# 2. FENESTRATION PRODUCTS

## 2.1. Overview

Much of the information in this chapter is taken from *Residential Windows: A Guide to New Technologies and Energy Performance* by John Carmody, Stephen Selkowitz, and Lisa Heschong.

Although glazing materials are the focus of much of the innovation and improvement in fenestration products, the overall performance of any unit is determined by the complete fenestration product assembly. The assembly includes the operating and fixed parts of the product frame as well as associated hardware and accessories. These are defined and illustrated at the beginning of this section. The next two sections address the different options available for sash operation and new advances in frame materials designed to improve product energy efficiency. Proper installation is an important aspect of their performance as well. The final section of this chapter discusses other installation issues.

## 2.2 Fenestration Product Sash Operation

There are numerous operating types available for fenestration products. Traditional operable types include the projected or hinged types such as casement, awning, and hopper, and the sliding types such as double- and single-hung and horizontal sliding. In addition, the current market includes storm windows, sliding and swinging patio doors, skylights and roof-mounted (i.e., sloping) windows, and systems that can be added to a house to create bay or bow windows, miniature greenhouses, or full sun rooms.

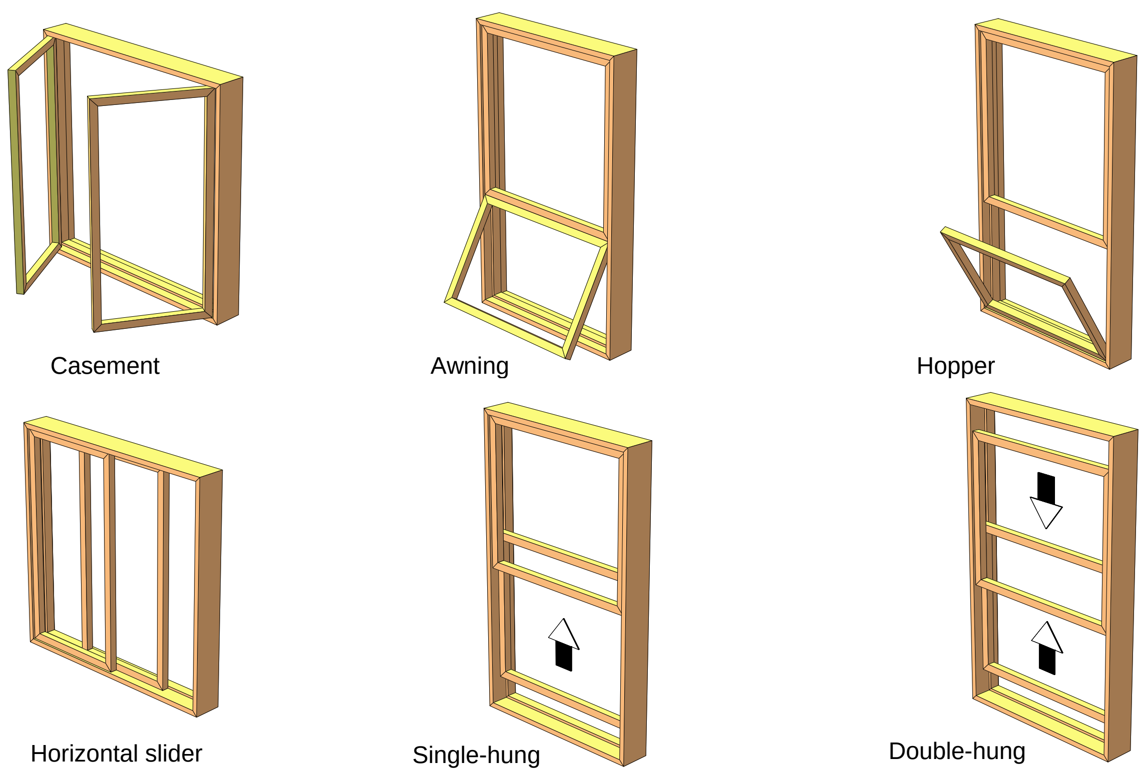


*Figure 2-1. Fenestration Operator Types*

### 2.2.1. Projected or Hinged Windows

Hinged windows include casements, awnings, and hoppers—hinged at the side, top, and bottom, respectively. Some manufacturers also make pivoting and combination windows that allow for easier cleaning of the exterior surfaces. Hinged windows, especially casements, project outward, providing significantly better ventilation than sliders of equal size. Because the sash protrudes from the plane of the wall, it can be controlled to catch passing breezes, but screens must be placed on the interior side. Virtually the entire casement window area can be opened, while sliders are limited to less than half of the window area.

### 2.2.2. Sliding Windows

Sliders are the most common type of windows and include horizontal sliders and single-hung and double-hung windows. Ventilation area can vary from a small crack to an opening of one-half the total glass area. Screens can be placed on the exterior or interior of the window unit.

In double-hung or double-sliding units, both sashes can slide. In double-sliding units, the same net amount of glass area can be opened for ventilation as in single sliders, but it can be split between the top and bottom or two ends of the window for better control of the air flow.

### 2.2.3. Sliding Glass Doors

Sliding glass doors (patio doors) are essentially big sliding windows. As extremely large expanses of glass, patio doors exaggerate all of the issues related to comfort and energy performance. Since the proportion of glass to frame is very high for a glass sliding door, the selection of high-performance glass can have significant benefits.

### 2.2.4. French Doors and Folding Patio Doors

French doors and folding glazed doors are growing in popularity. A basic double French door consists of two hinged doors with no center mullion, resulting in a 1.5 to 1.8 m (5- to 6-foot) wide opening. Folding doors are typically made of pairs of hinged doors, so that a double folding door with two pairs of doors can create an opening of 3.7 m (12 feet) or more.

### 2.2.5. Skylights and Roof Windows

The vast majority of skylights are permanently fixed in place, mounted on a curb above a flat or sloped roof. However, hatch-style skylights that can be opened with an extended crank, push latch, or remote control motor are becoming more common. Some skylights have a domed profile made of one or two layers of tinted or diffusing plastic.

A roof window is a hybrid between a skylight and a standard window. They have become increasingly popular as homeowners and designers seek to better utilize space in smaller houses by creating habitable rooms under sloping roofs. They are glazed with glass rather than plastic and are available with most of the glazing and solar control options of standard windows. Both fixed and operable versions are available, and the operable roof windows can be opened manually or by a motorized system. In addition, some manufacturers offer special venting mechanisms that allow some ventilation air flow without actually opening the window. Operable skylights or vents allow hot air that rises to the ceiling level to be effectively exhausted from the space.

Skylights and roof windows present a special case for insulating around windows because they are typically set into the thickest, most heavily insulated framing in the house, and they must also meet much more stringent conditions for shedding water. In order to create a positive water flow around them, skylights are commonly mounted on "curbs" set above the roof plane. These curbs, rising 15 to 30 centimeters (6 to 12 inches) above the roof, create additional heat loss surfaces, right where the warmest air of the house tends to collect. Ideally, they should be insulated to the same level as the roof. In practice, it is often difficult to achieve insulation levels much above R-11. Some manufacturers provide curbs prefabricated out of a rigid insulating foam, which can be further insulated at the site.

Roof windows, mounted in a sloping roof, often include a metal flashing system. If this metal flashing is in contact with a metal window frame, it can create additional surfaces for conducting heat. Thus, as with thermally broken aluminum windows, care should be taken to ensure a thermal separation between the cold outer metal surfaces and metal parts of the window frame that are exposed to the warm interior air.

## 2.3 Performance Implications of Basic Fenestration Types

There are subtle performance differences between a fixed and operable fenestration product that fills an identical rough opening. The fixed unit will typically have a smaller fraction of frame and proportionately more glass than the similar operable unit. Thus, fixed products with high-performance glass will have a better, lower U-factor, but a higher SHGC due to a smaller frame area and larger glass area. Fixed products have very low infiltration rates, but then they also do not provide natural ventilation and do not satisfy building code requirements for fire egress.

For operating fenestration products, the type of operation has little direct effect on the U-factor or SHGC of the unit, but it can have a significant effect on the air infiltration and ventilation characteristics. Operation can be broken into two basic types: sliding products and hinged products. The comments below are a general characterization of American fenestration products; however, they may not apply to a specific product made by a given manufacturer.

### 2.3.1. Hinged Windows

Hinged windows such as casements, awnings, and hoppers generally have lower air leakage rates than sliding windows from the same manufacturer because the sash closes by pressing against the frame, permitting the use of more effective compression-type weatherstripping. In most types, the sash swings closed from the outside, so that additional external wind pressure tends to push the sash more tightly shut. Hinged windows require a strong frame to encase and support the projecting sash. Also, because projecting-type sashes must be strong enough to swing out and still resist wind forces, the stiffer window units do not flex as readily in the wind. In addition, hinged windows have locking mechanisms that force the sash against the weatherstripping to maximize compression. These design details tend to reduce air infiltration of hinged windows in comparison to sliders.

### 2.3.2. Sliding Windows

Sliding windows, whether single-hung, double-hung, or horizontal sliders, generally have higher air leakage rates than projecting or hinged windows. Sliding windows typically use a brush-type weatherstripping that allows the sash to slide past. This type is generally less effective than the compression gaskets found in projecting windows. The weatherstrip effectiveness also tends to be reduced over time due to wear and tear from repeated movement of the sliding sash. The frames and sashes of sliding units can be made with lighter, less rigid frame sections since they only need to support their own weight. This lightness may permit the sliding frames to flex and can allow more air leakage under windy conditions. Manufacturers can choose to engineer greater stiffness in their products by design and material selection.

Slider window performance can also be improved with latching mechanisms that compress the sash to the fixed frame and by the addition of compression weatherstripping at the head and sill of double-hung windows or the end jamb of horizontal sliders.

### 2.3.3. Sliding Glass and French Doors

As previously noted, sliding doors are essentially big sliding windows. However, they are more complicated because of their size and weight and because the sill is also a door threshold, which must keep water out while allowing easy passage of people and objects. The threshold is typically the most difficult part of the frame to weatherstrip effectively.

French doors benefit from being much more like traditional doors than sliding doors. French doors can use weatherstripping and operating hardware designed for similar non-glazed doors. However, when there are large openings with multiple hinged doors, it is more difficult to positively seal the joints between door leaves and to create the stiffness that will resist infiltration.

## 2.4 Frame Materials

The material used to manufacture the frame governs the physical characteristics of the fenestration product, such as frame thickness, weight, and durability, but it also has a major impact on the thermal characteristics of the product. Increasingly, manufacturers are producing hybrid or composite sash and frames, in which multiple materials are selected and combined to best meet the overall required performance parameters. Thus, a simple inspection of the inner or outer surface of the frame is no longer an accurate indicator of the total material or its performance. Since the sash and frame represent from 10 to 30 percent of the total area of the fenestration unit, the frame properties will significantly influence the total product performance.

### 2.4.1. Wood Frames

Wood fenestration products are manufactured in all configurations, from sliders to swinging windows. Wood is favored in many residential applications because of its appearance and traditional place in house design.

A variation of the wooden product is to clad the exterior face of the frame with either vinyl or aluminum, creating a permanent weather-resistant surface. Clad frames thus have lower maintenance requirements, while retaining the attractive wood finish on the interior.

From a thermal point of view, wood-framed products perform well. The thicker the wood frame, the more insulation it provides. Wood-framed fenestration products typically exhibit low heat loss rates.

However, metal cladding, metal hardware, or the metal reinforcing often used at corner joints can degrade the thermal performance of wood frames. If the metal extends through the fenestration product from the cold side to the warm side of the frame, it creates a thermal short circuit, conducting heat more quickly through that section of the frame.

### 2.4.2. Aluminum Frames

The biggest disadvantage of aluminum as a fenestration product frame material is its high thermal conductance. It readily conducts heat, greatly raising the overall U-factor of a fenestration unit. Because of its high thermal conductance, the thermal resistance of an aluminum frame is determined more by the amount of surface area of the frame than by the thickness or the projected area, as with other frame materials. Thus, an aluminum frame profile with a simple compact shape will perform much better than a profile with many fins and undulations.

In cold climates, a simple aluminum frame can easily become cold enough to condense moisture or frost on the inside surfaces of fenestration product frames. Even more than the problem of heat loss, the condensation problem spurred development of a more insulating aluminum frame.

The most common solution to the heat conduction problem of aluminum frames is to provide a “thermal break” by splitting the frame components into interior and exterior pieces and use a less conductive material to join them. There are many designs available for thermally broken aluminum frames. The most prevalent technique used in residential fenestration products is called “pouring and debridging.” The frame is first extruded as a single piece with a hollow trough in the middle. This is filled with a plastic that hardens into a strong intermediate piece. The connecting piece of aluminum is then milled out, leaving only the plastic to join the two halves of aluminum. Functionally, the resulting piece is cut, mitered, and assembled like a simple aluminum extrusion. Thermally, the plastic slows the heat flow between the inside and outside. There are other manufacturing techniques for producing a thermal break (such as crimped-in-place polymer strips), but the thermal results are similar.

### 2.4.3. Vinyl Frames

Plastics are relative newcomers as fenestration product frame materials in North America. Vinyl, also known as polyvinyl chloride (PVC), is a versatile material with good insulating value.

The thermal performance of vinyl frames is roughly comparable to wood. Large hollow chambers within the frame can allow unwanted heat transfer through convection currents. Creating smaller cells within the frame reduces this convection exchange, as does adding an insulating material. Most manufacturers are conducting research and development to improve the insulating value of their vinyl fenestration product assemblies.

### 2.4.4. Fiberglass and Engineered Thermoplastics

In addition to vinyl fenestration products two other polymer-based technologies have become available, fiberglass and thermoplastics. Frames can be made of glass-fiber-reinforced polyester, or fiberglass, which is pultruded into lineal forms and then assembled into fenestration products. These frames are dimensionally stable and have good insulating value by incorporating air cavities (similar to vinyl).

### 2.4.5. Wood Composites

Most people are familiar with composite wood products, such as particle board and laminated strand lumber, in which wood particles and resins are compressed to form a strong composite material. The wood fenestration product industry has now taken this a step further by creating a new generation of wood/polymer composites that are extruded into a series of lineal shapes for frame and sash members. These composites are stable, and have the same or better structural and thermal properties as conventional wood, with better moisture resistance and more decay resistance. They can be textured and stained or painted much like wood. They were initially used in critical elements, such as sills and thresholds in sliding patio doors, but are now being used for entire units. This approach has the added environmental advantage of reusing a volume of sawdust and wood scrap that would otherwise be discarded.

### 2.4.6. Hybrid and Composite Frames

Manufacturers are increasingly turning to hybrid frame designs that use two or more of the frame materials described above to produce a complete fenestration product system. The wood industry has long built vinyl- and aluminum-clad products to reduce exterior maintenance needs. Vinyl manufacturers and others offer interior wood veneers to produce the finish and appearance that many homeowners desire. Split-sash designs may have an interior wood element bonded to an exterior fiberglass element.

## 2.5 Basic Glazing Materials

Two basic materials are used for fenestration product glazing: glass, which is by far the most common, and plastics, which have many specialized applications.

### 2.5.1. Glass

Traditionally, fenestration products have been made of clear glass. Most residential-grade clear glass today is produced with the float technique in which the glass is "floated" over a bed of molten tin. This provides extremely flat surfaces, uniform thicknesses, and few if any visual distortions. The glass has a slight greenish cast, due to iron impurities, but this is generally not noticeable except from the edge. An even higher-quality glass with reduced iron content eliminates the greenness and also provides a higher solar energy transmittance. This is commonly called "water-white glass."

Obscure glasses still transmit most of the light but break up the view in order to provide privacy. This effect is generally achieved either with decorative embossed patterns or with a frosted surface that scatters the light rays.

By adding various chemicals to glass as it is made, glass can be produced in a wide variety of colors. Glass colors are typically given trade names, but the most frequently used colors can be generally described as clear, bronze, gray, and blue-green. After clear glass, the gray glasses are most commonly used in residential construction, as they have the least effect on the perceived color of the light. Tinted glass is discussed later in this chapter.

The mechanical properties of glass can be altered, as well as its basic composition and surface properties. Heat-strengthening and tempering make glass more resistant to breakage. Heat-strengthened glass is about twice as strong as standard glass. Tempered glass is produced by reheating and then quickly chilling the glass. It breaks into small fragments, rather than into long, possibly dangerous shards. Laminated glass is a sandwich of two outer layers of glass with a plastic inner layer that holds the glass pieces together in the event of breakage. Fully tempered and laminated glass is required by building codes in many door and fenestration product applications.

### 2.5.2. Plastics

Several plastic materials have been adapted for use as glazing materials. Their primary uses are fenestration products with special requirements and skylights.

The following list of plastic glazing materials covers the major types of plastic glazing materials and compares their general properties:

- Clear acrylic is widely available and relatively inexpensive. It is available in various tints and colors. It has excellent visible light transmittance and longevity. However, it is softer than glass, which makes it vulnerable to scratching.
- Frosted acrylic is like clear acrylic, except that it diffuses light and obscures the view. It comes in varying degrees of light transmittance. Most bubble skylights are made of frosted acrylic.
- Clear polycarbonate is like acrylic sheet, but it is harder and tougher, offering greater resistance to scratching and breakage. It is more expensive than acrylic.
- Fiber-reinforced plastic is a tough, translucent, flexible sheet material with good light-diffusing properties. Short lengths of fiberglass are embedded in a polymer matrix to form flat or ribbed sheets. Stiff, insulating, translucent panels are created by bonding double layers to a metal frame and adding fiberglass insulation. It is also formed into corrugated sheets as a translucent roofing material. Surface erosion may shorten its useful life.
- Extruded multicell sheet, usually made with acrylic or polycarbonate plastic, is a transparent or tinted plastic extruded into a double- or triple-wall sheet with divider webs for stiffness, insulating value, and light diffusion.
- Polyester is a thin film used to carry specialized coatings and/or to divide the air space between two layers of glass into multiple air spaces. Highly transparent, it is protected from abuse and weathering by

the two exterior glass layers. It can also be used in tinted or coated forms as film that is glued to the inner surface of existing fenestration products for retrofitting applications.

## 2.6 Improved Glazing Products

There are three fundamental approaches to improving the energy performance of glazing products:

1. Alter the glazing material itself by changing its chemical composition or physical characteristics. An example of this is tinted glazing. The glazing material can also be altered by creating a laminated glazing.
2. Apply a coating to the glazing material surface. Reflective coatings and films were developed to reduce heat gain and glare, and more recently, low-emittance and spectrally selective coatings have been developed to improve both heating and cooling season performance.
3. Assemble various layers of glazing and control the properties of the spaces between the layers. These strategies include the use of two or more panes or films, low-conductance gas fills between the layers, and thermally improved edge spacers.

Two or more of these approaches may be combined. Each of these improvements to the glazing is discussed below

### 2.6.1. Tinted Glazing

Both plastic and glass materials are available in a large number of tints. The tints absorb a portion of the light and solar heat. Tinting changes the color of the fenestration product.

Tinted glazings retain their transparency from the inside, so that the outward view is unobstructed. The most common colors are neutral gray, bronze, and blue-green, which do not greatly alter the perceived color of the view and tend to blend well with other architectural colors. Many other specialty colors are available for particular aesthetic purposes.

Tinted glass is made by altering the chemical formulation of the glass with special additives. Its color changes with the thickness of the glass and the addition of coatings applied after manufacture. Every change in color or combination of different glass types affects transmittance, solar heat gain coefficient, reflectivity, and other properties. Glass manufacturers list these properties for every color, thickness, and assembly of glass type they produce.

Tinted glazings are specially formulated to maximize their absorption across some or all of the solar spectrum and are often referred to as "heat-absorbing." All of the absorbed solar energy is initially transformed into heat within the glass, thus raising the glass temperature. Depending upon climatic conditions, up to 50 percent of the heat absorbed in a single layer of tinted glass may then be transferred via radiation and convection to the inside. Thus, there may be only a modest reduction in overall solar heat gain compared to other glazings.

There are two categories of tinted glazing: the traditional tints that diminish light as well as heat gain, and spectrally selective tints that reduce heat gain but allow more light to be transmitted to the interior. The traditional tinted glazing often forces a trade-off between visible light and solar gain. For these bronze and gray tints, there is a greater reduction in visible light transmittance than there is in solar heat gain coefficient. This can reduce glare by reducing the apparent brightness of the glass surface, but it also reduces the amount of daylight entering the room.

To address the problem of reducing daylight with traditional tinted glazing, glass manufacturers have developed new types of tinted glass that are "spectrally selective." They preferentially transmit the daylight portion of the solar spectrum but absorb the near-infrared part of sunlight. This is accomplished by adding special chemicals to the float glass process. Like other tinted glass, they are durable and can be used in both monolithic and multiple-glazed fenestration product applications. These glazings have a light blue or green tint and have visible transmittance values higher than conventional bronze- or gray-tinted glass, but have lower solar heat gain coefficients. Because they are absorptive, they are best used as the outside glazing in a double-glazed unit. They can also be combined with Low-E coatings to enhance their performance further.

### 2.6.2. Reflective Coatings and Films

As the solar heat gain is lowered in single-pane tinted glazings, the visible light transmission drops even faster, and there are practical limits on how low the solar heat gain can be made using tints. If larger reductions are desired, a reflective coating can be used to lower the solar heat gain coefficient by increasing the surface reflectivity of the material. These coatings usually consist of thin metallic layers. The reflective coatings come in various metallic colors (silver, gold, bronze), and they can be applied to clear or tinted glazing (the substrate). The solar heat gain of the substrate can be reduced a little or a lot, depending on the thickness and reflectivity of the coating, and its location on the glass.

As with tinted glazing, the visible light transmittances of reflective glazings are usually reduced substantially more than the solar heat gain.

### 2.6.3. Double Glazing

Storm windows added onto the outside of window frames during the stormy winter season were the first double-glazed fenestration products. They reduce infiltration from winter winds by providing a seal around all the operating sash and they improve the insulating value of the glazing as well.

When manufacturers began to experiment with factory-sealed, double-pane glass to be installed for year-round use, they encountered a number of technical concerns, such as how to allow for different thermal movement between the two panes, how to prevent moisture from forming between the panes and condensing on an inaccessible surface, and how to allow for changes in atmospheric pressure as the assembly was moved from factory to installation site. These issues have been successfully addressed over the years with a variety of manufacturing techniques and material selections.

When double-glass units first came on the market, the two glass layers were often fused around the perimeter to make a permanently sealed air space. In recent years, however, spacers and polymer sealants have largely replaced glass-to-glass seals, and have proven sufficiently durable for residential applications. The layers of glass are separated by and adhere to a spacer, and the sealant, which forms a gas and moisture barrier, is applied around the entire perimeter. Normally, the spacer contains a desiccant material to absorb any residual moisture that may remain in the air space after manufacture. Sealed insulating glass units are now a mature, well proven technology. Designs utilizing high-quality sealants and manufactured with good quality control should last for decades without seal failure.

### 2.6.4. Glass Coatings and Tints in Double Glazing

Both solar reflective coatings and tints on double-glazed fenestration products are effective in reducing summer heat gain; however, only certain coatings contribute to reducing winter heat loss, and tints do not affect the heat loss rates at all. It is possible to provide reflective coatings on any one of the four surfaces, although they are usually located on the outermost surface or on the surfaces facing the air space. Coating location can also depend on the type of coating. Some vacuum-deposited reflective coatings must be placed in a sealed air space because they would not survive exposure to outdoor elements, finger prints, or cleaning agents. Pyrolytic coatings that are created with a high-temperature process as the glass is formed are extremely hard and durable and can be placed anywhere. Each location produces a different visual and heat transfer effect. Other advanced coatings such as low-emittance and spectrally selective coatings are normally applied to double-glazed or triple-glazed fenestration products. These applications are discussed later in this chapter.

Double-pane units can be assembled using different glass types for the inner and outer layers. Typically, the inner layer is standard clear glass, while the outer layer can be tinted, reflective, or both. The solar heat gain coefficient is reduced because the tinted glass and clear glass both reduce transmitted radiation. In addition, this design further reduces solar heat gain because the inner clear glass, the gas fill, and any Low-E coating keep much of the heat absorbed by the outer glass from entering the building interior.

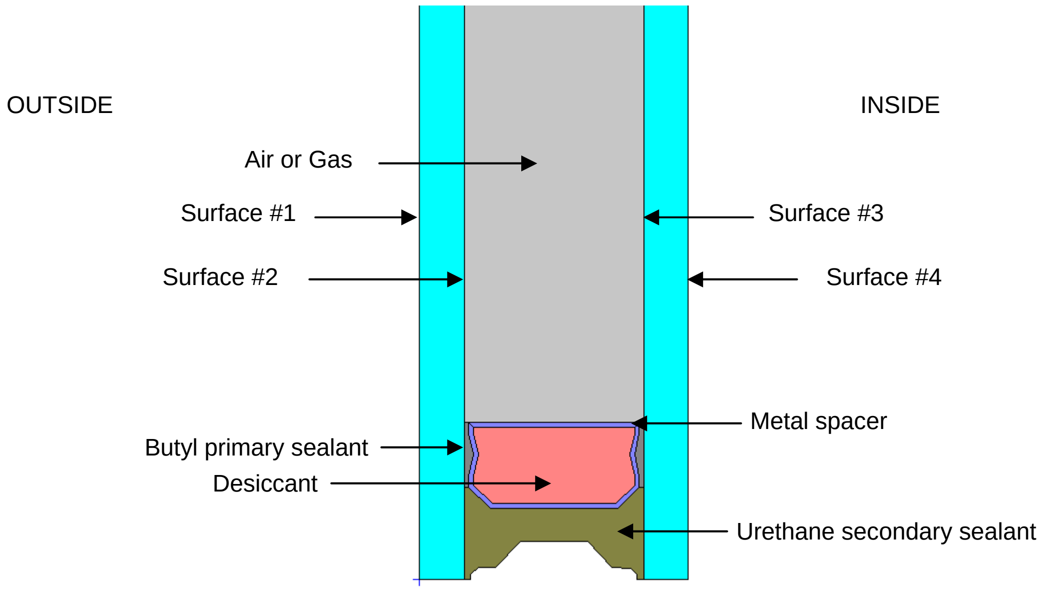


*Figure 2-2. Insulating Glass Unit (IGU).*

### 2.6.5. Gap Width in Multiple Glazed Units

Fenestration product manufacturers have some flexibility to reduce heat transfer by selecting the best gap width between two or more glazings. The air space between two pieces of glass reaches its optimum insulating value at about 1/2-inch (12 mm) thickness when filled with air or argon. As the gap gets larger, convection in the gap increases and slowly increases heat transfer. Below 3/8 inch (9 mm), conduction through the air gap increases and the U-factor rises more rapidly. Krypton gas has its optimum thickness at about 1/4 inch (6 mm), so that if smaller air gaps are required, for example in a three-layer fenestration product whose overall exterior dimensions are limited, krypton may be the best selection, although it is also more costly.

### 2.6.6. Divided Lights

Manufacturers have been struggling with the problem of many homeowners' preference for traditional, divided light fenestration products, which have many small panes separated by thin bars called muntins. With single-pane glass, true divided lights actually improved the thermal performance of the fenestration product because the wood muntins had a higher insulating value than the glass. Some manufacturers have introduced "true divided light" insulated units, in which traditional-looking muntins hold small, individual, insulated panes. However, these are expensive and difficult to fabricate with insulated glass and have greater thermal losses due to the number of edges, which now have metal in them.

A second option is to produce a single, large sealed glass unit with "muntins" glued to the inside and outside surfaces, while a grid is placed in the middle of one large insulated unit, giving the visual effect of divided lights. This reduces fabrication costs but does not reduce resistance to heat flow if the muntins in the middle are metal and if they touch both lights of glass.

A third option, which is more energy efficient, is to build a large-pane insulated unit that has snap-on or glued-on grilles to simulate the traditional lights.

The energy performance of the simple snap-on grid will be similar to a unit without any mullions; however, the true divided lights will result in greater heat transfer because of the additional edges.

### 2.6.7. Special Products

Glass blocks present a very special case of double glazing. They provide light with some degree of visual privacy. Plastic blocks, which have a lower U-factor than glass, are also available. However, when installed, the necessary grouting reduces the energy efficiency. Also, metal mesh and steel reinforcing bars, used between blocks to provide structural stability, provide thermal bridges which also reduce energy efficiency.

Plastic glazings are available in a number of configurations with double layers. Double-glazed acrylic bubble skylights are formed with two layers separated by an air space of varying thickness, ranging from no separation at the edges to as much as 3 inches (7.6 cm) at the top of the bubble. The average separation is used to calculate the effective U-factor.

Multicell polycarbonate sheets, which can be mounted with the divider webs running vertically or horizontally, are available. The divider webs increase the effective insulating value of the glazing by reducing convection exchange within the cells, especially when they are mounted horizontally.

### 2.6.8. Multiple Panes or Films

By adding a second pane, the insulating value of the fenestration product glass alone is doubled (the U-factor is reduced by half). As expected, adding a third or fourth pane of glass further increases the insulating value of the fenestration product, but with diminishing effect.

Triple- and quadruple-glazed fenestration products became commercially available in the 1980s as a response to the desire for more energy-efficient products. There is a trade-off with this approach, however. As each additional layer of glass adds to the insulating value of the assembly, it also reduces the visible light transmission and the solar heat gain coefficient, thereby reducing the fenestration product's value for providing solar gains or daylighting. In addition, other complications are encountered. Additional panes of glass increase the weight of the unit, which makes mounting and handling more difficult and transportation more expensive.

Because of the difficulties discussed above, it is apparent there are physical and economic limits to the number of layers of glass that can be added to a fenestration product assembly. However, multiple-pane units are not limited to assemblies of glass. One popular innovation is based on substituting an inner plastic film for the middle layer of glass. The plastic film is very lightweight, and because it is very thin, it does not increase the thickness of the unit. The glass layers protect the inner layer of plastic from scratching, mechanical abuse, corrosion, weathering, and visual distortions caused by wind pressure. Thus, the strength and durability of plastic as a glazing material are no longer issues when the plastic is protected from physical abuse and weathering by inner and outer layers of glass. The plastic films are specially treated to resist UV degradation and they are heat shrunk so they remain flat under all conditions.

The plastic inner layer serves a number of important functions. It decreases the U-factor of the fenestration product assembly by dividing the inner air space into multiple chambers. Units are offered with one or two inner layers of plastic. Secondly, a Low-E coating can be placed on the plastic film itself to further lower the U-factor of the assembly. Also, the plastic film can be provided with spectrally selective coatings to reduce solar gain in hot climates without significant loss of visible transmittance. The performance of multiple-pane fenestration product assemblies with low-emittance coatings and gas fills is described in the following sections.

### 2.6.9. Low-Emittance Coatings

The principal mechanism of heat transfer in multilayer glazing is thermal radiation from a warm pane of glass to a cooler pane. Coating a glass surface with a low-emittance material and facing that coating into the gap between the glass layers blocks a significant amount of this radiant heat transfer, thus lowering the total heat flow through the fenestration product. The improvement in insulating value due to the Low-E coating is roughly equivalent to adding another pane of glass to a multipane unit.

The solar spectral reflectances of Low-E coatings can be manipulated to include specific parts of the visible and infrared spectrum. A glazing material can then be designed to optimize energy flows for solar heating, daylighting, and cooling.

With conventional clear glazing, a significant amount of solar radiation passes through the fenestration product, and then heat from objects within the house is reradiated back through the fenestration product. For example, a glazing design for maximizing solar gains in the winter would ideally allow all of the solar spectrum to pass through, but would block the reradiation of heat from the inside of the house. The first Low-E coatings were designed to have a high solar heat gain coefficient and a high visible transmittance to transmit the maximum amount of sunlight into the interior while reducing the U-factor significantly.

A glazing designed to minimize summer heat gains but allow for some daylighting would allow visible light through, but would block all other portions of the solar spectrum, including ultraviolet light and near-infrared, as well as long-wave heat radiated from outside objects, such as paving and adjacent buildings, as shown in Figure 2-3. These second-generation Low-E coatings were designed to reflect the solar near-infrared, thus reducing the total solar heat gain coefficient while maintaining high levels of light transmission. Variations on this design (modified coatings and/or glazings) can further reduce summer solar heat gain and control glare.

There are three basic types of Low-E coatings available on the market today:

1. **High-transmission Low-E:**
   These Low-E glass products are often referred to as pyrolitic or hard coat Low-E glass, due to the glass coating process. The properties presented here are typical of a Low-E glass product designed to reduce heat loss but admit solar gain.
2. **Moderate-transmission Low-E:**
   These Low-E glass products are often referred to as sputtered (or soft-coat products) due to the glass coating process. (Note: Low solar gain Low-E products are also sputtered coatings.) Such coatings reduce heat loss and let in a reasonable amount of solar gain.
3. **Low-transmission Low-E:**
   These Low-E products are often referred to as sputtered (or soft-coat) due to the glass coating process. (Note: Moderate solar gain Low-E products are also sputtered coatings.) This type of Low-E product, sometimes called spectrally selective Low-E glass, reduces heat loss in winter but also reduces heat gain in summer. Compared to most tinted and reflective glazings, this Low-E glass provides a higher level of visible light transmission for a given amount of solar heat reduction.

The type and quality of Low-E coating will affect not only the U-factor, but also the transmittance and solar heat gain coefficient of a glass. All these properties (U-factor, VT, and SHGC) need to be taken into consideration in characterizing a particular glazing product.

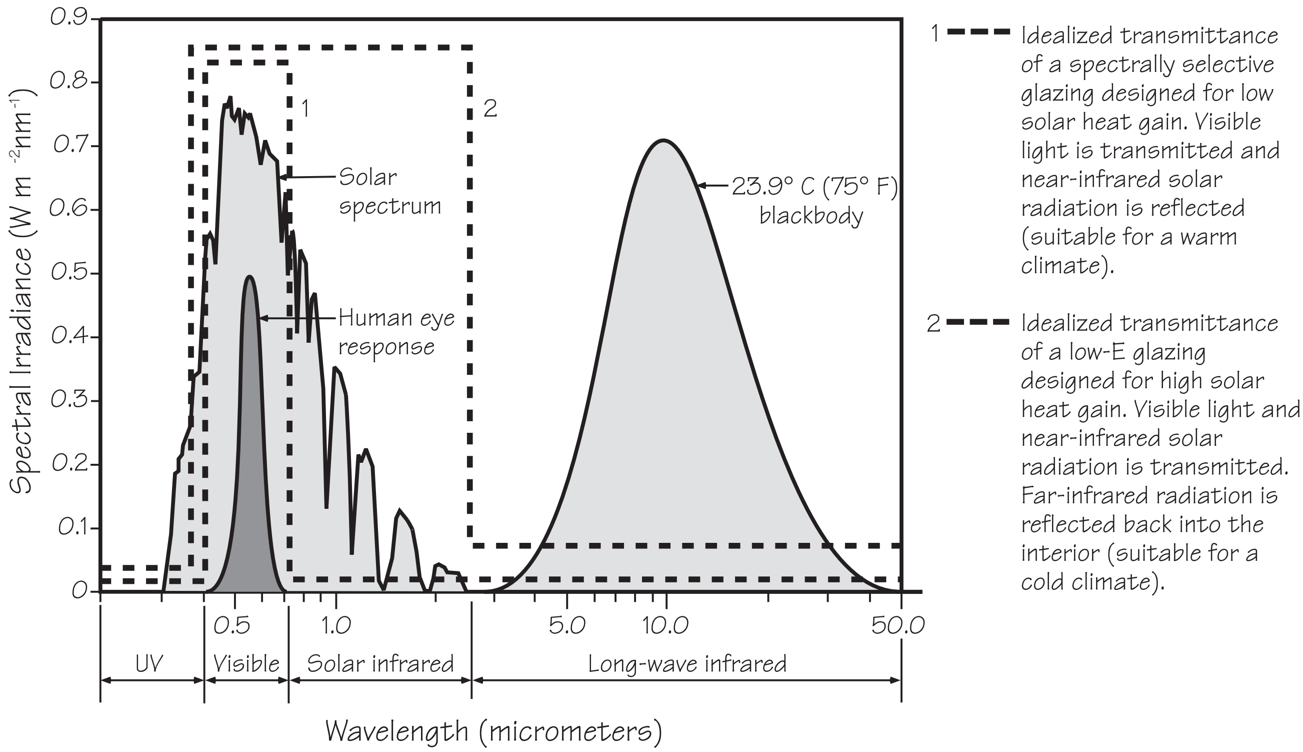


*Figure 2-3. Ideal spectral transmittance for glazings in different climates. (Source: "Sensitivity of Fenestration Solar Gain to Source Spectrum and Angle of Incidence." ASHRAE Transactions 10, R. McCluney, June 1996).*

### 2.6.9.1. Coating Placement

The placement of a Low-E coating within the air gap of a double-glazed fenestration product does not significantly affect the U-factor but it does influence the solar heat gain coefficient (SHGC). That is why, in heating-dominated climates, placing a Low-E coating on the #3 surface (outside surface of the inner pane) is recommended to maximize winter passive solar gain at the expense of a slight reduction in the ability to control summer heat gain. In cooling climates, a coating on the #2 surface (inside surface of the outer pane) is generally best to reduce solar heat gain and maximize energy efficiency. Manufacturers sometimes place the coatings on other surfaces (e.g., #2 surface in a heating climate) for other reasons, such as minimizing the potential for thermal stress. Multiple Low-E coatings are also placed on surfaces within a triple-glazed fenestration product assembly, or on the inner plastic glazing layers of multipane assemblies referred to as superwindows (discussed later in this chapter), with a cumulative effect of further improving the overall U-factor.

### 2.6.9.2. Coating Types

There are two basic types of Low-E coatings – sputtered and pyrolytic, referring to the process by which they are made. The best of each type of coating is colorless and optically clear. Some coatings may have a slight hue or subtle reflective quality, particularly when viewed in certain lighting conditions or at oblique angles.

A sputtered coating is multilayered (typically, three primary layers, with at least one layer of metal) and is deposited on glass or plastic film in a vacuum chamber. The total thickness of a sputtered coating is only 1/10,000 of the thickness of a human hair. Sputtered coatings often use a silver layer and must be protected from humidity and contact. For this reason they are sometimes referred to as “soft coats.” Since sputtering is a low-temperature process, these coatings can be deposited on flat sheets of glass or thin plastic films. While sputtered coatings are not durable in themselves, when placed into a sealed double- or triple-glazed assembly they should last as long as the sealed glass unit. Sputtered coatings typically have lower emittances than pyrolytic coatings. They are available commercially with emittance ratings of e = 0.10 to as low as e = 0.02 (e = 0.20 means that 80 percent of the long-wavelength radiant energy received by the surface is reflected, while e = 0.02 means 98 percent is reflected). For uncoated glass, e = 0.84, which means only 16 percent of the radiant energy received by the surface is reflected.

A typical pyrolytic coating is a metallic oxide, most commonly tin oxide with some additives, which is deposited directly onto a glass surface while it is still hot. The result is a baked-on surface layer that is quite hard and thus very durable, which is why this is sometimes referred to as a "hard coat." A pyrolytic coating can be ten to twenty times thicker than a sputtered coating but is still extremely thin. Pyrolytic coatings can be exposed to air, cleaned with normal cleaning products, and subjected to general wear and tear without losing their Low-E properties.

Because of their greater durability, pyrolytic coatings are available on single-pane glass and separate storm windows, but not on plastics, since they require a high-temperature process. In general, though, pyrolytic coatings are used in sealed, double-glazed units with the Low-E surface inside the sealed air space. While there is considerable variation in the specific properties of these coatings, they typically have emittance ratings in the range of e = 0.20 to e = 0.10.

A laminated glass with a spectrally selective Low-E sputtered coating on plastic film sandwiched between two layers of glass offers the energy performance of single-pane, spectrally selective glass and the safety protection of laminated glass. However, in this configuration, since the Low-E surface is not exposed to an air space, there is no effect on the glazing U-factor.

### 2.6.10. Gas Fills

Another improvement that can be made to the thermal performance of insulating glazing units is to reduce the conductance of the air space between the layers. Originally, the space was filled with air or flushed with dry nitrogen just prior to sealing. In a sealed glass insulating unit air currents between the two panes of glazing carry heat to the top of the unit and settle into cold pools at the bottom. Filling the space with a less conductive gas minimizes overall transfer of heat between two glass layers.

Manufacturers have introduced the use of argon and krypton gas fills, with measurable improvement in thermal performance. Argon is inexpensive, nontoxic, nonreactive, clear, and odorless. The optimal spacing for an argon-filled unit is the same as for air, about 1/2 inch (12 mm). Krypton has better thermal performance, but is more expensive to produce. Krypton is particularly useful when the space between glazings must be thinner than normally desired, for example, 1/4 inch (6 mm). A mixture of krypton and argon gases is also used as a compromise between thermal performance and cost.

Filling the sealed unit completely with argon or krypton presents challenges that manufacturers continue to work on. A typical gas fill system adds the gas into the cavity with a pipe inserted through a hole at the edge of the unit. As the gas is pumped in, it mixes with the air, making it difficult to achieve 100 percent purity. Recent research indicates that 90 percent is the typical concentration achieved by manufacturers today. Some manufacturers are able to consistently achieve better than 95 percent gas fill by using a vacuum chamber. An uncoated double-pane unit filled with 90 percent argon gas and 10 percent air yields a slightly more than 5 percent improvement in the insulating value at the center of the glass, compared to the same unit filled with air. However, when argon and krypton fills are combined with Low-E coatings and multipane glazings, more significant reductions of 15 to 20 percent can be achieved. Since the Low-E coating has substantially reduced the radiation component of heat loss, the gas fill now has a greater proportional effect on the remaining heat transfer by convection and conduction.

## 2.7 Thermally Improved Edge Spacers

The layers of glazing in an insulating glass (IG) unit must be held apart at the appropriate distance by spacers. The spacer system must provide a number of additional functions in addition to keeping the glass units at the proper dimension:

- accommodate stress induced by thermal expansion and pressure differences;
- provide a moisture barrier that prevents passage of water or water vapor that would fog the unit;
- provide a gas-tight seal that prevents the loss of any special low-conductance gas in the air space;
- create an insulating barrier that reduces the formation of interior condensation at the edge.

Older double-pane wood fenestration products used a wood spacer that could not be hermetically sealed and thus was vented to the outside to reduce fogging in the air gap. Modern versions of this system function well but, because they are not hermetically sealed, cannot be used with special gas fills or some types of Low-E coatings. Early glass units were often fabricated with an integral welded glass-to-glass seal. These units did not leak but were difficult and costly to fabricate, and typically had a less-than-optimal narrow spacing. The standard solution for insulating glass units (IGUs) that accompanied the tremendous increase in market share of insulating glass in the 1980s was the use of metal spacers, and sealants. These spacers, typically aluminum, also contain a desiccant that absorbs residual moisture. The spacer is sealed to the two glass layers with organic sealants that both provide structural support and act as a moisture barrier. There are two generic systems for such IGUs: a single-seal spacer and a double-seal system.

In the single-seal system , an organic sealant, typically a butyl material, is applied behind the spacer and serves both to hold the unit together and to prevent moisture intrusion. These seals are normally not adequate to contain special low-conductance gases.

In a double-seal system , a primary sealant, typically butyl, seals the spacer to the glass to prevent moisture migration and gas loss, and a secondary backing sealant, often silicone, provides structural strength. When sputtered Low-E coatings are used with double-seal systems, the coating must be removed from the edge first (“edge deletion”) to provide a better edge seal.

Since aluminum is an excellent conductor of heat, the aluminum spacer used in most standard edge systems represented a significant thermal “short circuit” at the edge of the IGU, which reduces the benefits of improved glazings. As the industry has switched from standard double-glazed IGUs to units with Low-E coatings and gas fills, the effect of this edge loss becomes even more pronounced. Under winter conditions, the typical aluminum spacer would increase the U-factor of a Low-E, gas fill unit slightly more than it would increase the U-factor of a standard double-glazed IGU. The smaller the glass area, the larger the effect of the edge on the overall product properties. In addition to the increased heat loss, the colder edge is more prone to condensation.

Fenestration product manufacturers have developed a series of innovative edge systems to address these problems, including solutions that depend on material substitutions as well as radically new designs. One approach to reducing heat loss has been to replace the aluminum spacer with a metal that is less conductive, e.g., stainless steel, and change the cross-sectional shape of the spacer. Another approach is to replace the metal with a design that uses materials that are better insulating. The most commonly used design incorporates spacer, sealer, and desiccant in a single tape element. The tape includes a solid, extruded thermoplastic compound that contains a blend of desiccant materials and incorporates a thin, fluted metal shim of aluminum or stainless steel. Another approach uses an insulating silicone foam spacer that incorporates a desiccant and has a high-strength adhesive at its edges to bond to glass. The foam is backed with a secondary sealant. Both extruded vinyl and pultruded fiberglass spacers have also been used in place of metal designs.

There are several hybrid designs that incorporate thermal breaks in metal spacers or use one or more of the elements described above. Some of these are specifically designed to accommodate three- and four-layer glazings or IGUs incorporating stretched plastic films. All are designed to interrupt the heat transfer pathway at the glazing edge between two or more glazing layers.

Warm edge spacers have become increasingly important as manufacturers switch from conventional double glazing to higher-performance glazing. For purposes of determining the overall fenestration product U-factor, the edge spacer has an effect that extends beyond the physical size of the spacer to a band about 63.5 mm (2.5 inches) wide. The contribution of this 63.5 mm (2.5-inch) wide "glass edge" to the total fenestration product U-factor depends on the size of the product. Glass edge effects are more important for smaller fenestration products, which have a proportionately larger glass edge area. For a typical residential-size window (0.8 by 1.2 meters , 3 by 4 feet), changing from a standard aluminum edge to a good-quality warm edge will reduce the overall fenestration product U-factor by 0.01 to 0.02 Btu/hr- $ft^2$-°F.