This short document introduces the technical aspects of building enclosures, with a focus on high-performance walls. The functions required of all building enclosures, commercial and residential, are presented followed by concise descriptions of control functions.

**Introduction**

The building enclosure is defined as the physical component of a building that separates the interior from the exterior: it is an environmental separator. In practise the building enclosure must provide the “skin” to the building, i.e., not just separation but also the visible façade. Unlike the superstructure or the service systems of buildings, the enclosure is always seen and is therefore of critical importance to owners, the occupants, and the public. The appearance and operation of the enclosure have a major influence on the interior environment and on factors such as comfort, energy efficiency, durability, and occupant productivity and satisfaction.

To design a functional enclosure, the designer must understand what the environmental conditions on either side of the enclosure are. Climate, a measure of long-term weather, and extreme weather events (hurricanes, extreme cold days, etc.) can be quantified and classified. Two maps are provided below (Figure 1) for combined temperature and humidity and annual rainfall.
Enclosure Functions

In general the physical function of separation required of the building enclosure may be further grouped into three sub-categories as follows:

1. **Support** functions, i.e., to support, resist, transfer and otherwise accommodate all the structural forms of loading imposed by the interior and exterior environments, by the enclosure, and by the building itself. The enclosure or portions of it can be an integral part of the building superstructure, usually by design but sometimes not.

2. **Control** functions, i.e., to control, block, regulate and/or moderate all the loadings due to the separation of the interior and exterior environments. This largely means the flow of mass (air, moisture, etc.) and energy (heat, sound, fire, light, etc.).

3. **Finish** functions, i.e., to finish the surfaces at the interface of the enclosure with the interior and exterior environments. Each of the two interfaces must meet the relevant visual, aesthetic, wear and tear and other performance requirements.

A fourth building-related category of functions can also be imposed on the enclosure, namely:

4. **Distribution** functions, i.e., to distribute services or utilities such as power, communication, water in its various forms, gas, and conditioned air, to, from, and within the enclosure itself.
Almost all enclosures must satisfy support, control, finish and distribution functions. However, only the support and control functions must be provided over the entire surface of the enclosure: control and support functions must continue across every penetration, every interface, and every assembly. The lack of this required continuity is the cause of the vast majority of enclosure performance problems. The need for finish and distribution varies over the extent of the enclosure. It is rather unlikely to find an enclosure that requires a finish on the interior and exterior everywhere. It is even more unlikely to find a building that imposes the distribution function on the enclosure over its entire surface.

The support function is of primary importance. Without structural integrity, the remaining functions are useless. However, the industry has reached a high level of understanding and accomplishment in this area. Support systems have evolved from massive elements pierced at a few locations to efficient primary structural systems (such as steel or concrete frames) with lightweight framed infill and sheathing. The trend to lightweight enclosures is likely to continue as the demand for more resource-efficient buildings grows.

For physical performance, the most common required enclosure control functions include

- rain,
- air,
- heat,
- vapour,
- fire & smoke,
- sound,
- light (including view, solar heat, and daylight),
- insects,
- particulates, and
- access.

But there are many more. Like support, these control functions are required everywhere for acceptable or good performance and hence continuity of these control functions, especially at penetrations and connections, is critical to a successful enclosure. The most important control function with respect to durability is rain control followed by airflow control, thermal control, and vapour control. The level of fire and sound control required varies with code requirements and the owner’s desires.
Unlike the control and support functions, which rely on continuity to achieve performance, the **finish function** is optional, and may not be needed in some areas. For example, above suspended ceilings or in service or industrial spaces where the finish is often deemed unimportant. Exterior finish is often termed “cladding”, but the term is imprecise, since cladding systems and materials often includes some control functions (such as UV control, solar control, impact resistance, etc.) while also delivering the finish function.

The **service distribution function**, a *building* function often imposed on the enclosure, largely services the adjacent interior spaces and only needs to be met where there is a service or utility to be distributed – large proportions of most enclosures do not need to fulfill this building function. The distribution function of the building however usually impacts the control-related functions. For example, service entrances penetrate the entire enclosure, and pipes, ducts and wires that run through insulated stud spaces can seriously reduce the performance of insulation installed here.

Confusion about the classification of the functional roles of enclosure components and materials is far too common, and this confusion can cause serious performance and durability problems. For example,

- vinyl wallpaper is often applied as a finish, but in fact fulfills the control-related function of vapour diffusion control and acts as a low-permeance Class I vapour control layer. This unintentional control of diffusion can, and too often does, create serious mould problems in air-conditioned buildings.

- drywall is often seen as fulfilling a finish function, but in fact, the paint is more often the finish and the drywall often serves as a control layer for fire, sound, and air flow. If a designer or builder stops the drywall above a suspended ceiling because a finish function is not needed here, the required fire, sound, and airflow control will also be missing.

- a thick, self-adhered, bituminous membrane is often used to drain water and control airflow in high-performance assemblies. However, this membrane is also a very low permeance vapour control layer, and locating it on the outside of all or most of the insulation in a cold climate can lead to damaging cold weather condensation.

From a more practical point of view it is useful to divide the functions of the enclosure into various sub-categories to which we can assign actual products and
sub-system assemblies. With respect to the control function, these are termed control layers.

The most important and commonly defined enclosure control function layers are, in approximate order of importance:

1. water/rain control layer (e.g., drainage plane & gap or waterproofing),
2. airflow control layer (e.g., an air barrier system),
3. thermal control layer (e.g., insulation, radiant barriers, etc.), and
4. vapour control layer (e.g., vapour retarder or vapour barrier as required).

Each control “layer” may be a single material, or a sub-assembly of materials that together provide the control desired. In many cases, two or more of the control functions are provided by a single material or layer (e.g., a membrane may provide water and air control, or spray foam insulation may provide vapor, air, and thermal control).

The “Perfect” Enclosure

Figure 2 shows an idealized enclosure with the four control layers labelled, along with cladding, support and interior finish function layers.

![Figure 2: Idealized enclosure showing the four primary control layers](image-url)
The water, air and vapor control layers are shown as thin lines to indicate that they can, in reality, be quite thin (e.g. less than 1/16” or 1 mm) and still perform their functions very well. Some materials, such as precast concrete, can be used as a water, air and vapour control layer only if they are thicker, e.g., 4” or 100 mm.

The support and the thermal control layer are shown as thicker components, because in practice these layers need to be thicker (e.g., well over 1” or 25 mm) to perform their function. Depending on the span and to a lesser extent the magnitude of the loads (snow, wind, dead, etc.), the support structure will usually be in the range of 3” to 8” (75 to 200 mm) for walls with a span height of 8’ to 20’ (2.4 to 6 m). Depending on its material properties, the climate, and building design, the thermal control layer will usually be 2” to 10” thick (50-250 mm).

Figure 3 depicts the special, but common and practical, case of an assembly that collapses the water, air, and vapor control layers into a single physical material (typically a polymer such as a plastic or bituminous membrane), and provides an optional service distribution space and interior finish.

![Figure 3: Idealized enclosure with service distribution and finishes](image)

**Rain Control**

Rain control is the most important practical control function to provide. There is little acceptance or forgiveness for failure.

There are three recognized design strategies to control rain penetration within and through the enclosure (Straube & Burnett 1999, CMHC 1999):
1. Drained/Screen
2. Mass/Storage
3. Perfect Barrier

The categorization described is independent of materials or design intent and is based solely on the method by which a wall system controls rain penetration.

Historically, the best performance for water penetration control has been from drained/screen assemblies. Some examples of drained wall systems include cavity walls, brick and stone veneer, vinyl siding, metal panels, two-stage joints, and drained EIFS. Screened/drained walls assume some rainwater will penetrate the outer surface (hence the cladding “screens” rain) and remove this water by designing an assembly that provides drainage within the wall.

All drained (aka “rainscreen”) systems must have five components:

1. a rainscreen or cladding (one that leaks rain)
2. a drainage gap (often a clear air space),
3. a drainage plane (water control later, a water repellent plane, WRB.),
4. flashing at the base to direct water outwards (waterproof), and
5. drain holes (weep holes) to allow water out of the drainage gap.

Figure 4: Examples of Drained/Screen Assemblies
Figure 5: Examples of Mass/Storage Wall Assemblies

Mass walls require the use of an assembly of materials with enough safe storage capacity and moisture tolerance to absorb all rainwater that is not drained or otherwise removed from the outer surface. The infiltration occurs through micro cracks and pores in the assembly and is driven predominantly from gravity and capillary forces. Wind is generally not as much of a factor due to the size of the cracks and the relative magnitude of the capillary forces. In a functional mass or storage wall, evaporative drying and diffusion eventually removes moisture before it reaches the inner surface of the wall.

Figure 6: Examples of Perfect Barrier Assemblies
Perfect barriers, the third type of rain control strategy, stop all water penetration at a single plane. Such perfect control required the advent of modern materials. Some examples of perfect barrier walls are some window frames, and some metal and glass curtain wall systems. Because it is difficult to build and maintain a perfect barrier wall, most walls are designed as, or perform as, imperfect barrier wall systems of either the mass type or the screened type. However, some systems, usually factory built, provide wall elements that are practical perfect barriers, and while the panels themselves can be considered perfect barriers, the joints are often susceptible to infiltration.

The joints between perfect barrier elements may be also designed as perfect barriers (e.g. a single line of caulking). Such joints have a poor record of performance and should not be used to control rain entry. Alternately, for large panels, such as precast panels and window-wall joints it becomes practical to design the joints drained systems.

![Diagram of Mass Joint, Perfect Barrier Joint, Drained Joint]  
*Figure 7: Examples of Perfect Barrier Assemblies*

The most important joint is often the joint between windows, doors, curtainwalls and the wall in which they are installed. This joint should be designed as a two-stage drained joint with flashing at the bottom to collect and reject water outward.
Masonry Veneer, Metal Panel, and EIFS Claddings

Masonry veneer, metal panels and drained EIFS systems are very commonly used drained assemblies that have demonstrated reliable performance for managing rain water. However, since the assemblies are made up of multiple layers and are site constructed, certain elements can affect the performance of the assemblies.

It has long been known that water is able to penetrate through masonry veneers due to a combination of gravity-driven water leakage and capillary forces. The water control layer in a drained system is called the drainage plane or water resistive barrier (WRB). It is the last layer available to resist further water penetration into the assembly and is intended to exclude all the water to which it is exposed. The WRB is most commonly made of engineered building wraps, asphalt impregnated building paper, fluid or sheet-applied membranes, or water-resistive sheathing with taped or sealed joints. The water resistive barrier needs to be installed with no discontinuities and/or all seams, joints, and penetrations shingle lapped to drain liquid water out and away from the assembly.

A significant amount of forgiveness is built into the system due to the air space between the brick and the back up wall construction. This air space acts a capillary break and drainage gap. Most of the rainwater that penetrates through the cladding drains down the backside of the cladding and out at the weep hole locations so the actual moisture load on the WRB is minimal in most cases.
**Air Flow Control**

Air movement through an enclosure assembly is driven by air pressure differences between the interior and the exterior. These air pressure differences are caused by a combination of wind, stack effect (natural buoyancy of air), and mechanical pressurization. The combined effect of these forces can be quite significant and lead to a large volume of air movement. To control air movement through the assembly, a continuous barrier to air movement is required (the air control layer). The location of the air barrier in the assembly is not strictly important (this is not the case for convective loops discussed later). The air barrier can be on the interior, exterior, at a location in the middle, or made up of an entire composite assembly. In order for the air barrier to be effective it must be continuous in the field of the wall as well as at the connections to other components (such as at foundation, roof, and windows and doors). The last 30 years of practical field experience with air barrier performance has resulted in two outcomes, difficult to prove in the lab, but repeatedly demonstrated in the field: air barriers installed to the exterior of the primary support structure and interior partitions are far easier to build reliably air tight, and fully-adhered or clamped (e.g. not loose) membranes are superior to loose-applied membranes. All types of systems can work, but those two lessons result in either higher performance, lower risk of failure, or lower cost for the same performance relative to other approaches.

![Diagram](image)

**Figure 9:** Air barriers on the exterior of the primary framing are preferred for practical reasons, especially in light-framed wall systems.

The air barrier can be a single material or a layer of materials acting together as a composite to resist the imposed air pressure loads without rupturing. Materials, such as sheet polyethylene or taped foil- or kraft-paper facings, which historically were introduced as vapor barriers, have demonstrated poor performance as an air barrier (due to their inability to resist air pressure loads). Masonry materials (such
as masonry block) do not function as air barriers because they are too air porous, but thick elastomeric paints can render masonry airtight and precast concrete is dense and exceptionally airtight. Materials such as fluid-applied or sheet membranes fully-adhered to a solid substrate (exterior gypsum, masonry, concrete) have demonstrated high levels of performance in practice (due to the structural nature of the combined membrane and solid substrate).

It is critical that the air barrier be continuous from one assembly to another (roof to wall, wall to foundation, and window/door to wall). If the air barrier is not continuous, then leakage of air will occur. The path of air movement will depend on the design of the assemblies and the location of the discontinuity. Condensation within the assembly will occur if moisture-laden air moving through the assembly comes into contact with a cold surface (surface temperature below the dew point temperature of the air). There must be air movement (overall air tightness) and cold surfaces along the path of flow for interstitial condensation problems to occur.

Figure 10: A mechanically –attached membrane air-water barrier held tightly to the wall with furring strips provides good performance. Nails or screws through the furring are self-sealing, unlike nails and screws driven through the thin membrane.
Thermal Control

A continuous and effective thermal control layer is required to provide good thermal comfort, reduce the risk of condensation, and reduce operating energy consumption.

All materials and layers in a building assembly have some resistance to heat flow. However, materials with an R-value of about 2/inch or more (k-value less than 0.07 W/m∙K) are deliberately used in building assemblies for their ability to retard the flow of heat. These building products are called thermal insulations. Three material categories, polymeric foams, mineral fibre (i.e., glass, slag, or rockwool), and organic fiber (e.g., cellulose, cotton, polyester, etc.), are used to produce almost all common building insulation products (Table 1). Insulations are usually solid materials, but radiant barriers that control only radiation heat transfer across air spaces are also sometimes used, especially in glazing systems (the low-e coatings that commonplace).

Insulation products can be produced in at least five common physical forms: loose, batt, roll, board, and spray (Table 2). Each form has advantages and disadvantages, and some materials can be purchased in all five forms, and some only in one.

<table>
<thead>
<tr>
<th>Material Category</th>
<th>Examples</th>
<th>Moisture</th>
<th>Fire</th>
<th>Vapor Permeance</th>
<th>Air Permeance</th>
</tr>
</thead>
<tbody>
<tr>
<td>Mineral fiber</td>
<td>Fiberglass, stone, slag</td>
<td>Tolerant</td>
<td>Non-combustible</td>
<td>high</td>
<td>high</td>
</tr>
<tr>
<td>Organic Fiber</td>
<td>Cellulose, cotton, wool, straw</td>
<td>Sensitive</td>
<td>Combustible</td>
<td>high</td>
<td>high</td>
</tr>
<tr>
<td>Plastic foam</td>
<td>Polystyrene, polyurethane, polyisocyanurate</td>
<td>Tolerant</td>
<td>Combustible</td>
<td>Low-medium</td>
<td>low</td>
</tr>
<tr>
<td>Mineral foam</td>
<td>Foamglass, pumice, airkrete, aerogel</td>
<td>Tolerant</td>
<td>Non-combustible</td>
<td>low</td>
<td>low</td>
</tr>
</tbody>
</table>

Table 1: Four material categories, with a range of physical attributes, describe most insulation products used in buildings

High performance building enclosures generally require continuous thermal control layers on the exterior of the structure to ensure continuity. This layer can be board or spray foam as well as semi-rigid fiberglass or rockwool insulation. If organic-fiber products are used, they can only be used inside of the enclosure assembly’s water control layer or they will be damaged in-service.

Locating all insulation as a continuous layer on the exterior of the structure effectively eliminates low-cost fibrous batt and loose-fill insulations from a designer’s palette. Such low-density fibrous insulations are still important to fill
interior voids and can supplement (never replace) the exterior insulation layer, especially for wood-framed assemblies. To ensure all spaces and voids in framing cavities are filled properly (to control convective loops), spray or blown insulation is preferred when cavity fills are appropriate. Whenever air and vapour-permeable insulation is added to a cavity, extra care is required in the location and selection of the vapour control layer and the location of the air control layer.

Cellular foam plastics are often used when air impermeable and/or moisture tolerant materials are required. They are the most common type of semi-rigid insulation. Products such as expanded polystyrene (EPS), extruded polystyrene (XPS), and faced polyisocyanurate (“polyiso” or PIR) have long been used behind claddings and outboard of the water control layer. Polyiso should not be used in applications where it can be immersed in water for long periods of time: this is not a concern for above-grade walls, but does limit its use below grade. Extruded polystyrene is the material that has the highest resistance to water, and should be used when repeated or extended water immersion and/or long-term high vapour pressure drives are expected in service.

<table>
<thead>
<tr>
<th>Form</th>
<th>Installation</th>
<th>Limits to use</th>
</tr>
</thead>
<tbody>
<tr>
<td>Loose</td>
<td>poured or blown</td>
<td>may settle, easily compressed</td>
</tr>
<tr>
<td>Batt</td>
<td>friction fit</td>
<td>held in place by friction, easily compressed</td>
</tr>
<tr>
<td>Roll</td>
<td>friction fit / mechanically attached</td>
<td>as for batts</td>
</tr>
<tr>
<td>Board</td>
<td>mechanically, adhesively attached</td>
<td>resistant to mechanical pressure</td>
</tr>
<tr>
<td>Spray</td>
<td>spray in place</td>
<td>sticks to adjoining surfaces, resilient</td>
</tr>
</tbody>
</table>

Table 2: Insulations of can take on a wide range of forms, which may limit how they are used.

Expanded polystyrene (EPS, sometimes called “bead board”) is very similar to extruded polystyrene (XPS) especially at higher densities, although it has a lower thermal resistance, and absorbs more water. Widely used outside the water control layer in above-grade wall assemblies, it can also be used very effectively below grade and has long been accepted in the Canadian building code for this use. Experience has shown than it cannot be used in protected membrane roofs (i.e., above a low slope roof membrane) without absorbing too much water.

Medium-density closed-cell spray polyurethane (ccSPF) is an increasingly common product that is spray-applied to appropriate substrates. It has even been used under slabs by spraying it directly to the earth. This product can act as part of the rain, air, vapour, and heat flow control layers of an assembly if care is taken to maintain
continuity at transitions and the potential cracks due to movement (during service) or cooling shrinkage (during initial curing).

Insulation products are often selected not just on the basis of their fire and moisture resistance, but also because they may assist, or take the primary role, in controlling air and vapour flow.

Most rigid foam board products, especially those with facers (e.g. the aluminum facer on polyiso intended for walls, faced EPS board), can act as part of the water and/or vapour, and/or air flow control so long as other requirements, such as structural support, durability, and continuity at joints, are met.
<table>
<thead>
<tr>
<th>Material</th>
<th>Form</th>
<th>Uses</th>
<th>Vapor Permeance</th>
<th>Air Permeance</th>
</tr>
</thead>
<tbody>
<tr>
<td>Fiberglass</td>
<td>loose</td>
<td>packed into spaces, laid on ceilings</td>
<td>high</td>
<td>high</td>
</tr>
<tr>
<td></td>
<td>batt</td>
<td>friction fit between closely spaced framing, laid on ceilings</td>
<td>high</td>
<td>high</td>
</tr>
<tr>
<td></td>
<td>spray</td>
<td>partially filling irregularly shaped volumes</td>
<td>high</td>
<td>high</td>
</tr>
<tr>
<td></td>
<td>semi-rigid board</td>
<td>duct insulation</td>
<td>high</td>
<td>high</td>
</tr>
<tr>
<td>Stonewool</td>
<td>loose</td>
<td></td>
<td>high</td>
<td>high</td>
</tr>
<tr>
<td></td>
<td>batts</td>
<td>as for FG</td>
<td>high</td>
<td>high</td>
</tr>
<tr>
<td></td>
<td>spray</td>
<td>partially filling irregularly shaped volumes</td>
<td>high</td>
<td>high</td>
</tr>
<tr>
<td></td>
<td>semi-rigid board</td>
<td>cavity insulation, covering interior surface, roofs</td>
<td>high</td>
<td>high</td>
</tr>
<tr>
<td>Polyisocyanurate (PIC)</td>
<td>board,foil-faced</td>
<td>sheathing, covers surfaces, cavity walls, inside roofs, on top of roof</td>
<td>low</td>
<td>low</td>
</tr>
<tr>
<td></td>
<td>glass or paper-faced</td>
<td></td>
<td>med</td>
<td>low</td>
</tr>
<tr>
<td>Extruded Polystyrene (XPS)</td>
<td>board</td>
<td>sheathing, covers surfaces, cavity walls, inside roofs, on top of roof, underslab, wet zones</td>
<td>low-med</td>
<td>low</td>
</tr>
<tr>
<td></td>
<td>faced</td>
<td></td>
<td>low</td>
<td>low</td>
</tr>
<tr>
<td>Expanded Polystyrene (EPS)</td>
<td>board</td>
<td>sheathing, covers surfaces, cavity walls, inside roofs, on top of roof</td>
<td>med</td>
<td>low</td>
</tr>
<tr>
<td></td>
<td>faced</td>
<td></td>
<td>low</td>
<td>low</td>
</tr>
<tr>
<td>Cellulose</td>
<td>loose</td>
<td>packed into spaces, laid on ceilings</td>
<td>high</td>
<td>high</td>
</tr>
<tr>
<td></td>
<td>spray or packed</td>
<td>partially filling irregularly shaped volumes</td>
<td>high</td>
<td>med</td>
</tr>
<tr>
<td>Fiberboard</td>
<td>board</td>
<td>dry sheathing roofing floors</td>
<td>high</td>
<td>med</td>
</tr>
<tr>
<td>Straw</td>
<td>bales</td>
<td>self-supporting when dense, and supports cladding</td>
<td>high</td>
<td>med</td>
</tr>
<tr>
<td>open-cell spray polyurethane (ocSPF)</td>
<td>spray</td>
<td>partially filling irregularly shaped volumes, adhered to underside poured onto ceilings</td>
<td>high</td>
<td>low</td>
</tr>
<tr>
<td>closed-cell spray polyurethane (ccSPF)</td>
<td>spray</td>
<td>As ocSPF, but more water resistant</td>
<td>med</td>
<td>low</td>
</tr>
</tbody>
</table>

Table 3: Different Insulation Products, Their Uses, and Air-Vapor Permeance Properties
Figure 11: Extruded Polystyrene (XPS) insulated used as continuous insulated sheathing for a house. Note the red tape used to create a continuous water-air control layer

Semi-rigid fibrous insulation boards can only act as heat flow control layers, although they can provide a drainage path (i.e., they provide a drainage gap in the large air voids between fibers) for rain water, either by design or in actuality\(^1\). In many applications, air- and vapour-permeable mineral-fibre semi-rigid insulations (MFI), such as fiberglass and rockwool can be used as exterior continuous insulation and have a very long track record of good performance. To perform in unsupported applications, fiberglass products generally require a minimum density in the range of 2.5-4 pounds per cubic foot (40-70 kg/m\(^3\)), whereas rockwool should have a density of over about 3 pcf (50 kg/m\(^3\)). Such MFI products tend to be less expensive, and are always more fire resistant, than foamed plastics.

\(^1\) Semi-rigid mineral fiber insulation (MFI), particularly rockwool, provides a drainage path in the fibers of the outer 1/8” – ¼” (3-6 mm) without materially affecting its thermal resistance. MFI have been used in drained masonry cavity walls with great success for over 50 years in most parts of the world and have been widely deployed as below-grade drainage layers with some insulating value.
Figure 12: Closed-cell spray polyurethane foam (ccSPF) has been used for decades as a combined thermal insulation, air barrier material, drainage plane, and vapor control product. Note the extensive use of transition membranes at penetrations.
Figure 13: Rockwool semi-rigid board insulation used as continuous exterior insulation in an institutional building over a fluid-applied asphaltic air-water barrier over CMU.
Layer | R-value | RSI (m²K/W)
--- | --- | ---
Empty studspace 0.75”-6” (20-140 mm) | 0.85 – 1.4 | 0.15 – 0.25 m²K/W
Empty space (3.5” / 90 mm) | 1 | 0.18 m²K/W
Empty space (5.5”/140 mm) | 1 | 0.18 m²K/W
CMU 8” / 200 mm normal weight | 2.0 | 0.35 m²K/W

| Insulation material | R-value/inch | k (W/mK)
--- | --- | ---
Batt (mineral fiber) | 3.4-4.3 | 0.032 - 0.042
Extruded polystyrene (XPS) | 5.0 | 0.029
Polyisocyanurate (PIC) | 5.5-6.0 | 0.024 - 0.027
Expanded polystyrene (EPS) | 3.6-4.4 | 0.033 - 0.040
Semi-rigid mineral fiber (MFI) | 3.6-4.4 | 0.033 - 0.040
Spray fiberglass | 3.8-4.3 | 0.034 - 0.040
Closed-cell spray foam (2 pcf) ccSPF | 5.8-6.2 | 0.023 - 0.025
Open-cell spray foam (0.5 pcf) ocSPF | 3.6 | 0.040
Aerogel | 10 | 0.015
Vacuum Insulated Panels (VIP) | 18-30 | 0.005-0.008

Table 4: Representative Insulation Material Properties and their R-values

Radiant Barriers and Low-E Coatings

Some thermal control products are designed to primarily control radiation heat transfer. Radiant barrier sheets can be provided as a sheet, be adhered to sheathing and insulation products, or be part of a roof or sheathing membrane. Transparent metallic coatings are can be applied to any of the surfaces of glazing.

In all cases the efficacy of radiation control can be measured in the infra-red region by emissivity. Low emissivity, low-e, surfaces neither emit nor absorb energy effectively in the infra-red temperature (from -40 °F/-40°C to over 200 °F/90 °C). Normal building materials have an emissivity of around 0.90, or 90%. Low-e surfaces, almost always based on some metallic compound, have emissivities of well below 0.20, and the best coatings have values of 0.03 or even lower. A low-e surface will reduce the radiation that transfers across an air space regardless of which side of the airspace it is applied. Applying a low-e coating to both sides will have only a very small additional benefit. In all cases, a radiant barrier must have an air space associated with it to have any benefit to thermal control.
The most powerful application of radiation control is in the form of transparent coatings on glass, the ubiquitous low-e coating. The coating is usually applied to one of the surfaces facing a sealed air gap in an insulated glazing unit (IGU). In this location, the surface is protected from corrosion, condensation, dust, and dirt, and therefore the emissivity of the coating is protected from change. Low-e coatings increase the apparent thermal resistance of a ½" (13 mm) air gap in a sealed IGU by from R1 to R2. When the gap is filled with a less conductive gas such as argon, the benefit is even larger, boosting the R-value of a double-glazed IGU from around R2 to around R4. Some newer glazing systems are adding a low-e coating to the inside face of the glass as well: this improves R-value and occupant radiant comfort but does result in colder glass surface temperatures.

Low-emissivity coatings or films are often applied to carrier sheets, insulation boards, or sheathing. These coating may initially have emissivities as low as 0.05, but the value tends to rise in service as dust, corrosion, and aging increases the emissivity. Some low-e paints and coatings may have emissivities as high as 0.30: the benefit of these coatings are pretty small.

As radiation emission increases with the four power of absolute temperature, radiation is more important at high temperatures than at cold temperatures. Hence, radiant barriers / low-e coatings are slightly more important at high temperatures than low temperatures. As heat is carried by rising air, heat flow upward across a horizontal air space is dominated by convection, whereas heat flow downward is dominated by radiation: the impact of low-e coatings will be very important in the latter case and not the former. All of these varied factors means there is no one correct apparent thermal resistance for an airspace with low-e coating, or a radiant barrier product exposed to an air space.

**Thermal Bridging**

When heat flows at a much higher rate through one part of an assembly than another, the term *thermal bridge* is used to reflect the fact that the heat has bridged over / around the thermal insulation. Thermal bridges become important when:

- they cause cold spots within an assembly that might cause performance (e.g., surface condensation), durability or comfort problems. This is particularly important in buildings with higher interior humidity during winter.
- they are either large enough or intense enough (highly conductive) that they affect the total heat loss through the enclosure. This effect has become rather
significant as higher R-values in the rest of the enclosure increase in high performance buildings.

Thermal bridging, especially by steel framing, or at the intersection of wall corners with roofs and floors, projecting structural elements like cantilevered balconies and perimeter concrete slabs often causes cold interior surface temperatures and thus condensation as well as unwanted energy loss and gain. Attached figures provide a schematic of how temperatures at studs and near corners can cause low surface temperatures. In the case of the steel framing shown, an exterior temperature of –10 °C can result in interior surface temperatures of 5 to 10 °C at studs, and below freezing at floor to wall corners.

All enclosures should be designed to avoid a large number and extreme thermal bridges. The most effective solution, exterior continuous insulation (e.g., insulating wall sheathings such as semi-rigid stonewool and rigid foam), are quite useful for “blunting” thermal bridges and also offer energy saving benefits, and improve resistance to exfiltration condensation. Cladding attachments and window frames require thermal breaks, whereas most structural framing such as steel studs and beams, concrete walls and frames, and wood should be covered with insulation. For conditions such as balconies, and brick shelf angles and canopy projections, either structural thermal breaks should be used or the area of highly conductive materials penetrating the insulation should be strictly limited.

**High-Performance Enclosures**

The key to high performance is that the four control layers be provided and that they be as continuous and unbroken as possible across penetrations and transitions. The design and construction team must be able to identify which materials/sub-assemblies are providing each of the four control functions. Once the control layers in each enclosure component (e.g., window, roof, wall) are identified or specified, continuity analysis is conducted by drawing a line for each control layer around the entire enclosure through all penetrations and transitions. Any interruption in a line is a defect that must be rectified.

Figure 14 provides an example of a common type of building enclosure for commercial and institutional construction: a steel-framed primary superstructure, with light-gauge steel stud infill, and a brick veneer cladding. High-performance aspects include
• a continuous air-water-vapor control layer applied to the exterior of the primary structure and enclosure support (to ensure it is easy and practical to achieve continuity), and

• a continuous layer of thermal control on the exterior of the air-water control layer, uninterrupted by thermal bridges (especially the steel structure). The insulation within the framing is optional, and often not worth the risk of moisture problems for the small performance gain provided.

**Figure 14: Steel-Framed, steel-stud infill enclosure with brick cladding**

Different claddings, insulations, and control layer material choices are minor relative to the robust technical and practical advantages of the layering. Of course, different solutions will appear different, e.g., wood framing is less concerned with thermal bridging, and concrete masonry infill will always locate all of its thermal control on the exterior.
**Common Wood-Framed Assemblies**

Load-bearing wood framed enclosures are widely used for low-rise housing, and increasingly be applied to buildings of 4 storeys and more. High-rise steel, concrete frame or even heavy timber buildings of 6 to 30 stories have or are being built with infill, non-loadbearing wood frame walls, often prefabricated panels hung from the frame much like precast concrete or curtainwall assemblies.

Because wood framing is thermally far superior to steel framing or concrete blocks, it is common to fill the studspace with insulation. For high-performance enclosures, the air and water control layers should in most cases be located outboard of the wood framing and sheathing—this protects the moisture-sensitive wood and has the very significant practical benefit of making continuity at partition walls, floors, and service distribution penetrations much easier to achieve.

A common and flexible form of a high-performance wood-framed enclosure: the control layers are all identified and continuous, all materials are widely available, and construction is simple. Increasing the thermal performance of the assembly to meet different climate challenges and energy performance targets is achieved simply by changing the thickness of the exterior insulation.
Common Commercial Assemblies

The control layers can be identified in all functional building enclosures: the quality of the control may be marginal, or the control may be provided by a collection of materials, but it must be present or the enclosure is not functional. The figure below provides examples of numerous systems along with the identified control layers.
Historic and Alternate Construction

Although control layers are commonly defined and even labeled as such in modern enclosure designs, they are often more difficult to identify in existing and historic buildings and some alternate modern approaches to building. Older buildings used masonry as the primary water control layers (i.e., the storage or mass approach to rain control) as well as the support function (Figure 15). Air flow control was often a layer of interior plaster or exterior stucco, although sufficiently thick and impermeable masonry could fulfill that role.

A masonry wall retrofit for improved thermal control often uses spray foam as both a thermal control layer and air control, and requires a new interior finish / fire control layer in the form of gypsum board on steel studs (Figure 16). Alternatively, a higher performance lower-moisture-risk retrofit that changes the exterior appearance could use EIFS on the exterior, and empty steel studs on the interior (Figure 17). Labeling the control layers acts as a design quality control tool, as well as a means of effective communication in construction documentation.
Figure 15: Historic solid masonry wall showing control layers

Figure 16: Interior retrofit of solid masonry wall showing control layers
Figure 17: Exterior retrofit of solid masonry wall showing control layers

One of the more common modern alternative systems that is routinely and successfully used in modern, higher performance buildings is architectural precast. The use of high quality concrete allows the support and primary air and water control functions to be located on the exterior, and still provide good long-term durability. For durable high performance the challenge remains to ensure thermal control, avoiding condensation, and proper joint detailing. An example of a successful design of a precast concrete enclosure system is shown in the figure below.
Numerous other systems exist that may be more difficult to analyze. Insulated Concrete Forms (ICF), Structural Insulated Panel Systems (SIPS), Insulated Metal Panels (IMP), etc. However, each of these systems provides some, or all in the case of IMPs, of the support, control and finish functions.

1 References
