# Thermal Control Layers: Insulation Materials and Systems

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. Two material categories in foamed or fibrous form 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 commonplace low-e coating).

| **Material Category** | **Examples** | **Moisture** | **Fire** | **Vapor Permeance** | **Air Permeance** |
|---|---|---|---|---|---|
| Mineral fiber | Fiberglass, stone, slag | Tolerant | Non-combustible | high | high |
| Organic Fiber | Cellulose, cotton, wool, straw | Sensitive | Combustible | high | high |
| Plastic foam | Polystyrene, polyurethane, polyisocyanurate | Tolerant | Combustible | Low-medium | low |
| Mineral foam | Foamglass, pumice, airkrete, aerogel | Tolerant | Non-combustible | low | low |

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

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.

High-performance building enclosures generally require continuous thermal control layers on the exterior of the structure to ensure continuity. This layer can be foam board or spray foam, semi-rigid fiberglass or stonewool insulation: it must only be moisture tolerant. 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* (not 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.

| Form | Installation | Limits to use |
|---|---|---|
| Loose | poured or blown | may settle, easily compressed |
| Batt | friction fit | held in place by friction, easily compressed |
| Roll | friction fit / mechanically attached | as for batts |
| Board | mechanically, adhesively attached | resistant to mechanical pressure |
| Spray | spray in place | sticks to adjoining surfaces, resilient |

**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 movement (during service)/shrinkage (during initial curing) cracks.

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. Table 3 summarizes most available insulation types by their material, form and common use.

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.

| Material | Form | Uses | Vapor Permeance | Air Permeance |
|---|---|---|---|---|
| Fiberglass | loose | packed into spaces, laid on ceilings | high | high |
| | batt | friction fit between closely spaced framing, laid on ceilings | high | high |
| | spray | partially filling irregularly shaped volumes | high | high |
| | semi-rigid board | duct insulation | high | high |
| Stonewool | loose | | high | high |
| | batts | as for FG | high | high |
| | spray | partially filling irregularly shaped volumes | high | high |
| | semi-rigid board | cavity insulaton, covering interior surface, roofs | high | high |
| Polyisocyanurate (PIC) | board,foil-faced | sheathing, covers surfaces, cavity walls, inside roofs, on top of roof | low | low |
| | glass or paper-faced | | med | low |
| Extruded Polystyrene (XPS) | board | sheathing, covers surfaces, cavity walls, inside roofs, on top of roof, underslab, wet zones | low-med | low |
| | faced | | low | low |
| Expanded Polystyrene (EPS) | board | sheathing, covers surfaces, cavity walls, inside roofs, on top of roof | med | low |
| | faced | | low | low |
| Cellulose | loose | packed into spaces, laid on ceilings | high | high |
| | spray or packed | partially filling irregularly shaped volumes | high | med |
| Fiberboard | board | dry sheathing roofing floors | high | med |
| Straw | bales | self-supporting when dense, and supports cladding | high | med |
| open-cell spray polyurethane (ocSPF) | spray | partially filling irregularly shaped volumes, adhered to underside poured onto ceilings | high | low |
| closed-cell spray polyurethane (ccSPF) | spray | As ocSPF, but more water resistant | med | low |

**Table 3: Different Insulation Products, Their Uses, and Air-Vapor Permeance Properties**

**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, can provide a drainage path between 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. They do not provide a ventilated space: there is far too much airflow resistance for that purpose.

**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 to ensure continuity of the air and water control.**

**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 ($m^2K/W$)** |
|---|---|---|
| Empty studspace 0.75”-6” (20-140 mm) | 0.85 – 1.4 | 0.15 –0.25 $m^2K/W$ |
| Empty space (3-6” / 75-150 mm) | ≈1 | 0.18 $m^2K/W$ |
| CMU 8” / 200 mm normal weight | ≈2 | 0.35 $m^2K/W$ |
| **Insulation material** | **R-value/inch** | **k (W/mK)** |
| Batt (mineral fiber) | 3.4-4.3 | 0.033 - 0.042 |
| Extruded polystyrene (XPS) | 5.0 | 0.029 |
| Polyisocyanurate (PIC) | 5.0-6.0 | 0.024 - 0.027 |
| Expanded polystyrene (EPS) | 3.6-4.2 | 0.034 - 0.040 |
| Semi-rigid mineral fiber (MFI) | 3.6-4.2 | 0.034 - 0.040 |
| Spray fiberglass | 3.8-4.2 | 0.036 - 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**

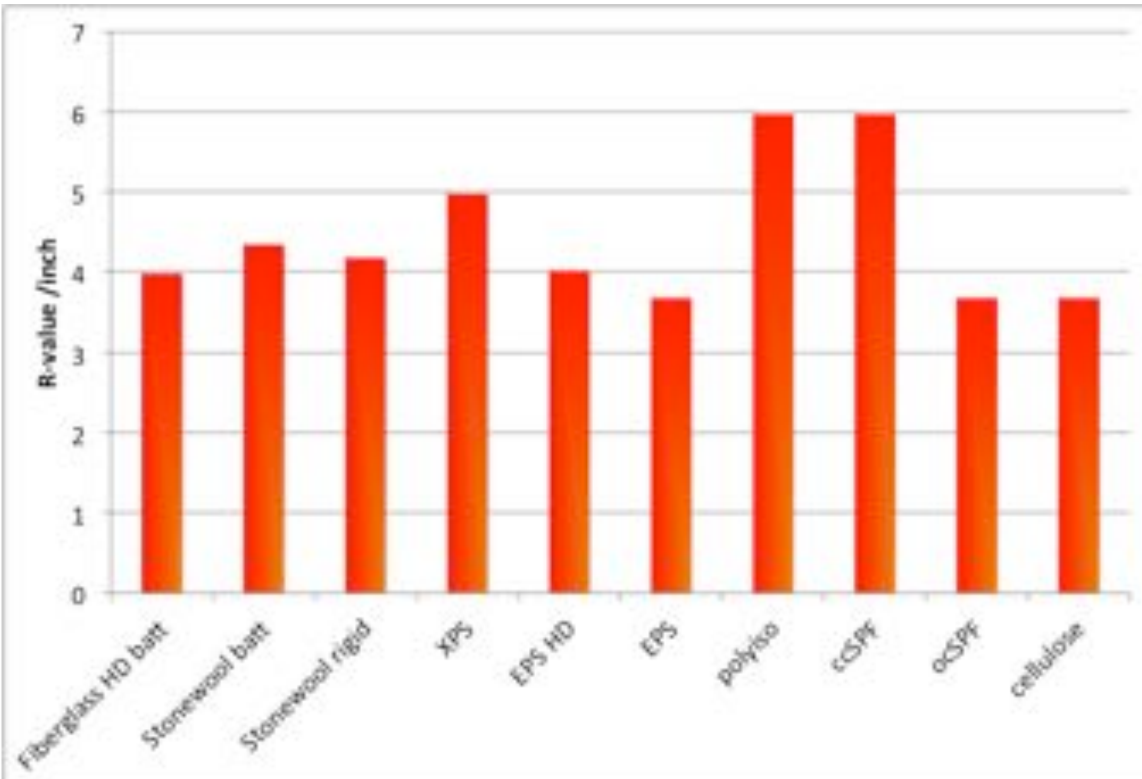


**Figure 1: Approximate R-value/inch of common insulation materials**

## 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. These products make a large improvement when no other insulation is present and in high temperature (high radiation) scenarios. However, they are mostly used in practise to avoid the use of higher levels of insulation and are often seen in mild climate buildings without demanding requirements.

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.

**Radiant ceiling cover in a California premanufactured steel building**

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 fourth 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 particularily important in buildings with higher interior humidity during winter.
- 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.

As the thermal resistance of building enclosures increases, the impact of thermal bridging becomes very significant to the overall R-value, especially for walls without continuous insulation layers. For example, the R-value of 6" steel stud with R-20 batt is often only around R-5 or 6, and continuous Z-girts penetrating R16 exterior insulation will perform with an R-value of R-8 or less.

Thermal bridging, especially by metal framing (including window frames), 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.

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 offer energy saving benefits and improved 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, 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.