Related Commercial Resources

CHAPTER 45. BUILDING ENVELOPES

PROPER building envelope design requires knowledge of the physics governing building performance as well as of building materials and how they are assembled. This chapter provides practical information for designing new building envelopes and retrofits to existing envelopes, always with the notion that the envelope must work well in concert with the building's surroundings and the HVAC system. The information can also be useful for those involved with building envelope investigation and analysis.

This chapter was developed with the integrated design approach in mind and assumes that the architect, HVAC designer, building envelope designer, and others involved in envelope design and construction communicate and understand the interrelationships between the building enclosure and mechanical systems. Integrated design requires a clear statement of the owner's project requirements (OPR) and design intent, and is described in greater detail in Chapter 60. That chapter may be used as a basis for finding common agreement among designers and engineers using the integrated design approach. The growing use of integrated design in project delivery highlights the building envelope as the principal site where architectural design and mechanical engineering meet.

A successful building envelope design requires that the team be knowledgeable about and responsible for the performance requirements described in this chapter. This chapter does not distinguish the individual responsibilities of each team member, but rather is intended to serve the team as a whole.

Buildings are designed and constructed to provide shelter from the weather and house conditioned, habitable spaces for occupants. The **building envelope** is an assembly of components and materials that separate the conditioned indoor environment from the outdoor environment. The envelope typically includes the **foundation**, **walls**, **windows**, **doors**, and **roof**. Partitions between interior building zones that have substantially different environmental conditions (such as a swimming pool compared to an office area) are often required to function similarly to building envelopes.

Performance requirements for the building envelope include the following (Handegord and Hutcheon 1989; Hendriks and Hens 2000; Hutcheon 1963):

- Control heat flow
- Control airflow, including airborne contaminants
- Control liquid water penetration (with rain as the most important source)
- Control water vapor flow
- Control light, solar, and other radiation
- Control noise
- Control fire
- Provide strength and rigidity against outside influences (sometimes structural)
- Be durable
- Be constructable, maintainable, and repairable
- Be aesthetically pleasing
- Be economical
- Be sustainable

These performance requirements and their effects on one another must be understood by the project team. Building envelopes should be designed for good overall performance. The first eight listed items arise from the envelope's function of separating the conditioned and unconditioned environments. Parties responsible for HVAC and building envelope design must be knowledgeable about how each system affects the performance of the other. Review of the heat, air, and moisture characteristics of the proposed envelope is needed for appropriate design of HVAC systems. The building envelope must also be designed with an understanding of the interior and exterior environmental design conditions; consequently, the architect or principal designer needs to provide the specific performance requirements to the HVAC designer, including provisions to achieve minimum airtightness, interior occupancy criteria, and special-use considerations. With a building envelope design suited to the operating requirements, the space-conditioning (HVAC) system generally is smaller in capacity and may have simpler control and distribution systems, normally resulting in a system with greater efficiency.

This chapter applies information in Chapters 25 to 27 of the 2021 *ASHRAE Handbook—Fundamentals* to building envelope design. It also incorporates much of the material from previous versions (until 2005) of that volume's Chapter 24.

1. TERMINOLOGY

For definitions related to the physics of heat air and moisture transport, see the Terminology section in Chapter 25 of the 2021 *ASHRAE Handbook—Fundamentals*.

An **air barrier component** is a premanufactured element with air leakage characteristics that are determined during manufacturing.

An **air barrier material** is a material with a low air leakage.

An **air barrier accessory** is an element used to connect air barrier materials and components to form an air barrier assembly or an air barrier system, or used to fasten the air barrier material to a substrate or to framing members.

An **air barrier assembly** is a combination of air barrier materials and air barrier accessories that forms a continuous barrier that controls airflow in its immediate area.

An **air barrier system** is a combination of air barrier assemblies, components, and accessories in a building envelope, forming a continuous barrier that controls airflow across the envelope.

A **building assembly** is any part of the building envelope (e.g., wall, window, roof) that has boundary conditions at the conditioned space and the exterior.

A **building envelope** or **building enclosure** is the overall physical structure that provides separation between conditioned spaces and the outdoor environment or any indoor environment that is substantially different from the conditioned one.

A **(building) component** is any physical element or material within a building assembly.

Moisture **condensation** is the change in phase from vapor to liquid water. Condensation occurs typically on materials such as glass or metal that are not porous or hygroscopic and on capillary porous materials that are capillary saturated. Condensation should be distinguished from phase change between vapor and bound water in capillary or open porous materials (see **moisture content**).

Durability is the ability of a building or any of its components to perform its required functions in its service environment over a period of time without unforeseen cost for maintenance or repair (CSA 2007).

Fenestration includes all areas (including the frames) in the building envelope that let in light. Fenestration includes windows, curtain walls (vision areas), clerestories, skylights, and glazed doors. Fenestration excludes insulated spandrels and solid doors. **Fenestration area** is the total area of fenestration measured using the rough opening, including the rough opening for doors.

Hygrothermal design analysis is a set of calculation procedures that uses building design and component physical properties to predict heat, air, and moisture performance of envelopes and assemblies under design conditions. See Chapters 25 to 27 in the 2021 *ASHRAE Handbook—Fundamentals*.

Infiltration is uncontrolled inward air leakage through open, porous materials, cracks, and crevices in any building component and around windows and doors caused by pressure differences.

Exfiltration is uncontrolled outward air leakage through open, porous materials, cracks, and crevices in any building component and around windows and doors caused by pressure differences.

Wind washing is uncontrolled wind-induced flow of outdoor air in and behind insulation layers

Air intrusion is uncontrolled pressure-induced flow of indoor air in, through, and in front of air-permeable insulation layers, caused by wind pressures, stack effect, or HVAC systems.

Convective loop is uncontrolled stack-induced convective flow of cavity air in and around insulation layers

Thermal insulation is any material specifically designed to decrease heat flow by equivalent conduction through a building envelope or envelope assembly.

Moisture content is the ratio of mass of water to volume of dry material in porous and hygroscopic materials, in kg/m^3. **Bound water** describes the phase of water bound in hygroscopic materials. **Sorption** (and **desorption**) describes the change in phase between vapor and bound water.

A **plenum** is a compartment or chamber to which one or more ducts are connected, that forms part of an air distribution system, and is not used for occupancy or storage. A plenum is often under positive or negative air pressure relative to adjacent spaces.

The **R-value** of a material is the thermal resistance for a given thickness of that material, as provided by the manufacturer or listed in Table 4 of Chapter 26 in the 2021 *ASHRAE Handbook—Fundamentals*. The **system R-value** (R_S) is the sum of the individual R-values for each material, excluding air films. The **total R-value** (R_T) is the sum of the system R-value and the interior and exterior air-film resistances (see Chapter 25 in the 2021 *ASHRAE Handbook—Fundamentals*).

A **thermal break** is a thermally resistive element that decreases heat conduction through an assembly.

A **thermal bridge** is a thermally conductive element through an otherwise thermally resistive assembly.

U-factor or**thermal transmittance** is the rate of heat transfer per unit surface of an assembly per unit temperature difference between the environments at both sides of the assembly. The clear value only considers the surface film resistances and R-values of the material layers comprising the assembly. The U-factor is $1/R_T$. A **whole-wall** or **effective U-factor** also takes into account thermal bridging, convective loops, wind washing, and indoor air washing effects (see Chapter 25 in the 2021 *ASHRAE Handbook—Fundamentals*).

A **vapor retarder** or **vapor barrier** is any component in a building envelope with a low permeance to moisture flow by diffusion.

A **water-resistive barrier (WRB)** is a building envelope component designed to prevent inward movement of liquid water.

2. GOVERNING PRINCIPLES

The building envelope is the key element in managing the environmental loads on the building. These loads are a function of the climate and the indoor conditions, such as air temperature, relative humidity, and air pressure differential. There is a strong interdependence between a building HVAC system and the envelope that must be considered when designing or modifying a building. This interdependence centers on controlling heat flow, airflow (including control of airborne contaminants), and water and water vapor flow. Design parameters involved are as follows.

Design Parameters

Heat. The type and amount of insulation to be provided depends on the climate, governing codes, and building use. The insulation should be continuous, while considering the limitations of the materials and systems. Discontinuities (or thermal bridges) are the sites of unwanted heat transfer and reduce energy efficiency, which may result in premature soiling (e.g., ghosting), surface condensation, and/or mold growth. In heating- and cooling-dominated climates, reduced thermal performance can affect indoor conditions and increase HVAC loads. The thermal conductivities and R-values of insulating materials allow them to be compared for their effect on heat transfer, though their properties related to air and moisture transfer vary widely.

Air. Some buildings are designed for natural ventilation when building use and climate allow, and for mechanical space conditioning (with ventilation) at other times. During periods of space conditioning, the building envelope should show minimal air leakage. This allows better control of (1) HVAC, (2) inflow of airborne contaminants, and (3) noise transmission. The HVAC system can generate pressure differentials across the envelope that increase air leakage and may create moisture and thermal problems. It is important to review the interaction of the HVAC system and envelope at the design stage.

Moisture. Building envelopes should be designed to shed rainwater, prevent accumulation of moisture in moisture-sensitive materials, and allow draining and drying of water that accumulates. Airflow through openings in the envelopes a secondary means of moisture transport through building envelopes. Liquid water and frost can accumulate on cold materials in a wall assembly along air movement paths. Vapor diffusion can play a role in wetting and especially in drying of building materials.

Although vapor diffusion control in an envelope assembly is important, field experience shows that most moisture problems are associated with bulk water penetration and moisture accumulation caused by air leakage. Despite the historic and code emphasis on vapor barriers, their effect is often secondary.

A beneficial exercise during building envelope design is to trace the continuity of the elements providing thermal, air, and water protection to the envelope as assembly details are refined. Continuity of the WRB and the air barrier is essential to their performance. Absolute continuity of a vapor barrier is not essential to its performance.

Hygrothermal analysis can be used to predict envelope performance and compare these results with the requirements. ASHRAE *Standard* 160 provides guidance for performing a hygrothermal design analysis. Inputs for hygrothermal modeling include assembly configuration, material properties, initial conditions, and indoor and outdoor climate conditions. Analysis tools generate outputs that may include heat and moisture flux and material moisture content. Because of the number of assumptions and the limitations of calculations required to complete an analysis, results should be considered guidance to supplement the designer’s understanding of envelope performance. They should not be considered an absolute prediction of actual hygrothermal performance.

Other Important Performance Criteria

Strength and Rigidity. The air barrier system must be able to withstand air pressures to which the building will be subjected. These pressures can often be large, and strength is critical in severe-weather areas such as hurricane zones.

Noise. For most occupancies, building envelopes should be designed and constructed to reduce noise transfer between conditioned and unconditioned spaces. Sound insulation can be particularly important near noisy areas such as airports, railways, and highways, especially for occupancies that require indoor quiet (e.g., hospitals, hotels, residences, theaters).

Constructability. During design, how a building envelope will be built must be considered. If there are practical limitations to how the envelope elements are physically put together, the design intent will be lost and problems are likely to develop during construction. Simplicity in design is an effective way to improve the chances of construction in accordance with the design intent. Construction of the various components must be sequenced so that all components can be correctly assembled, particularly when coordination between multiple trades is required. Investigation of many building failures demonstrates that poor sequencing between trades is a common contributing factor. Integrating constructability early in project design minimizes the number of failures and helps maximize the potential to achieve the results described in this chapter. During construction review, specific attention should be given to areas of the building where multiple systems are connected and multiple trades are involved. Use of mockups, design reviews, modeling, and other methods can enhance constructability.

Maintainability and Repairability. Building envelopes comprise many parts and components, with different anticipated service lives. Exterior cladding materials and fenestration may need replacement during the expected life of a building. Foundations and framing are the core elements of a building and should last for the entire building service life. Care should be taken not to cover shorter-lived building components with components having a longer anticipated lifespan.

Maintenance of the envelope and HVAC system is important to ensure a functional building. A poorly maintained HVAC system can result in substantial energy loss and have a detrimental effect on the building envelope by subjecting it to unexpected pressures and/or moisture loads. Verification of airflows and pressure differentials has been incorporated into many sustainable design tools as a check to ensure the building mechanical system is functioning as intended long after commissioning.

Sustainability. ASHRAE (2006) defines sustainability as "providing for the needs of the present without detracting from the ability to fulfill the needs of the future." In this chapter, *sustainability* refers primarily to durability and energy performance. Durability is essential for sustainable buildings, and moisture control is essential to durability. Additional information on sustainability can be found in Chapter 35 of the 2021 *ASHRAE Handbook—Fundamentals*.

With regard to durability, thermal insulation keeps interior and exterior materials near their respective ambient temperatures. In a well-insulated building in a cold climate, the exterior materials are subjected to harsher conditions (lower temperatures, wetter conditions, slower drying, and longer periods at subfreezing temperatures) than in one poorly insulated. Exterior materials for well-insulated buildings should therefore be sufficiently robust to withstand the conditions to which they will be exposed.

From an energy perspective, completeness of the air and thermal barrier is critical to achieve good performance. For details on sustainable energy use in buildings, see ASHRAE *Standard* 90.1.

Quality Control. Ensuring good envelope performance demands a well-established quality control program: the design must minimize damage risk while maximizing thermal efficiency (quality assurance). For that purpose, redundancies should be incorporated to allow for imperfections in construction (e.g., providing for drainage or drying to remove moisture from wall cavities). The building should be designed to enable effective maintenance and repair over its anticipated service life. Quality control methods such as construction review and the use of site mock-ups can be invaluable tools to increase the likelihood of good construction.

The building envelope differs greatly from mechanical and lighting systems in terms of inspections and commissioning. The building envelope is normally inspected during key phases of construction to check compliance with the construction documents and design intent, before many of the elements are enclosed within a wall system. Once enclosed, it is often very difficult to return to these areas to make repairs. At these key phases of completion, inspection measures are critical to ensure that any changes in design maintain the intent. Mechanical and lighting systems, on the other hand, are normally commissioned at the end of a project, meaning that their full-service testing for compliance does not occur until the building is operational and occupied.

3. DESIGN PRINCIPLES

Air conditioning and humidification can substantially change the moisture loads on the building envelope. New building materials may have significantly different thermal and moisture characteristics than traditional materials. The interdependency between the building envelope and the HVAC system has greater consequences to building durability and performance under problematic heat, air, and moisture conditions.

Heat Flow Control

A building envelope must adequately reduce heat flow to maintain energy efficiency and ensure indoor thermal comfort. Generally, heat flow control is achieved by installing thermal insulation as part of a wall, floor, or roof assembly.

The most common insulation materials used in building envelopes are glass fiber, mineral wool, cellulose, foam boards, and spray-applied foams. All these materials have exposure and performance limitations (e.g., fire, noise, moisture, ultraviolet) and should be selected carefully to promote long-term performance (see Table 1 in Chapter 26 of the 2021 *ASHRAE Handbook—Fundamentals* for common insulation materials and their properties).

Depending on the type of envelope assembly, the location of insulation in the wall can have a direct effect on thermal performance. For example, placing continuous insulation, such as rigid foam or mineral fiber board, outboard of the exterior sheathing on stud walls reduces conductive heat transfer through the studs and improves overall thermal performance.

As with all building envelope assemblies, correct installation of insulation is important in maintaining good thermal performance. For example, small voids left in insulation can result in an appreciable increase in heat flow, with the voids having a greater significance in more highly insulated assemblies. Verschoor (1977) found that convective air currents around thin wall insulation installed vertically with air spaces on both sides increased heat loss by 60%. Lecompte (1990) found losses up to 300% depending on 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.

The thermal barrier should be continuous around the building envelope. This means aligning insulation planes in walls with thermal breaks in windows or providing continuity of the thermal plane around corners or at wall/roof connections.

Thermal Performance

Table 1 in Chapter 26 of the 2021 *ASHRAE Handbook—Fundamentals* gives thermal resistances of building materials. The thermal resistance of building assemblies is usually less than the sum of the material resistances (and may be significantly so). Data for clear-wall areas (summarized by James and Goss [1993]) do not include the effects of intersections with floors, roofs, and partitions, and do not account for thermal bridges at framing and partitions, air leakage, or convective air loops.

To test the validity of applying clear-wall data to the wall system, a series of three-dimensional heat conduction simulations was performed on a single-family, detached, one-story house, assuming no air leakage (Kosny and Desjarlais 1994). These simulations showed that, for a conventional wood-frame stud wall system with studs installed on 400 mm centers and no continuous outboard insulation, the average area-weighted whole-wall R-value was 91% of the clear-wall R-value. For a similar wall using 90 mm steel studs, the whole-wall R-value was only 83% of the clear-wall R-value. A similar two-dimensional analysis of an attached, two-story, steel-stud house by Tuluca et al. (1997) showed the R-value for the wall system to be 40 to 50% of the clear-wall R-value. Thermal bridging occurred through framing, metal ties, and exposed slab edges. Simply using the published insulation R-values alone as the R-value for the whole wall overestimates the real thermal performance. For constructions containing steel studs, for example, use either the R-value zone method or the modified zone method to determine real thermal performance that considers framing effects (see Chapter 27 of the 2021 *ASHRAE Handbook—Fundamentals*).

Thermal Mass

Thermal mass describes the ability of a material layer to store thermal energy and the ability of an opaque envelope component to dampen and delay transfer of heat. That damping, if combined with moderate glazing, effective solar shading, a correct ventilation strategy, and indoor partitioning with high thermal storage, can help moderate indoor temperature fluctuation under outdoor temperature swings (Brandemuehl et al. 1990). Increased thermal mass may also positively affect energy efficiency (Kosny et al. 1998; Newell and Snyder 1990; Wilcox et al. 1985). Finally, increased thermal mass can help to shift demand for heating and cooling to off-peak periods. Thermal mass is effective as a design tool where the outdoor diurnal temperature fluctuates around the indoor comfort range. In areas where this does not occur, thermal mass has little effect.

Damping and time delay are defined by the order in which opaque envelope components are arranged. Best results are achieved when the thermal insulation faces outside and layers with large heat capacity face the interior, as confirmed by an in-depth study of six wall configurations by Kosny et al. (1998). Damping capability of such walls also increases with thermal resistance (Van Geem 1986).

Hourly-based computer simulations using transient energy simulation tools may provide a good estimate of thermal mass effects.

Thermal Bridges

A thermal bridge is an envelope area with significantly higher rate of heat transfer than the contiguous enclosure. Primary causes for thermal bridging are (1) parts with low thermal resistance perforating layers with high thermal resistance, (2) geometries that create zones where large exterior surfaces connect to much smaller interior surfaces, and (3) chilled or warmed edges at the edge of insulation as a result of discontinuities.

Thermal bridges increase energy use. They may lead to moisture condensation in and on the envelope, result in possible mold growth, accelerate surface fouling (ghosting), increase crack risk, and create surfaces with non-uniform temperatures that can result in indoor comfort problems.

Slab edges, perimeter beams, balconies, and decks protruding from the building envelope are common areas for thermal bridging.

The effect of thermal bridges in envelopes can be assessed using the zone method, modified zone method, acceptable sources of test data, or computer simulation tools. Refer to Chapter 27 of the 2021 *ASHRAE Handbook—Fundamentals* for details.

Thermal bridges created by webs of concrete masonry units (CMUs) dictate the maximum thermal efficiency a CMU can attain. To reduce this effect, blocks containing two webs, instead of the usual three, have been used, and web cross section has been reduced by up to 40%. However, even such changes in block design have not significantly improved wall R-value. Instead, applying low-density concrete with significantly lower thermal conductivity effectively improved thermal performance of these masonry units (Kosny and Christian 1995a, 1995b). The same strategy can be used for CMUs containing core-insulating inserts or insulation fill.

A comparison between the uninsulated slab edge detail of Figure 1A and the insulated version in Figure 1B illustrates the importance of designing to reduce thermal bridging. (See Steven Winter Associates [1988] for numerical examples summarized in this section.)]

Air inside a masonry cavity often is at or near the outdoor air temperature. Figure 1A shows that, without cavity insulation, the concrete slab edge and steel beam are exposed to that outdoor air temperature. Both of these elements are made of relatively thermally conductive materials, steel being considerably more conductive than concrete. The result is significant heat loss and a low floor surface temperature near the slab edge, which can be a source of occupant discomfort and possible condensation if indoor humidity is sufficiently high. Adding insulation on the outside of these elements (Figure 1B) keeps them inside the thermal envelope. It keeps the structural steel warm, and prevents cold-weather condensation that could lead to corrosion, damage to the masonry below, and moisture damage to the surrounding finishes that could lead to interior mold growth.

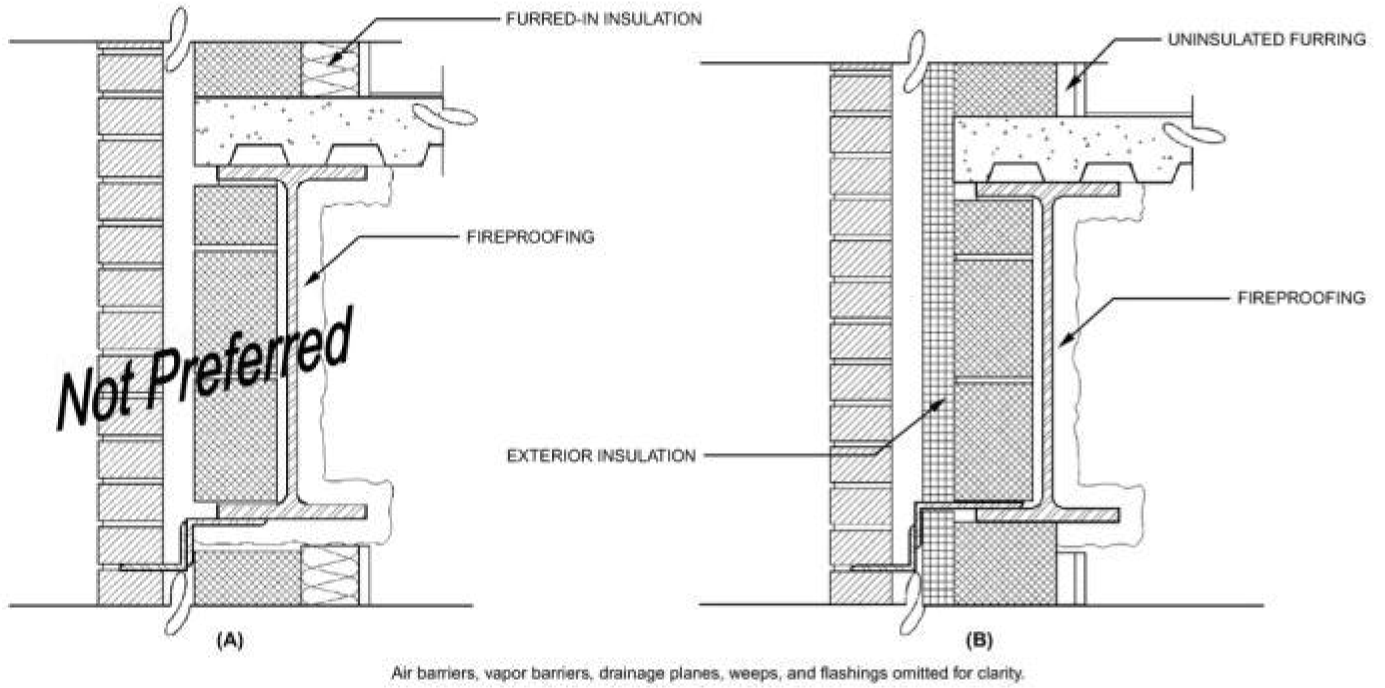


Figure 1. Schematic Detail of (A) Uninsulated and (B) Insulated Slab Edge and Metal Shelf Angle.

Insulation is sometimes specified for the interior surface of the perimeter beam to increase the thermal resistance of this wall segment. Site conditions rarely allow thorough installation, so the top and bottom flange edges remain exposed, creating a strong thermal bypass and marginalizing the insulation's effectiveness. Moreover, use of a vapor-permeable insulation makes vapor condensation more likely because it decreases the temperature of the beam chord but does not stop water vapor migration.

Concrete balcony decks are often formed by slab extensions that pass through the building envelope. As the exposed exterior surface exchanges heat with the outdoors, the result is extra heat loss at the interior floor and low floor temperatures during cold weather. These low temperatures may extend to the top and bottom of close-by interior walls, with condensation each time their surface temperature drops below the dew point of the interior air. The same mechanism can increase energy use during hot weather because building mechanical systems compensate for additional heat gain. Thermal break elements between slab and balcony or a careful addition of insulation panels can moderate the thermal bridge effect. One- or two-dimensional heat transfer models can be used to analyze more complicated assemblies.

Air Leakage Control

Uncontrolled air leakage in the form of infiltration, exfiltration, intrusion, and wind washing increases space conditioning costs and may cause moisture problems (see Chapter 25 of the 2021 *ASHRAE Handbook—Fundamentals*). Air leakage is much more effective than diffusion for transporting water vapor in the building envelope and causing interstitial condensation. Forensic field observations support these research results. Uncontrolled air leakage also short-circuits the transient response of envelope assemblies. It degrades sound insulation of the envelope and may cause draft and related thermal discomfort. These drawbacks underline the need to plan for airflow control in building envelope design by installing an air barrier.

Most published literature on air barrier requirements stipulates that an air barrier's air leakage permeance should not exceed 0.02 L/(s · m^2) at 75 Pa when tested in accordance with ASTM *Standard* E2178 (NRCC 2005; U.S. ACE 2009).

The air barrier must be sufficiently supported on both sides and be strong enough to resist expected loads from stack effect, mechanical-system-induced pressures, and wind. For example, a sheet-membrane air barrier material installed using staples against a sheathing in a cavity wall is well supported by the sheathing in a positive-pressure direction, but may be subject to tearing at the fastener points under negative pressures, which tend to pull the membrane away from the wall.

The air barrier must be continuous across the entire building envelope. To ensure continuity at windows and other penetrations, components creating the barrier must be connected with an airtight, durable joint. It is particularly important to ensure continuity of air barrier systems at junctions that create complicated geometries where two or more elements in different planes intersect (e.g., roof/wall intersections, wall/floor intersections, corners). Maintaining continuity at these assemblies can be further complicated because they often involve different construction trades, requiring coordination between workers.

Penetrations (e.g., electrical outlets, light fixtures, plumbing stacks) should be minimized and, if unavoidable, sealed carefully. Airtight electrical boxes are available. Maintaining air barrier system integrity throughout the building's life should also be considered. Cutting holes in gypsum board assemblies during renovations, for example, can result in widespread air barrier failure if the board is intended to be the primary air barrier in the assembly.

The best location for the air barrier is generally where it is easiest to assemble into a continuous and durable system. The location of the air barrier in a wall assembly may affect overall hygrothermal performance. Permeance properties of the barrier material may be important; see the section on Water Vapor Control.

Although the intent should be to construct an airtight building envelope, not all cracks and openings can be sealed in existing buildings, nor can an absolutely tight construction be achieved in new buildings. The objective is to provide an enclosure that is as tight as possible. Calling out a vapor barrier (see the section on Water Vapor Control) as "continuous" is not a sufficient specification for an air barrier.

Moisture Control

Building envelopes are subject to several moisture loads (moisture entry mechanisms), including liquid water and water vapor from air leakage and/or diffusion. Historically, the primary moisture control strategy for walls was to restrict water entry by collecting and redistributing moisture that enters with air, before evaporation. Today, good envelope design still requires minimizing accumulation and maximizing removal of moisture. Although weather-resistive components may be designed with the goal of eliminating water infiltration, some redundancy is obtained when assemblies are also designed to accommodate drainage and drying of incidental moisture intrusion. Hygrothermal modeling tools, as described in Chapters 25 and 27 of the 2021 *ASHRAE Handbook—Fundamentals*, can assist designers in understanding the drying potential of assemblies based on the assumed loads; however, current models cannot effectively predict drainage.

Liquid Water Control

Field observations indicate that moisture problems in buildings are most frequently caused by exterior liquid water penetrating or passing through the building envelope.

Rain is the most significant moisture source for buildings. Strategies to reduce the rain load on exterior walls include using building overhangs to prevent wetting, flashings, drip edges, and other water-shedding elements. During rain, poor flashing details at the interface of dissimilar materials, incomplete terminations of cladding systems, and other discontinuities in the moisture barrier may result in water entry, which can cause severe damage and loss of durability. For roofs and walls, cladding and building envelope components must be integrated to prevent water infiltration. At grade, rainwater should be carried away from the foundation through gutters, downspouts, and positive grading (i.e., sloping the surrounding grade to direct water away from the building).

An important consideration when designing an envelope for liquid water control is sequencing during construction and coordination between trades. Proper sequencing is essential to ensure that systems are correctly connected. Building envelope failure investigations often reveal that water penetration problems result from poorly constructed connections between various elements, often caused by inadequate site coordination. Important connection details should be included in the construction documents with enough clarity to allow suitable construction. Lack of detail on drawings and in specifications can result in too many construction decisions being made on site.

One method of minimizing moisture entry through the building envelope is to use face sealing (i.e., sealing the outer face of the wall/window junction, interfaces with dissimilar materials, and at building expansion joints). The sealed exterior surface protects against rain and air infiltration and must remain continuous over time to maintain functionality. One example of this type of system is the use of water-resistive coatings over masonry and concrete walls. Great care must be taken when using these coatings to ensure that, when moisture gets into these materials through cracks in the coatings or by other pathways, there is opportunity for it to dry. By nature, face-sealed systems have little or no redundancy to prevent water ingress and accumulation, and they require rigorous maintenance schedules for long-term performance.

Rain screen design has greater redundancy than face-sealed systems. Rain screen design minimizes penetration by raindrop momentum, capillarity, gravity, and air pressure differences. A rain screen wall contains several components from inside to outside: an air barrier, a WRB (which may perform as air, moisture, and vapor barrier), the air space, and a rain screen. The air space may be an empty air cavity or a cavity filled with a material that drains freely. The air space must be vented to the outdoors through the rain screen and flashed to drain water that penetrates the rain screen. The rain screen's airflow resistance must be much lower than that of the air barrier, so that it acts as a deterrent for water penetration but is not a watertight seal. It is prudent to protect the WRB and air barrier from temperature extremes and direct exposure to ultraviolet light. With little pressure difference across the rain screen and with good cavity drainage detailing of the cavity, the potential for rain entry into the wall is significantly reduced. Interfaces of the exterior wall air barrier with fenestration air barriers, floors, and interior partition walls must be carefully considered, and may require site mock-ups to adequately determine the best solution.

For greater liquid water control, the air cavity may be designed as a pressure-moderation chamber, which involves making the WRB airtight. The cavity should also be compartmented to avoid lateral airflow, especially around corners of the building.

Water Vapor Control

Water vapor entry into the building envelope can be limited by airflow control and water vapor barriers. As described previously, air barriers are intended to restrict air leakage and control convective water vapor ingress, whereas vapor barriers are designed to restrict vapor flow caused by diffusion. It is important for building designers to understand the difference between the two mechanisms and how they are controlled.

Moisture deposition caused by air leakage is a point-load problem: a large volume of water can be deposited in a discrete location, often near the air leakage point, and can result in substantial damage. For that reason, an air barrier has to be continuous and sealed. This differs from moisture deposition cause by vapor diffusion, which is an area function that is directly related to the vapor drive and the vapor permeability of the materials that separate the two zones. A vapor barrier should therefore be continuous, but does not necessarily have to be sealed. The only time a vapor barrier is required to be sealed is when it also functions as the air barrier.

Water Vapor Transport Through Air Movement. Air leakage is more effective than diffusion for transporting water vapor in the building envelope, and therefore it is more important to control. To minimize water vapor ingress, the building envelope should be as airtight as possible using the principles described here. Moisture accumulation in the building envelope can also be minimized by controlling the dominant direction of airflow by operating the building at a small negative or positive pressure, depending on climate. In cooling climates, the pressure should be positive to keep out humid outdoor air. In heating climates, the building pressure should remain neutral, or slightly negative or positive relative to the outdoors. Strong negative pressure could risk drawing soil gas or combustion products indoors. Strong positive pressure could risk driving moisture into the envelope.

In wall systems where the air barrier system also functions as the vapor barrier, it is important to consider its location relative to the expected vapor drive and temperature gradient across the wall. To avoid condensation on the air and vapor barrier, either its surface temperature must be kept above the dew point of the surrounding air by locating it on the warm side of the insulation, or the permeance of the assembly must allow vapor transmission if located at the cold side of the insulation. In the latter case, the air barrier no longer functions as a vapor barrier.

Water Vapor Transport Through Diffusion. Moisture migration by diffusion through materials is a slow process and, as discussed previously, is less likely to contribute to moisture problems in buildings compared to liquid water intrusion or air leakage. However, diffusion can cause moisture problems in special occupancy types or in buildings that experience high moisture loads.

The overall diffusion performance of a building is a product of the diffusion characteristics of the envelope materials. A vapor barrier is not necessarily a sheet of plastic; many different materials or combination of materials can be used to control vapor diffusion, depending on design conditions. Many building envelope components, such as some peel-and-stick membranes, metal panels, and glass, have very low vapor permeance. Design and selection of building materials should be based on analysis to verify the desired performance of the assembly under the applicable loads.

Many common building and finish materials with low vapor permeance can have undesirable effects when placed in high-moisture-risk environments. One example is vinyl wallpaper placed at the interior wall surfaces. Under large inward vapor drives or excessive water penetration, this vapor-impermeable layer can lead to moisture accumulation through condensation, or can prevent drying by limiting vapor flows, both of which can lead to significant moisture damage. Careful attention must be paid to the type of materials selected for a wall construction, and where they are located in the wall assembly.

Use of vapor-impermeable layers at both the interior and exterior should generally be avoided so that the assembly can dry. Heat, air, and moisture calculations and modeling can be used to analyze an assembly, its climatic exposure, and desired indoor operating conditions to determine what methods of vapor control are appropriate. For details, see Chapters 25 to 27 of the 2021 *ASHRAE Handbook—Fundamentals*.

Common Envelope Problems

Wall/Window Interface. Air infiltration at the wall/window interface can reduce window performance and damage surrounding building materials and even remote materials, depending on the leakage path. In cold climates, warm, humid indoor air can increase moisture content in the wall cavity around the window. Excess moisture may damage the interior finish, seals of glazing units, insulation, exterior cladding, and possibly structural elements. Uncontrolled cold-air infiltration through the interface in turn can affect occupants' health and comfort by creating a dry indoor environment, cold drafts, and surface condensation on the window frame and glass edges. In warm, humid climates, leakage at the wall/window interface can result in interior fungal growth, distortion of interior window trim, and deterioration of the interior gypsum wallboard, particularly in air-conditioned buildings (because their interior surfaces are colder).

Control of air and water leakage at the wall/window interface is often difficult because that is where multiple systems intersect. Each system may incorporate a different approach for air and water control and must be integrated to provide continuity. Additionally, the different systems are commonly installed by different trades, which require deliberate sequencing to achieve the intended result. These intersections are often complex, making it difficult to inspect and test for performance compliance. Water penetration can result in moisture damage in any climate, although it is generally most severe in climates that impose a low drying potential on a building.

Control of Surface Condensation

To reduce the potential for condensation on the interior surface of glazing and the window frame, as well as on the surrounding interior wall finishes, the indoor surface temperature can be controlled in the following ways:

- Select windows with appropriate condensation resistance for new construction or retrofit.
- Seal the wall/window interface and between the sash and frame of operable windows to minimize air leakage.
- Make the area of window frame exposed to the interior larger than the area exposed to the outdoors. Window and curtain wall systems with metal frame extensions on the inside have a higher resistance to condensation but contribute to heat loss.
- Reduce excessive interior humidity levels.
- Keep thermal breaks in the window system in the same plane as the wall insulation.

Continuity of the plane of thermal insulation between wall and window maximizes a window's thermal potential and reduces the potential for condensation on interior surfaces of the window frame, glass, and surrounding finish. Insulation in the joint between wall and window frame also compensates for the expected differential movement between the frame and the wall rough opening.

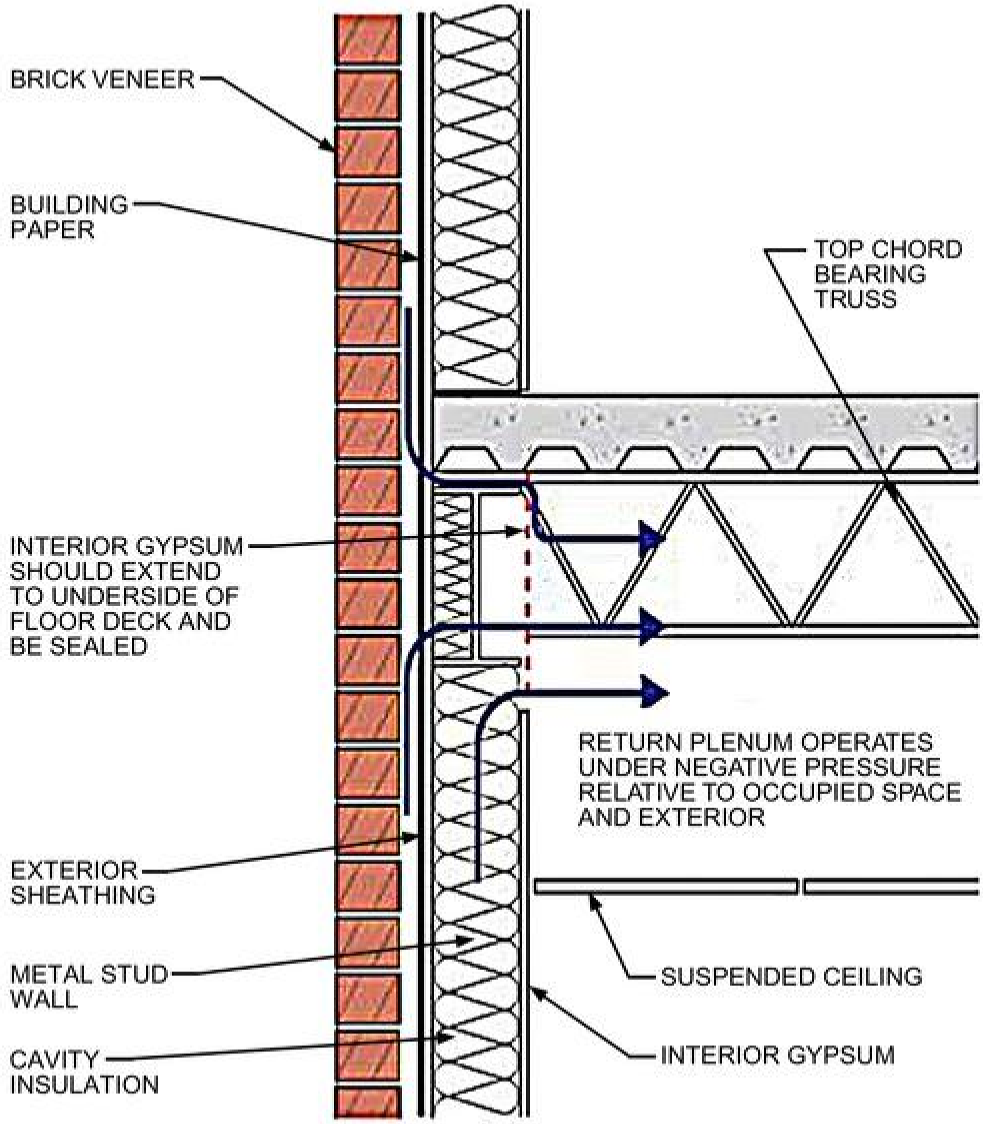
Interzonal Environmental Loads

Indoor partition walls separating zones such as indoor swimming pools, ice rinks, and freezers from zones conditioned as normal environments should be treated as envelope assemblies. Apart from weather-related loads, these partition walls must perform as building envelopes and need to control airflow, heat flow, liquid water (e.g., swimming pools, industrial settings), and water vapor flow.

Interstitial Spaces

Building envelope design must consider that modern buildings comprise a collection of interconnected internal chambers and cavities that provide potential pathways for unplanned airflows throughout the building. Concrete masonry cavity walls, wood- and steel-stud gypsum board partitions, chases, soffits, shafts, utility service penetrations, and many other details contain cavities that connect adjacent elements to varying degrees wherever holes and openings have not been closed and sealed. The amount of air leakage depends on pressure differences, number and size of openings, and length and tortuosity of paths. Pressure differences generally derive from HVAC operation, differences in air density, and wind. These unplanned airflows often have no obvious adverse effects on occupants or the building, but in many cases they can significantly negatively affect energy demand, moisture deposition, and indoor air quality. Uncontrolled air leakage paths also add to the risk of undesirable sound transmission between rooms. A full discussion of all possible sources of unplanned airflows is beyond the scope of this chapter; see the References and Bibliography for additional information sources.

A common practice in commercial buildings is to use the space above a dropped ceiling as the HVAC system's return air plenum (Figure 2). The complex three-dimensional assemblies where the exterior wall adjoins a roof or floor at the building perimeter can be difficult to seal against air leakage and thermal bridging if the unique conditions of each design situation are not deliberately addressed. The interior gypsum board in the occupied space often terminates above the visual sight line of the suspended ceiling without extending to the roof or floor deck above. Unless carefully detailed and constructed, this can result in a leakage point at the building perimeter where negative pressure in the plenum can draw outdoor air into the return air system. If it is cold outdoors, an accidental sensible load penalty is imposed. For hot and humid climates, accidental latent and sensible loads are added that not only affect the energy required to condition the building, but also may lead to moisture and indoor air quality problems from condensation on interior surfaces that are cooler than the dew-point temperature of the incoming outdoor air. Sustained elevated relative humidity in the ceiling space can perpetuate mold growth. In general, but especially for demanding applications such as health-care and laboratory buildings, ducted returns should be used rather than depressurizing the entire ceiling plenum. Air pressure between the ceiling plenum and the occupied space can be equalized by installing ceiling grates in the suspended ceiling. Other configurations that may be more appropriate to the specific building design conditions can also be effective.



Negative-pressure field in the dropped-ceiling return plenum extends to exterior, accidentally coupling the HVAC system to the building enclosure.

Figure 2. Dropped-Ceiling Return Plenum Lstiburek 2007

Similar considerations regarding energy loss and moisture deposition also apply to underfloor air supply systems that can force conditioned air out through the building envelope.

4. QUICK DESIGN GUIDE FOR HIGH-PERFORMANCE BUILDING ENVELOPES

1. Avoid excessive glazing. Follow energy standard and energy code requirements that set maximum glazed areas. Refer to the current version of ASHRAE *Standard* 90.1 for maximum roof and wall glazing areas.
2. Provide appropriate amounts of thermal insulation in foundation and above-grade walls and roofs. See current versions of ASH-RAE *Standards* 90.1 and 90.2.

3. The completed building envelope should be airtight. Determine the level of airtightness to be achieved. Design airtight connections at all junctures in the air barrier system. Construction sequence should allow visual review and ensure performance with the selected criterion.
4. Resolve vapor barrier and vapor control issues using simplified or full hygrothermal analysis (ASHRAE *Standard* 160). The necessity and requirements for vapor control are specific to building usage, materials, and climate, and should be included in the design process.
5. Provide for effective shedding of rainwater away from the exterior wall. Rain screen principles to drain water away from the building should be used where possible.
6. Provide sound insulation appropriate for the building application. Some specialized facilities such as hospitals, libraries, and theaters require additional care to control sound transmission.
7. Refer to the ASHRAE *Advanced Energy Design Guide* series for additional information on building design.

5. ROOFS

Low-Slope Roof Assemblies

Low-slope roofs are typically compact insulated assemblies of a waterproofing membrane together with structural and insulating board material. Insulation is usually rigid board or foam products. The insulation may be below the roofing product(s), or above for an inverted roof membrane assembly (IRMA). If below, it is usually installed in two or more layers with staggered joints to prevent airflow at the panel joint. Tobiasson (2010) showed that venting low-slope roof systems between the insulation and the membrane is not effective for moisture control.

All roofing systems must be designed and constructed to resist wind uplift. Common methods of securing the roofing system to the decking are mechanically fastened, fully adhered, and ballasted. Light-colored roofing products, including ballasted roofs, reduce cooling loads (if kept clean), and help moderate the heat island effects in cities. Proper flashing details are important at drains, scuppers, equipment supports, control joints, and other penetrations. For low-slope roofing design and practice, see the National Roofing Contractors Association's (NRCA) *Roofing Manual* series.

Parapets and overhangs should be detailed for continuity of the thermal insulation and air barrier. Wall insulation should meet the roof insulation, so there is no thermal bridge. Roof and wall air barriers must be continuous. These two continuity requirements may require the parapet or overhang to be specified to be installed after the continuity of the insulation and air barrier is ensured. Some parapet details, such as upper termination of interior drywall, flutes in steel decks, three-dimensional conditions, and fireproofing sequence for steel, are often overlooked. The roof/wall junction requires coordination and proper sequencing between trades to ensure proper continuity of the air and thermal control layers.

Steep-Roof Assemblies

There are two main insulation locations in steep-roof assemblies: at the roof (cathedral) and in the ceiling. For both types, exterior sheathing and roof materials should be able to accommodate wide temperature swings caused by radiant exchange with the sun and sky.

Insulated Sloped-Roof (ISR) Assembly. An insulated sloped roof assembly (e.g., cathedral ceiling) is a compact system with insulation parallel to the roof and no air cavity. Principles used in the design and construction of low-slope roofs may be applied in steep-sloped roof construction. According to Hens and Janssens (1999), moisture control is ensured only if airtightness is effective and can be maintained. Air entry and wind washing in insulated cathedral ceilings lead to degraded thermal and moisture (durability) performance. TenWolde and Carll (1992) showed that ventilation of ISR assemblies may increase air leakage, and that the net moisture effect depends on whether the principal source of makeup air is from indoors or outdoors. Use of vapor-permeable versus low-permeance thermal insulation in ISR assemblies can be an important factor in assembly design and performance. Their selection depends on the expected direction of vapor flow within the roofing system, drying potential, and other design considerations.

Attics. Standard North American attic construction provides for insulation at the ceiling plane level, leaving the attic space as unconditioned. The ceiling should be made airtight (Jordan et al. 1948). Air exchange with the outdoors provided by vents typically reduces attic air temperature on sunny afternoons. Other effects of ventilation, such as wood moisture content and roof surface temperature attenuation, depend more on factors other than the presence or absence of ventilation. TenWolde and Rose (1999) critically review four commonly cited reasons for attic ventilation: (1) preventing moisture damage, (2) enhancing the service life of temperature-sensitive roofing materials, (3) preventing ice dams, and (4) reducing cooling load.

The following additional design and construction elements should be considered for attics and insulated sloped-roof construction:

- Valleys are areas of high water concentration and are common sites of leaks. They should be designed to channel high volumes of water and for ease of repair.
- Mechanical equipment and ductwork should be placed in conditioned spaces. Their placement in unconditioned spaces leads to excess heat loss, energy consumption, and potential condensation on cold ductwork surfaces.
- Ice dams are typically caused by snow melting on the roof. Heat sources in the attic that could cause ice dams (e.g., chimneys, air leakage through the ceiling, attic-mounted equipment) should be identified and addressed.

Vegetated Roofing

There has been significant interest in vegetated roofing in recent years in an attempt to save energy or to control building rainwater outflow. On vegetated roofs, both growth medium and vegetation are installed on top of the roof. These assemblies normally require additional precautions and materials to protect the roof membrane from the plants. Quality control is even more critical during installation of a vegetated roof, because repair and eventual replacement are normally considerably more expensive and resource-intensive because of the presence of growing medium.

Storing rainwater on the roof can reduce the load on a municipality's storm system. There are many methods and products to achieve this. Storage of water and placement of a growing medium can add a considerable amount of mass to a roofing system. Checks to ensure structural capacity are essential for existing buildings, and new buildings must include structural provisions to support the additional weight. Some structural designers include provisions for the weight of a possible future vegetated roofing system because the incremental costs to do so are very small.

Vegetated roofing is often referred to as **green roofing**. Green roofing also refers to roofing systems that have other sustainability attributes such as high albedo.

6. WALLS

Curtain Walls

There has been tremendous growth in the use of curtain-wall systems for new building construction in recent years. A modern curtain-wall system is a highly engineered product based on mass production, standardization, and precise manufacturing (CMHC 2004). The systems generally consist of lightweight metal framing components connected to form a matrix to contain transparent and opaque wall areas. The framing is typically anchored to the building structural columns or floor slabs. Window wall systems are types of curtain walls that are typically installed floor to floor. Many older systems left slab edges exposed. New window wall systems often include drop-down panels that cover and provide thermal protection to the slab edge.

There are two basic kinds of systems: **stick built**, which are assembled on site from horizontal (rails) and vertical members (mullions), and **unitized systems**, which are largely assembled in a shop and delivered in sections that are then connected to form the wall. Both types are generally field glazed. Custom systems are also available for specialized applications. Glazing and opaque elements of the curtain-wall frame are fastened using exterior battens (pressure plates), structural sealant, or both.

Detailed information on the various types of curtain wall systems and glazing methods can be found in Canada Mortgage and Housing Corporation's *Best Practice Guide—Glass and Metal Curtain Walls* (CMHC 2004), or the National Institute of Building Sciences' *Whole Building Design Guide* (NIBS 2010).

Curtain-wall assemblies form the entire exterior wall where installed. They need to perform all the functions of a building envelope, though they have some significant differences from other walls. Curtain-wall assemblies are made of materials that have no moisture storage capabilities, whereas most other wall types (masonry, concrete, etc.) can store and release moisture over time. They nevertheless can retain significant volumes of water that may lead to penetration if watertightness and drainage are not provided.

There are two common methods for a curtain-wall system to manage exterior moisture: face-sealed and rain-screen design. **Face-sealed systems** are more susceptible to water penetration because they have no redundancy. Once water penetrates the exterior moisture barrier, there is no way for it to drain back to the exterior. **Rain screen designs** provide redundancy by draining moisture that bypasses the primary outer seal to the outdoors. This provides more protection from rain penetration than face-sealed systems.

Because curtain-wall systems are highly engineered and assembled out of precisely manufactured components, it is essential that they are assembled in accordance with manufacturers' specifications, with all recommended accessories installed. Omission of any components, such as corner blocks or other drainage elements, can result in reduced drainage capacity, water storage, and eventual penetration to the interior.

Curtain-wall systems can be used to cover floor slab edges to reduce thermal bridging. They bring in lots of natural light and can provide great occupant views. However, heavy use of glass often results in poorer thermal performance than for traditional wall assemblies, or even spandrel sections in a curtain-wall system. The large glazing areas in curtain walls should be considered in terms of solar gain and sizing of mechanical equipment. In cold climates, the large areas of glass and framing can have a radiative cooling effect on a space, and adversely affect thermal comfort.

Conversely, in hot climates, large areas of glass can result in heat gains that can overwhelm cooling equipment, or necessitate cooling equipment in areas where mechanical cooling is not typically required. Often, thermal performance of curtain-wall systems is overstated by reporting center-of-glass or center-of-spandrel-panel thermal performance values, rather than the overall thermal performance (U-value) of the assembly.

Whereas traditional wall assemblies are often built by a number of trades, curtain-wall systems are often constructed by one installer. Connecting the curtain-wall system to surrounding systems, such as roof assemblies or wall, requires coordination of trades. Common problems found in the field include

- Improper or poor connection of curtain wall to roofing system
- Missing corner blocks or drainage elements, resulting in reduced moisture performance
- Missing or blocked vertical drainage channels, resulting in stored water at the glazing head

Sloped glazing is similar to curtain-wall systems, although the importance of using a rain-screen design to prevent water penetration to a building interior is enhanced. Properly flashed head joints and detailed drainage at the base of the sloped glazing are essential for long-term performance.

Precast Concrete Panels

Insulated precast wall (sandwich) panels are often constructed with solid concrete at the perimeter that encloses the insulation (Figure 3A). This concrete has a much greater thermal conductivity than the insulation, resulting in appreciable heat loss through these areas, particularly when added up across an entire building envelope. By changing how panels are assembled (e.g., connecting inner and outer panel sections with plastic tie-rods), a much greater thermal performance is achieved and the excessive perimeter heat loss is eliminated (Figure 3B). These types of panels are more susceptible to water penetration, however, so proper panel joint design and execution are even more critical with these types of panels.

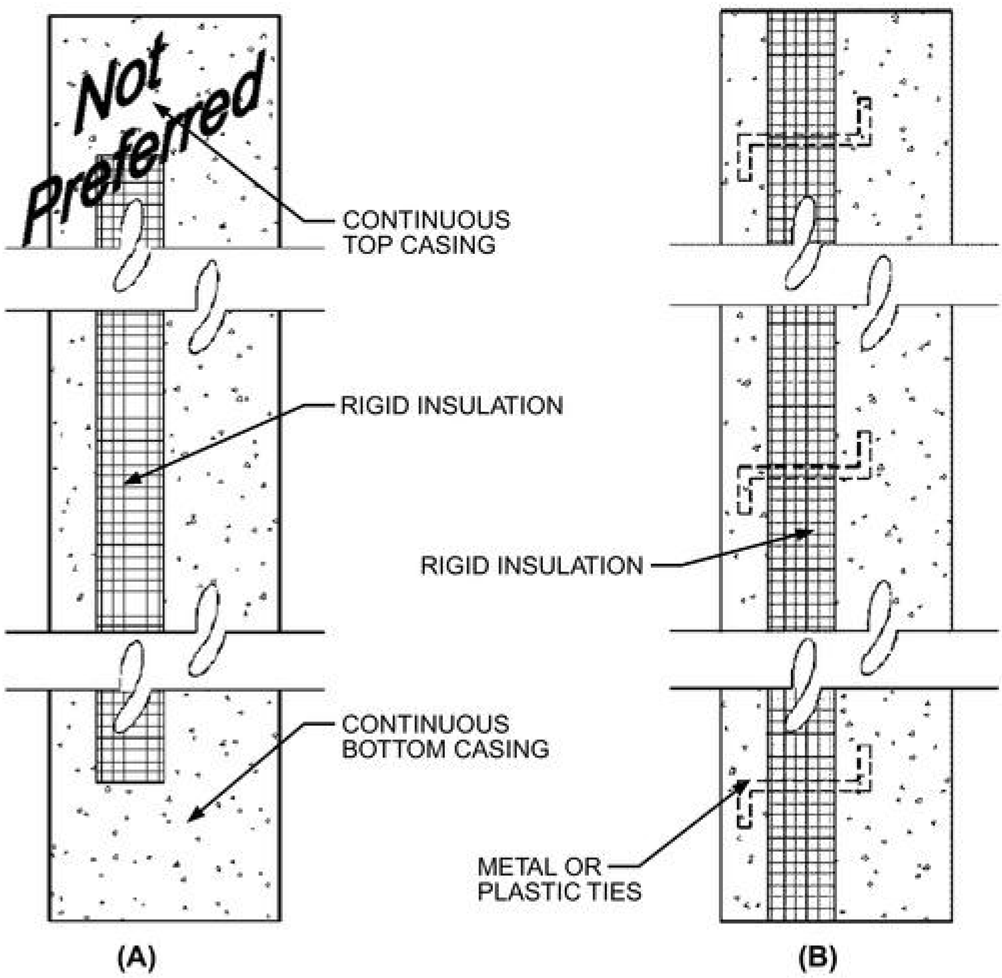


Figure 3. Sandwich Panel with Insulation Encased in Concrete

Precast concrete wall assemblies should be connected using two-stage jointing system. Two-stage joints consist of an inner and outer sealant joint. The exterior joint forms an outdoor weather barrier that keeps most exterior moisture from entering the joint. The inner joint is normally sloped at the bottom of each panel joint to drain water that bypasses the outer joint back to the outdoors, and forms part of the wall's air-barrier assembly. For more information on precast panel joinery, see CMHC (2002).

Steel-Stud Wall Assemblies

Steel-stud wall assemblies are commonly used in multifamily, commercial, and industrial construction. These wall assemblies represent a particular challenge because of the studs' high thermal conductivity. Adding thermal breaks can prevent excessive heat loss and problems associated with condensation in the wall assembly and on interior finishes.

Adding insulated sheathing or insulation outboard of the steel studs significantly reduces heat loss and helps avoid cold surfaces at the interior and in the wall cavity; however, system limitations and manufacturer's instructions should be considered.

Wall Geometry with High Thermal Conductivity

Concrete columns in masonry walls are often left uninsulated. Figure 4 illustrates a wall system with a column at the junction of two exterior brick walls with CMU back-up. The assembly in Figure 4A represents a significant thermal bridge. In Figure 4B, the walls are insulated with polystyrene on metal furring. The amount of heat flow is greatly reduced in this assembly, and no condensation or subsequent mold growth would be expected on interior surfaces of the column under normal operating conditions.

7. FENESTRATION

Conduction/Convection and Radiation Effects

Heat transfer through a window resulting from a temperature differential between the indoors and outdoors (i.e., conduction, convection, and radiation) is a complex and interactive phenomenon. Although glass itself is a poor insulator, technologies can be combined to improve a glazing system's overall thermal performance. Glass also decreases direct transmission of radiant energy from the room or ambient sources. Chapter 15 of the 2021 *ASHRAE Handbook—Fundamentals* discusses fenestration in much greater detail.

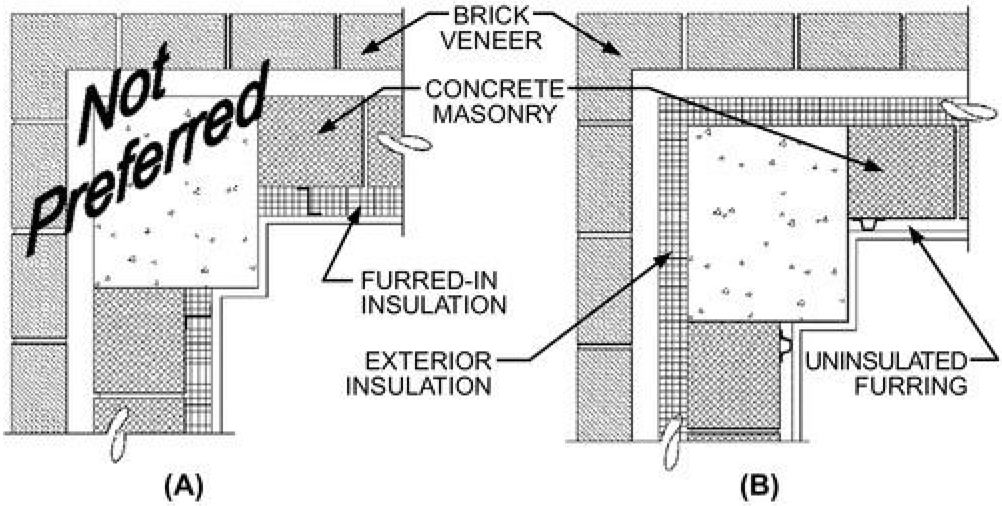


Figure 4. Details of Insulation Around Column in Masonry Wall

Examination of the modes of heat transfer in a double-glazed window indicates that approximately 70% of the heat flow is through radiation from one glazing layer to the other (Arasteh et al. 1985; Selkowitz 1979). Although glass is largely opaque to infrared radiation, energy is still absorbed and reemitted. Low-emittance coatings that are transparent to the eye significantly reduce the amount of radiant heat transfer through a glazing cavity. With that mode of heat transfer minimized, conductive and convective modes dominate. To reduce these effects, inert gases with low conductivity (e.g., argon, krypton) are used in low-emittance-coated, double-glazed windows. Inert-gas-filled triple or quadruple glazing layers with low-emittance coatings can additionally reduce heat transfer, although overall thermal performance normally remains significantly less than a common insulated wall assembly. See Chapter 15 of the 2021 *ASHRAE Handbook—Fundamentals* for design information.

Air Infiltration Effects

Air infiltration at fenestration is influenced by the pressure difference between the indoor and outdoor environments (a function of wind speed, indoor/outdoor temperature differences, and mechanical air balance) as well as window-sealing characteristics (Klems 1983; Weidt and Weidt 1980). The infiltration rate of a fenestration product is a function of its method of operating (if any), weatherstripping material used, and construction quality. See Chapter 16 of the 2021 *ASHRAE Handbook—Fundamentals* for design information.

Solar Gain

Solar gain through windows can play a significant role in a building's energy balance. Glazings transmit, reflect, or absorb a given wavelength of solar radiation, depending on glazing characteristics. Transmitted solar radiation contributes heat to a space. Absorbed solar radiation is reemitted and/or conducted either to the indoors or outdoors (depending on the glazing system configuration). Solar radiation that is reflected away from a building through the use of reflective glass does not contribute heat to a space (Arasteh et al. 1989), but the designer should be aware of the potential for secondary solar gains reflected from an adjacent structure. Clear glass, the most common glazing material, transmits fairly evenly across the solar spectrum. Tinted or heat-absorbing glass absorbs solar radiation and gives the glass a specific color. Some tints exhibit a significant degree of spectral sensitivity (i.e., they do not transmit, absorb, and reflect evenly across the solar spectrum). These types of glazing elements offer great flexibility and can be tailored for specific climates or uses (e.g., provide ample daylighting without overheating an interior space).

Interactions Between Thermal Loss and Solar Gain

In heating-dominated applications, solar gain provides a significant amount of heat. In some cases, heat supplied by the window can offset that lost through the window. The amount depends on characteristics of the site (e.g., how much solar gain is available, how cold the climate is) and the window (e.g., its U-factor and how much incident solar radiation is transmitted).

Typical passive solar applications try to maximize the amount of solar heat gain by installing significant areas of southeast- to southwest-facing glass, which receives the most solar radiation during the winter in the northern hemisphere. However, high-performance windows facing north in a heating-dominated but sunny climate can provide more solar gain to a space than heat loss (Arasteh et al. 1989; Dubrous and Wilson 1992; Sullivan et al. 1992).

Control of Rain Entry

Applying the rain screen principle at the wall/window interface requires the same features as applying it to the wall, including (1) an airflow retarder at the interior, (2) a rain deflector on the outside of the interface, and (3) a drainage path to the outdoors.

The line of airtightness is on the inside of the assembly, so it is protected from water, ultraviolet rays, and extremes of temperature. The rain deflector on the outside acts as a rain deterrent only, not as a watertight/airtight seal. A nonairtight rain deflector does not threaten system weathertightness, because pressure differences across the rain deflector are small. The key is to maintain airtightness on the inside of the joint. With little pressure difference across the rain deflector and with good detailing for outward drainage of the cavity, rain entry in the wall should be minimal. The interface between an exterior wall air barrier and an interior fenestration air barrier must be carefully considered during the design phase, and may require site mock-ups to adequately determine the best solution.

8. FOUNDATIONS

Three common types of below- and at-grade constructions are **basements**, **crawlspaces**, and **slabs**. Many buildings have combinations of these types. Key concerns for these assemblies are heat transfer and moisture management.

Heat Transfer

Heat transfer in below- and at-grade constructions is complex. Factors affecting it include thermal conductivity and wetness of the soil, height and temperature of the water table, amount and profile of insulation, and geometry. For a simplified means of estimating heat transfer in these constructions, see Chapter 18 of the 2021 *ASHRAE Handbook—Fundamentals*.

Measured heat transfer through slabs on grade with 10 different insulation profiles can be found in Bareither et al. 1948. Kusuda and Bean (1987) and Mitalas (1983) provide slab shape factors for steady-state calculations of heat loss. Transient calculations are provided in Hagentoft (1988) and Shipp (1982). An overview is provided in Labs et al. (1988). The following general principles may be applied:

- Heat loss through slabs is concentrated at the slab edge. Insulation is more critical there than in the center of the slab.

- For sections of basements or crawlspaces that are above grade or shallow below grade, insulation on the outside is more effective than insulation at the interior. For deeper parts of a basement, interior insulation is more effective because of the thermal bridge effect of the footing, which is typically uninsulated.
- In crawlspaces and basements, insulation may be applied in the foundation walls or in the floor system above. If insulation is applied in the floor system, the space below may be cold and wet. Some form of moisture protection on the underside of an insulated floor system may be necessary.

Moisture

Below- and at-grade constructions are affected by rainwater surrounding the building and by the below-grade water table. For all construction types, ensure that the soil or other finish outside the building is sloped away from the building. Discharge from scuppers, gutters, and downspouts should be conducted far enough from the building that discharge water cannot saturate soil that is in contact with the below- or at-grade assembly (Rose 2010).

Foundation depth should correspond to the hydrologic conditions of the building site, so that the underground water table is not allowed to encroach on the below-grade space. If it does, then a sump pump must be used to locally lower the water table.

Basements and crawlspaces may encounter some flooding in the course of their service lives. Consequently, basement finishes should be selected so that they can withstand water loading and are readily cleaned afterwards.

Crawlspaces have been known to be sources of moisture to the building since their introduction in the mid-1900s. Britton (1947) found that the use of low-vapor-permeance ground covers with ventilation resulted in drier conditions. This recommendation for ventilation was picked up by many codes and guidelines. Venting crawlspaces, however, creates an unconditioned space beneath the building, which may lead to energy penalties and high relative humidity during warm weather. It is therefore recommended that crawlspaces should be treated like basements with insulated perimeter walls, insulated bottom floors, and protection from moisture ingress. The crawlspace should be accessible, well illuminated, and clean.

In cold climates, building foundations should resist frost heave. This is commonly done by ensuring footings are below frost depth. The frost-protected shallow foundation uses below-grade insulation outboard of the foundation to ensure nonfreezing conditions at the slab edge. Attachment frost heaving may occur (Labs et al. 1988); it is prevented by avoiding puddles of water in contact with the foundation during freezing weather by draining water away from the building, as described previously.

9. EXISTING AND HISTORIC BUILDINGS

In recent years, there has been a noticeable shift in emphasis from new construction to work on existing buildings. There can be tremendous advantages in materials use, embodied energy, carbon dioxide emissions, and other environmental issues to renovating existing buildings rather than replacing them with new structures, or adding new structures. In the United States, work on buildings of historic significance is addressed by the Secretary of the Interior’s Standards for the Treatment of Historic Properties (1977). For more information, see Park (2009).

Determining what materials were used in the original construction and their actual properties can be a challenge. Many materials are hidden within the structure and require some disassembly to determine underlying structure and components. Necessary investigative work may range from review of accurate as-built drawings, to field testing, disassembly, and historical research. Depending on the age of the building, multiple renovations may have created many different assemblies in the building, so a review of available plans and permits issued for the building helps avoid unknown conditions during construction. Properties of older materials can be markedly different from their modern equivalents, so research may be necessary: in some cases, actual testing of the materials may be the only way to discover how the materials will react. Chemical compatibility between reused and newer materials may be a concern. For instance, new materials for roofing, waterproofing, and sealant or barrier systems may not be compatible with materials used in the past.

Existing buildings provide the benefit of having a performance history. This can be helpful in understanding the reality of energy consumption as well as moisture storage, air leakage, and water vapor movement through materials and assemblies. The building history can be used to identify defects or weak points in the assembly or interactions between the HVAC system and envelope. The building operates in an equilibrium that depends on indoor and outdoor conditions and building material properties. Changes to operating conditions or materials can affect everything and alter this equilibrium.

A review of changes such as HVAC upgrades or building envelope improvements should be incorporated into the design. Some sustainable practices are rapidly evolving, and applicable codes and guidelines are still developing. As a result, there can be challenges to following the letter of the code on renovation projects without fully understanding the physical phenomena behind envelope performance and interactions with HVAC system effects. This can result in problems ranging from water leakage to advanced degradation of wall components. Sometimes, novel approaches must be sought that allow compliance with the intent of the code while optimizing the durability and performance of existing materials/assemblies.

An additional concern for existing buildings involves a common practice of owners: some large-scale renovation projects are phased over a period of time. If an overall plan is not developed that includes understanding of the interdependence between the building envelope and HVAC systems, then problems and/or extra expense are very likely to occur over the multiple years that it takes to complete the entire renovation plan. The order in which changes are done (e.g., envelope first versus HVAC system first) could also greatly affect overall costs as well as the end result. For example, in hot, humid climates, if the HVAC system is replaced before an envelope-tightening project, extra capacity may have to be installed to meet the interim needs. This extra capacity could cause problems with overcooling and high relative humidity after the envelope tightening occurs.

Successful renovation projects begin with documenting existing conditions and careful analysis of the effects of potential changes. New materials and systems are selected based on compatibility with existing materials and systems as well as durability and long-term performance characteristics.

Building Materials

Specific issues to be considered for material changes and selections include addition of new materials, removal of old materials, and replacement of existing materials with a modern equivalent; a full understanding of the purpose of specific layers and materials in the original design is also required. An example involves the use of stone or brick masonry. In older buildings, solid stone or brick masonry walls were designed to perform as barrier systems by absorbing and gradually releasing moisture. These materials relied on heat flow to keep them dry and prevent freeze/thaw damage in cold climates.

Reuse of wall systems during energy retrofits poses particular challenges in cold climates. Adding exterior insulation has the benefit of providing continuous insulation and moisture control while insulating structural elements from thermal and moisture extremes, but it may conflict with preservation aesthetics as well as zoning requirements. Adding interior insulation increases thermal stresses while reducing the drying potential of the exterior facade, and may lead to increased freeze/thaw cycling in cold climates. It is also difficult to achieve continuous thermal insulation and air barrier around existing interior wall elements. Unavoidable discontinuities create thermal bridges that could become condensation sites. Floors supported by exterior masonry are one example. See Chapter 27 of the 2021 *ASHRAE Handbook—Fundamentals* for examples of calculating thermal resistance values for complex wall assemblies.

Hygrothermal analysis and understanding of the potential consequences of measures planned on the durability of facades and structural elements must be part of the renovation design process, because this may impose limits on the insulation strategy. Guidance for performing hygrothermal analysis can be found in ASHRAE *Standard* 160.

Changing HVAC Equipment and/or Control Strategy

When upgrading or replacing existing mechanical systems, the effect of the new HVAC system on the building envelope must be considered. This is particularly important with the addition of humidification. In cold, and even some mild, climates, humidifying a previously nonhumidified space may lead to damaging moisture accumulation in walls and roofs unless the building envelope can withstand the loads. For a typical nonhumidified building, the interior relative humidity is normally lowest when the exterior temperature is also at a minimum. This is beneficial to the building, because condensation risk on the interior is moderated during the coldest period of the year. Adding humidification (by mechanical means or occupant activities) reduces this benefit, and in cold climates may result in surface condensation and/or mold growth for several months out of the year. Durability often is negatively impacted when humidification is added to an existing building unless changes are also made to the envelope to resist condensation.

The building envelope requires more attention than just estimating its properties to calculate heating and cooling loads for new equipment. In older buildings with little to no insulation, successful HVAC system design needs to counteract the large envelope losses and solar gains; otherwise, occupant comfort can suffer. This can be particularly noticeable adjacent to windows with single-pane glazing or thermally inefficient walls where additional heating or cooling maybe required to compensate for excessive heat loss. Localized use of space heaters or fans in an existing building indicates deficiencies in the previous HVAC system. HVAC system design may have to include perimeter heaters, specialized VAV distribution, or localized heating to prevent low temperatures or moisture accumulation in concealed spaces. Additionally, information on existing drawings used to determine thermal performance properties for equipment sizing calculations may not reflect changes already made to the building envelope. Important changes that can affect performance can include window replacements or reflective coatings, adding insulation during reroofing or interior renovation projects, etc. Changing the pressure distribution in building zones or across the exterior envelope also significantly affects the building envelope’s moisture performance.

Envelope Modifications Without Mechanical System Upgrades

Building envelope systems are often upgraded without corresponding upgrades to mechanical systems. Failure to modify the existing mechanical system to account for changes in the dynamic performance of the building envelope can result in problems such as excess humidity or lack of interior environmental control. Retrofitting a building for improved thermal insulation or solar control at glazing systems can effectively reduce cooling loads. If the mechanical systems are not modified accordingly, they become oversized for the renovated conditions. This can result in numerous problems, such as poor interior temperature and relative humidity control, or more subtle issues such as inefficient operation. Retaining an older mechanical system may also prevent the full energy savings of an enclosure upgrade from being realized.

Improved airtightness should be a criterion of any building envelope retrofit project. For buildings in cold climates that previously relied on incidental air leakage to provide ventilation, reducing leakage rates may result in high interior air moisture levels. In the previously leaky building, incidental leakage was sufficient to dilute interior moisture with dry outdoor air and maintain reasonable humidity levels. These buildings should use a ventilation system using appropriate energy recovery techniques to maintain adequate fresh air.

Designers should assess the relationship between the building envelope and mechanical system, and design appropriate modifications. Design considerations for converting existing buildings to high-performance buildings include the following:

- Investigate existing building envelope conditions, taking care to note sites of damage and repair that may affect performance. In many cases, it may be beneficial to gather information on the building's historical performance, including utility bills and past occupancy types.
- Provide documentation of existing conditions in the building, building envelope, and mechanical systems. For historic buildings, complete a historic structures report.
- Identify major air and/or water leakage sites, and provide remedial measures to correct flow through these sites. If appropriate, adopt a strategy to reach an airtightness performance target.
- Consider improving thermal performance. Exterior insulation is often preferred over interior or cavity insulation, because cavity or interior insulation typically allows structural and other members to act as thermal bridges. Local preservation requirements may govern the location of insulation.
- Review possible changes to envelope operating characteristics that result from adding thermal insulation or changing HVAC operation. A change in the moisture and/or heat flow function of the envelope can have a significant effect on durability.
- With improved envelope performance, consider downsized mechanical equipment.

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