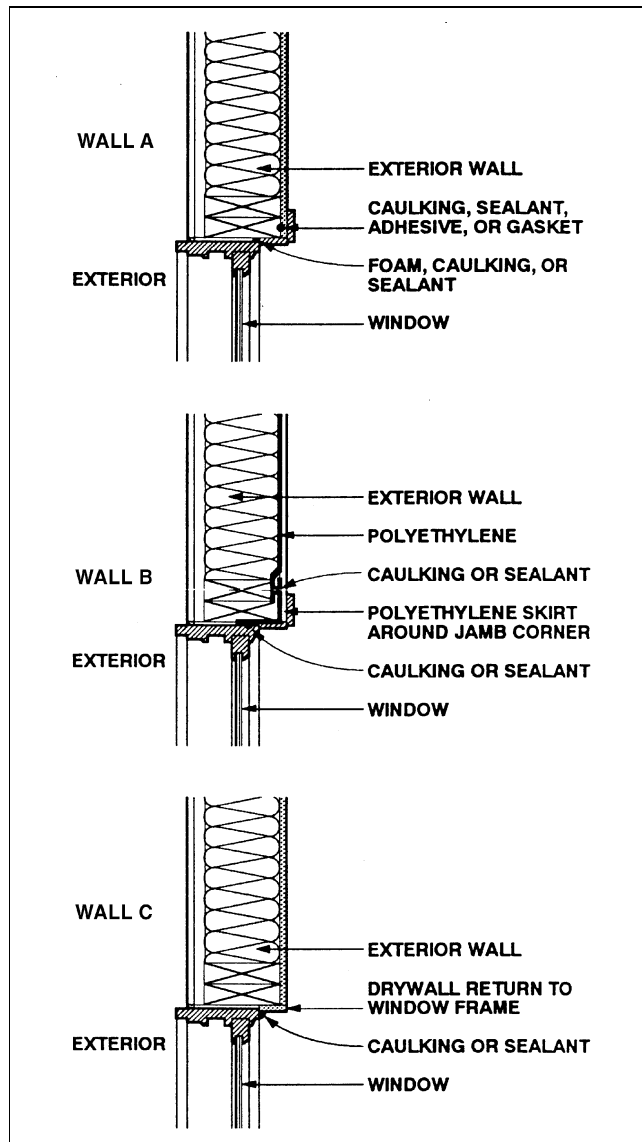


Fig. 7 Interior Airflow Retarder Details at Window Jamb
 Source: Lstiburek and Carmody (1991). Reprinted with permission.

Materials commonly used in commercial and institutional construction tend to be more moisture-tolerant and decay-resistant than those used in residential construction. Airflow retarder systems are often poorly designed and executed. As a result, air leakage through the building envelope is common. Air leakage through hollow concrete masonry is often greater than in other types of construction. Upward airflow in the cavities is not always adequately blocked, and parallel random leakage paths are found between gypsum wall-board or other finishes and the block face.

Air can leak through exterior walls where the structural system or services penetrate the air barrier or at joints between dissimilar materials or components. For example, masonry cannot form a tight seal with structural steel columns and beams. To reduce this problem, the structural frame should be inside and separate from the exterior wall. The resulting curtain wall can then incorporate a more continuous air barrier and be protected from the fluctuating weather by insulation applied to the outside. Exterior cladding to control rain penetration is best applied following the weather-tightening system. The interior wythe (masonry course) and air barrier should be accessible for maintenance of the air seal and joints.

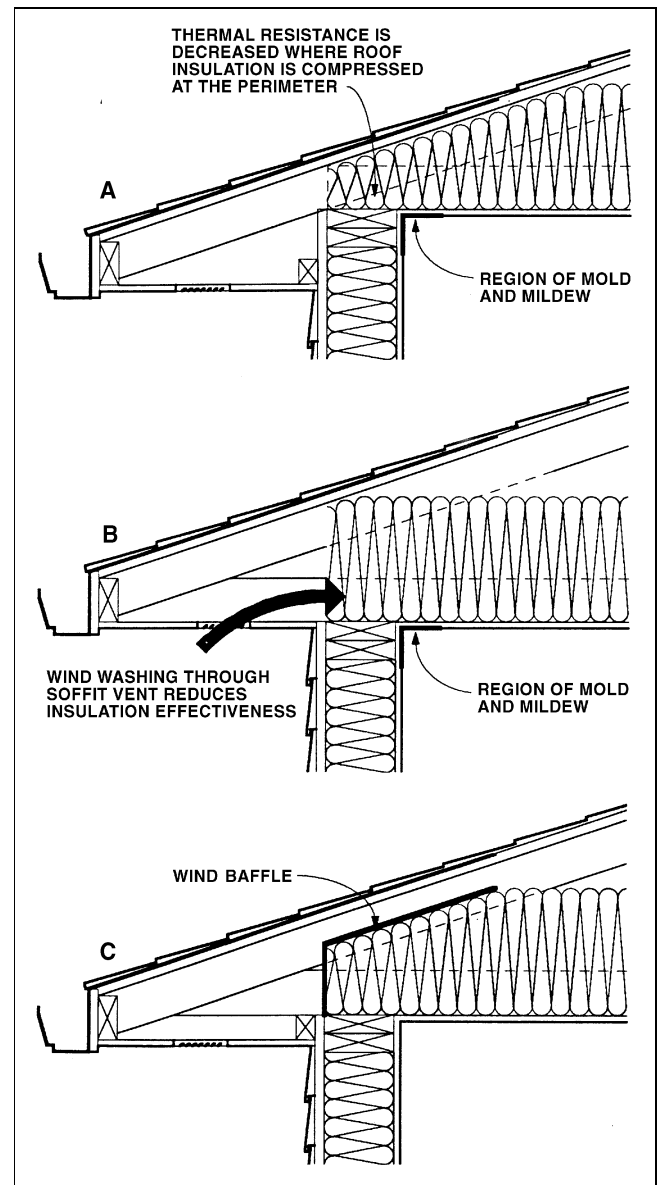


Fig. 8 Heat Loss Effect at Ceiling Edge
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The deterioration of exterior structural elements of a building and damage to the interior through condensation from air leakage has an important bearing on the operation and maintenance costs of the building. Improving the airtightness of internal floors and partitions, particularly in high-rise buildings, redistributes the pressure differences caused by the stack effect and reduces the pressure difference across the exterior wall on each floor. This approach also improves ventilation and air distribution and reduces the air circulation between occupancies on different floors. It also helps control smoke movement in the case of fire and may enable a more equitable apportioning of energy charges for space heating between individual units in apartment buildings.

Leakage in actual buildings often occurs through holes cut accidentally or deliberately in a reasonably tight membrane or component, such as the penetration of services through specified air or vapor retarders or solid components. Other leakage openings in the exterior envelope result from dimensional changes in improperly placed materials or from inadequate sealants or membranes applied to bridge joints or cracks that will eventually open.

INDUSTRIAL AND COMMERCIAL INSULATION PRACTICE

For pipe materials, selection, application, and installation, see [Chapter 41 of the ASHRAE Handbook—Systems and Equipment](#). For insulation systems for refrigerant piping, see also [Chapter 32 of the ASHRAE Handbook—Refrigeration](#).

If the equipment is subject to wide changes in temperature, the insulation installation should be designed to accommodate the associated dimensional change. If the equipment is operated at below ambient temperature, the application should be designed to resist the accumulation of moisture in the insulation.

PIPES

Small pipes are insulated with cylindrical half-sections of insulation, with factory-applied jackets that form a hinge-and-lap, or with flexible, closed-cell material. Large pipes can be insulated with flexible material or with curved, flat segmented, or cylindrical half-, third-, or quarter-sections of rigid insulation, particularly where removal for frequent servicing of the pipe is necessary. Fittings (valves, tees, crosses, and elbows) are insulated with preformed fitting insulation, fabricated fitting insulation, individual pieces cut from sectional straight pipe insulation, or insulating cements. Fitting insulations should always be equal in thermal performance to the pipe insulation.

Securing Methods

The method of securement varies with the size of pipe, form and weight of the insulation, and the type of jacketing (i.e., separate or factory-applied). Insulation with certain factory-applied jacketing can be secured on small piping by cementing the overlapping jacket. Large piping may require supplemental wiring or banding. Insulation on large piping requiring separate jacketing is wired or banded in place, and the jacket is cemented, wired, or banded, depending on the type. Insulation with factory-applied metal or PVC jacketing is secured by specific design of the jacket and its joint closure. The flexible closed-cell materials require no jacket for most applications and are applied using specially formulated contact adhesives.

Insulation Finish for Above-Ambient Temperatures

Pipe insulation finishes for indoor use are usually governed by location. The finishes are factory-applied jackets designed to meet fire safety requirements. For maximum fire safety, unusual exposure conditions, or appearance, factory or separately applied metal or PVC jackets may be used. An outdoor finish protects the insulation from the weather. Chemical exposure, mechanical abuse, and appearance are additional considerations.

Pipes that operate at temperatures above 260°C may require two layers of insulation in order to accommodate the large dimension change of pipe and insulation materials.

Insulation Finish for Below-Ambient Temperatures

Piping at temperatures below ambient is insulated to control heat gain and prevent condensation of moisture from the ambient air. Because piping is an absolute barrier to the passage of water vapor, the outer surface of the insulation must be covered by an impervious membrane or cover, which also helps protect the pipe against corrosion.

Retarder treatment should be recommended by the insulation manufacturer as established by performance testing. The insulation should be as dry as possible, and therefore should be protected from undue weather exposure.

Vapor seals for straight pipe insulation are generally designed to meet operating temperature, fire safety, and appearance requirements. Jacketing commonly consists of various combinations of laminates of paper, aluminum foil, plastic film, and glass fiber

reinforcing. An important feature of such jacketing is very low permeance in a relatively thin layer, which provides flexibility for ease of cementing and sealing laps and end-joint strips. This type of jacketing is commonly used indoors without additional treatment. In some cases of operating temperatures below –20°C, multilayer insulation and jacketing may be used. Flexible closed-cell materials must be carefully cemented to avoid openings in the insulations.

Insulation fittings are usually vapor sealed by applying suitable materials in the field, and may vary with the type of insulation and operating temperature. For temperatures above –12°C, the vapor seal can be a lapped spiral wrap of plastic film adhesive tape or a relatively thin coat of vapor-seal mastic. For temperatures below –12°C, common practice is to apply two coats of vapor-seal mastic reinforced with open weave glass or other fabric. The thickness of the mastic increases with decreasing temperature. With long lines of piping, the insulation should be sealed off every 5 or 6 m to limit water penetration if vapor seal damage occurs.

For dual-temperature service, where piping is alternately cold and hot, the vapor-seal finish, including mastics, must withstand pipe movement and exposure temperatures without deterioration. When flexible closed-cell insulation is used, it should be applied slightly compressed to prevent it from being strained when the piping expands.

Outdoor pipe insulation may be vapor-sealed in the same manner as indoor piping, by applying added weather protection jacketing without damage to the retarder and sealing it to keep out water. In some instances, heavy-duty weather and vapor-seal finish may be used.

Because cold piping frequently operates year-round, a constant vapor drive exists under humid conditions. Even with vapor retarder insulation, jackets, and vapor sealing of joints and fittings, moisture inevitably accumulates in permeable insulations. This moisture not only reduces the thermal resistance of the insulation, it also accelerates condensation on the jacket surface. Since periodic insulation replacement is the only known solution, the piping installation should be accessible for such replacement and should have a means for draining water. As an alternative, very low-permeance insulating materials (e.g., materials not exceeding $0.6 \text{ ng}/(\text{s} \cdot \text{m}^2 \cdot \text{Pa})$ by the wet cup method) have been used to extend the life of the system and reduce replacement frequency. The lower the permeance of the insulation material, the longer its life, provided good workmanship is practiced during installation.

Surface Temperature

In elevated-temperature applications, the surface temperature of the insulation system should be below that at which personnel coming into contact with the surface could be harmed. In below-ambient temperature applications, the surface temperature of the system should be above the dew point to prevent condensation.

Compared to a jacket with a nonreflective surface, a jacket with a reflective surface has a higher surface temperature for hot applications and a lower surface temperature for cold-temperature applications, because the lower emissivity reduces the rate of heat exchange. Therefore, adding a reflective jacket could produce a surface temperature capable of burning personnel on hot applications and causing condensation on cold applications. The jacketing material used also contributes to the relative safety at a given surface temperature. For example, at 80°C, a stainless steel jacket blisters skin more severely than a canvas jacket does.

Insulating Pipes to Prevent Freezing

If the surrounding air temperature remains sufficiently low for an extended period, insulation cannot prevent freezing of still water or of water flowing at a rate insufficient for the available heat content to offset the heat loss. Insulation can only prolong the time required

Table 1 Estimated Requirements to Prevent Freezing of Water in Pipes

Steel Pipe Nominal Diameter, mm	Insulation Thickness, mm					
	50	75	100	50	75	100
	Time to Cool Water to Freezing, h			Water Mass Flow Rate per Unit Length of Exposed Pipe to Prevent Freezing, g/(s·m)		
15	0.27	0.32	0.36	0.23	0.19	0.16
25	0.61	0.75	0.85	0.29	0.23	0.20
40	1.16	1.46	1.69	0.37	0.29	0.24
50	1.67	2.13	2.49	0.44	0.33	0.27
80	2.83	3.71	4.42	0.61	0.43	0.35
100	4.07	5.43	6.54	0.77	0.53	0.42
125	5.45	7.36	8.96	0.97	0.64	0.50
150	6.86	9.37	11.5	1.20	0.76	0.58
200	9.59	13.3	16.5	1.79	1.03	0.76
250	12.6	17.6	22.1	2.54	1.32	0.93
300	15.4	21.7	27.4	3.71	1.69	1.14

Design Conditions: Surrounding air temperature $t_a = -28^\circ\text{C}$, initial water temperature $t_i = 5.5^\circ\text{C}$, and insulation thermal conductivity $k_I = 0.043 \text{ W/(m}\cdot\text{K)}$. Thermal resistances of pipe and air film at surface of insulation are ignored.

Calculations are for 40ST steel pipe. See [Table 2 in Chapter 41 of the ASHRAE Handbook—Systems and Equipment](#) for actual pipe dimensions.

for water to freeze or prevent freezing if water flow is maintained at a sufficient rate. The first section of [Table 1](#) can be used to estimate the thickness of insulation necessary to prevent freezing of still water in pipes. The second section of [Table 1](#) gives the minimum flow of water at an initial temperature of 5.5°C to prevent the temperature of the pipe from reaching 0°C at the end of the exposed length.

To calculate time θ (in hours) required for water to cool to 0°C , the following equation can be used:

$$\theta = \frac{\rho c_p \pi \left(\frac{D_i}{2}\right)^2}{3600} R_{T(\alpha)} \ln \left[\frac{t_i - t_a}{t_f - t_a} \right] \quad (1)$$

where

- θ = time for water to cool to freezing, h
- ρ = density of water = 1000 kg/m^3
- c_p = specific heat of water = $4200 \text{ J/(kg}\cdot\text{K)}$
- D_i = inside diameter of pipe, m
- D_p = outer diameter of pipe or inner diameter of insulation, m
- D_I = outer diameter of insulation, m
- $R_T = R_p + R_I + R_a$ = combined thermal resistance of pipe wall, insulation, and exterior air film per metre of pipe, $\text{m}\cdot\text{K/W}$
- $R_a = 1/(h_a \pi D_I)$ = resistance between ambient air and outer surface of insulation per metre of pipe, $\text{m}\cdot\text{K/W}$
- h_a = air heat transfer coefficient (see [Chapter 3](#) for values)
- $R_I = \ln(D_I/D_p)/(2\pi k_I)$ = resistance of thermal insulation per metre of pipe, $\text{m}\cdot\text{K/W}$
- $R_p = \ln(D_p/D_i)/(2\pi k_p)$ = resistance of pipe per metre of pipe, $\text{m}\cdot\text{K/W}$ ($R_p \approx 0$ for metal pipe)
- k_I = thermal conductivity of insulation, $\text{W/(m}\cdot\text{K)}$
- k_p = thermal conductivity of pipe material, $\text{W/(m}\cdot\text{K)}$ (see [Table 7 in Chapter 41 of the ASHRAE Handbook—Systems and Equipment](#) for thermal conductivity of various plastic pipes)
- t_a = ambient air temperature, $^\circ\text{C}$
- t_i = initial water temperature, $^\circ\text{C}$
- t_f = freezing temperature, $^\circ\text{C}$

When unusual conditions make it impractical to maintain protection with insulation alone, a hot trace pipe or, preferably, electric resistance heating cable is required along the bottom or top of the water pipe. The heating system then supplies the heat lost through the insulation. The insulation thickness is determined by the cost of the heating system, the insulation, and the heat loss.

Pipe bursting is not an immediate consequence of water pipes reaching freezing temperatures. Clean water and pipes usually supercool several degrees below freezing before any ice is formed. Then, upon nucleation, dendritic ice forms in the water and the temperature rises to freezing. Ice can be formed from water only by the release of the latent heat of fusion (334 kJ/kg) through the pipe insulation. With well-insulated pipes, this release of latent heat may be greatly retarded. Pipe bursting in water pipes has been shown (Gordon 1996) to be a consequence not of ice crystal growth in the pipe, but of elevated fluid pressure within a confined pipe section occluded by a growing ice blockage.

Underground Pipe Insulation

Both heated and cooled underground piping systems are insulated. Protecting underground insulated piping is more difficult than protecting aboveground piping. Groundwater conditions, including chemical or electrolytic contributions by the soil and the existence of water pressure, require a special design to protect insulated pipes from corrosion. Walk-through tunnels, conduits, or integral protective coverings are generally provided to protect the pipe and insulation from water. Examples and general design features of conduits and a description of tunnels can be found in [Chapter 11 of the ASHRAE Handbook—Systems and Equipment](#).

Temperatures Above Ambient. Piping for heated systems in walk-through tunnels is usually covered with sectional insulation and finished with effective mechanical protection such as metal or waterproofing jackets. The use of walk-through tunnels is declining because of cost.

Conduit systems are generally used for underground insulated piping systems. The most successful application is sectional insulation with the conduit sized for drainage and adequate drying of insulation on heated piping in the event of accidental flooding. BRAB (1975) gives detailed design criteria for conduit systems. The criteria require that (1) all systems provide for draining and insulation drying, (2) the insulation withstand boiling and drying without physical damage and loss of insulating value, and (3) the conduit casing is watertight in the field. The insulation should be a nonconductor of electricity, verminproof, and chemically and dimensionally stable at the operating temperature of the pipe.

BRAB (1964) describes evaluative tests and field investigations, which have shown that calcium silicate is resistant to severe boiling action. Fibrous glass (density of 64 to 110 kg/m^3) will not withstand boiling when a conduit becomes flooded, and wet poured-in-place insulations are likely to remain partially wet for their installed life.

The thickness of insulation for underground piping is not determined on the same basis as above ground piping. [Chapter 11 of the ASHRAE Handbook—Systems and Equipment](#) provides details for determining thickness.

Temperatures Below Ambient. Integrally protected, insulated piping buried directly in the ground is commonly used for chilled water. However, since no heat is available to drive out moisture, an absolute protective covering against water and insulation with low permeance and water absorption is extremely important. Cellular glass with proper protection has been widely used for this type of application. The acceptance of plastic foams is increasing, but their long-term performance has not yet been established.

Conduit for chilled water piping requires a different approach than for hot piping. Insulation must have low conductivity, and conduit design must use this low conductivity and maintain continuing performance. More recent designs use low-conductivity plastic foam insulation with plastic pipe as the internal water-carrying piping and as the external conduit.

Where the temperature difference between the pipe at 5°C and the soil at 13 to 16°C is small, pipe size, length, and flow rate may economically justify direct burial without insulation. However, good piping protection may be required.

DUCTS

The need for duct insulation is influenced by (1) duct location, whether indoors or outdoors; (2) the effect of heat loss or gain on equipment size and operating cost; (3) the need to prevent condensation on low-temperature ducts; (4) the need to control temperature change in long duct lengths; and (5) the need to control noise with interior duct lining.

All ducts exposed to outdoor conditions, as well as those passing through unconditioned spaces, should be insulated. While analyses of temperature change, heat loss or gain, and other factors affecting the economics of thermal insulation are seldom made for residential installations, they are essential for large commercial and industrial projects.

The U-factor for uninsulated sheet metal ducts is affected by air velocity, the emittance of the metal, and the shape of the duct. An approximate value of $5.7 \text{ W}/(\text{m}^2 \cdot \text{K})$ may be used. For insulated ducts, U-factors of 1.4 and $0.74 \text{ W}/(\text{m}^2 \cdot \text{K})$ represent 25 and 50 mm thick rigid insulation with a thermal conductivity of $0.039 \text{ W}/(\text{m} \cdot \text{K})$ at 24°C mean temperature. A method for determining heat loss or gain for ducts is given in [Chapter 34](#).

Materials for Ducts, Insulations, and Liners

Ducts within buildings can be of insulated sheet metal, fibrous glass, or insulated flexible ducts, all of which provide combined air barrier, thermal insulation, and sound absorption. Ducts embedded in or below floor slabs may be of compressed fiber, ceramic tile, or other rigid materials.

Duct insulations include semirigid boards and flexible blanket types, composed of organic and inorganic materials in fibrous, cellular, or bonded particle forms. Insulations for exterior surfaces may have attached vapor barriers or facings, or vapor barriers may be applied separately. When applied to the duct interior as a liner, insulation both insulates thermally and absorbs sound. Duct liner insulations have sound-permeable coatings or other treatment on the side facing the airstream to withstand air velocities or duct cleaning without deterioration.

Per UL *Standard* 181, fibrous glass air ducts are tested to 63.5 m/s and are rated at 25 m/s and at a pressure of at least 500 Pa. Primary use is for low-pressure systems tested at 1.5 times the recommended static pressure. Maximum recommended air temperature is 120°C . A complete system provides greater decibel attenuation than is usually provided by standard duct liners, with greater reduction in airborne equipment noise and crosstalk. Higher design velocities are also possible.

To satisfy most building codes, duct insulation and fibrous glass duct materials must meet the fire hazard requirements of (1) NFPA *Standard* 90A, to restrict spread of smoke, heat, and fire through duct systems, and to minimize ignition sources; and (2) NFPA *Standard* 90B, on supply ducts, controls, clearances, heating panels, return ducts, air filters, and heat pumps. Local code authorities should also be consulted.

Where thermally insulated air-conditioning ducts pass through unconditioned spaces, such as attics, the maximum allowable heat flux should be no greater than that required by NFPA *Standard* 90A.

Securing Methods

Exterior rigid duct insulation can be attached with adhesive, with supplemental preattached pins and clips, or with wiring or banding. Liners can be attached with adhesive and supplemental pins and clips. Flexible duct wraps do not require attachment except on bottom duct panels greater than 600 mm wide. For larger ducts a pin no more than 600 mm on center is sufficient.

Manufacturers provide information on the construction of fibrous glass duct systems. Preformed round duct for straight runs is combined with fittings fabricated from straight duct. Rectangular ducts and fittings are fabricated by grooving, folding, and taping.

Metal accessories such as turning vanes, splitters, and dampers are incorporated into the system. When rectangular ducts exceed predetermined dimensions for particular static pressures, ductwork must be reinforced. The Sheet Metal and Air Conditioning Contractors National Association's (SMACNA) *Fibrous Glass Duct Construction Standards* (1992) have further information.

Heating Ducts

The effect of duct insulation on residential heating system equipment size can be marginal. However, insulation can reduce operating costs significantly, depending on unit costs for heating and the extent of duct exposed to outside conditions. In addition, duct insulation maintains the supply air temperature, which may keep the air entering the conditioned space within a more comfortable range.

Vapor retarders are not required on exterior insulation of ducts used only for heating, but they must be provided for ducts used for alternate heating and cooling.

Cooling Ducts

Insulation can significantly reduce operating costs and cooling equipment size. The advantage of adequate insulation is especially significant in areas with high dry-bulb and dew-point temperatures. Ducts for summer air conditioning are insulated with the same materials as heating ducts. Ducts in any unconditioned space should be insulated and have vapor retarders to prevent condensation. Joints and laps in the vapor retarder must be sealed. Flexible closed-cell insulation does not always need a supplemental vapor retarder, but care must be taken to form vapor-tight seams at joints.

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