

FENESTRATION

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FENESTRATION is an architectural term that refers to the arrangement, proportion, and design of window, skylight, and door systems within a building. Fenestration components include glazing material, either glass or plastic; framing, mullions, muntins, dividers, and opaque door slabs; external shading devices; internal shading devices; and integral (between-glass) shading systems. For our purposes, **fenestration** and **fenestration systems** will refer to the basic assemblies and components of exterior window, skylight, and door systems within the building envelope. Fenestration can serve as a physical and/or visual connection to the outdoors, as well as a means to admit solar radiation. The solar radiation provides natural lighting, referred to as **daylighting**, and heat gain to a space. Fenestration can be fixed or operable, and operable units can allow natural ventilation to a space and egress in low-rise buildings.

Fenestration affects building energy use through four basic mechanisms—thermal heat transfer, solar heat gain, air leakage, and daylighting. The energy impacts of fenestration can be minimized by (1) using daylight to offset lighting requirements, (2) using appropriate glazings and shading strategies to control solar heat gain to supplement heating through passive solar gain and minimize cooling requirements, (3) using appropriate glazing to minimize conductive heat loss, and (4) specifying low air leakage fenestration products. In addition, natural ventilation strategies can reduce energy use for cooling and fresh air requirements.

Today designers, builders, energy codes, and energy-efficiency incentive programs [such as Energy Star (www.energystar.gov) and the LEED Green Building Program (www.usgbc.org)] are asking more and more from fenestration systems. Window, skylight, and door manufacturers are responding with new and improved products to meet those demands. With the advent of computer simulation software, designing to improve thermal performance of fenestration products has become much easier. Through participation in rating and certification programs (such as those of the National Fenestration Rating Council) that require the use of this software, fenestration manufacturers can take credit for these improvements through certified ratings that are credible to designers, builders, and code officials. A designer should consider architectural requirements, thermal performance, economic criteria, and human comfort when

selecting fenestration. Typically, a wide range of fenestration products are available that meet the specifications for a project. Refining the specifications to improve the energy performance and enhance a living or work space can result in lower energy costs, increased productivity, and improved thermal and visual comfort. Carmody et al. (1996) and CEA (1995) provide guidance for carrying out these requirements.

FENESTRATION COMPONENTS

Fenestration consists of glazing, framing, and in some cases shading devices and insect screens.

Glazing

The glazing unit may have single glazing or multiple glazing. The most common glazing material is glass, although plastic is also used. The glass or plastic may be clear, tinted, coated, laminated, patterned, or obscured. **Clear** glass transmits more than 80% of the incident solar radiation and more than 75% of the visible light. **Tinted** glass is available in many colors, all of which differ in the amount of solar radiation and visible light they transmit and absorb. **Coatings** on glass affect the transmission of solar radiation, and visible light may affect the absorbance of room temperature radiation. Some coatings are highly reflective (such as mirrors), while others are designed to have a very low reflectance. Some coatings result in a visible light transmittance that is as much as 1.4 times higher than the solar heat gain coefficient (desirable for good daylighting while minimizing cooling loads). **Laminated** glass is made of two panes of glass adhered together. The interlayer between the two panes of glass is typically plastic and may be clear, tinted, or coated. **Patterned** glass is a durable ceramic frit applied to a glass surface in a decorative pattern. **Obscured** glass is translucent and is typically used in privacy applications.

Insulating Glazing Units

Insulating glazing units (IGUs) are hermetically sealed, multiple-pane assemblies consisting of two or more glazing layers held and bonded at their perimeter by a spacer bar typically containing a desiccant material. The desiccated spacer is surrounded on at least two sides by a sealant that adheres the glass to the spacer. [Figure 1](#) shows the construction of a typical IGU.

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Glazing. Common types of glass used in IGUs are clear, tinted, and low emissivity (low-e). Due to its energy efficiency, daylighting, and comfort benefits, low-e coated glass is now used in more than 30% of all the fenestration products installed in the United States. Tinted and reflective glazing can also be used to reduce solar heat gain through fenestration products. Low-e coatings can also be applied to thin plastic films for use in IGUs. There are two types of low-e coating: **high-solar-gain** and **low-solar-gain**. The first of these primarily reduces heat conduction through the glazing system and is intended for cold climates. The second, for hot climates, reduces solar heat gain by blocking admission of the infrared portion of the solar spectrum. There are two ways of achieving low-solar-gain low-e performance. The first is with a special multilayer solar infrared reflecting coating. The second is with a solar infrared absorbing outer glass. To protect the inner glazing and the building interior from the absorbed heat from this outer glass, a cold-climate-type low-e coating is also used to reduce conduction of heat from the outer pane to the inner one. In addition, argon and krypton gas are used in lieu of air in the gap between the panes in combination with low-e glazing to further reduce energy transfer. Some manufacturers construct IGUs with one or more suspended, low-e coated plastic films between the glass panes and with a spacer that has better insulating properties and a dual sealant that improves the seal around the gas spaces.

Spacer. The spacer serves to separate the panes of glass and to provide the surface for primary and secondary sealant adhesion. Several types of spacers are used in IGU construction today. Each type provides different heat transfer properties depending on the spacer material and geometry.

Heat transfer at the edge of the IGU is greater than at the center of the IGU due to greater heat flow through the spacer system. Spacer systems have been developed to minimize the heat flow at the edge of the IGU. These spacer systems are referred to as **warm edge spacers**. In IGU construction, warm edge spacer designs reduce edge heat transfer by substituting materials that have lower thermal conductivity than aluminum (e.g., stainless steel, galvanized steel, tin plated steel, polymers, or foamed silicone). Traditional spacers are often made of aluminum.

Fusing or bending the corners of the spacer minimizes moisture and hydrocarbon vapor transmission into the air space through the corners. Desiccants such as molecular sieve or silica gel are also used to absorb moisture that was initially trapped in the IGU during assembly or gradually diffuses through the seals after construction.

Sealant(s). Several different sealant configurations are being used successfully in modern IGU construction. In all sealant configurations, the primary seal minimizes moisture and hydrocarbon

transmission. In dual-seal construction, the secondary seal provides structural integrity between the lites of the IGU. A secondary seal ensures long-term adhesion and greater resistance to solvents, oils, and short-term water immersion. In typical dual-seal construction, the primary seal is made of compressed polyisobutylene (PIB), and the secondary seal is made of silicone, polysulfide, or polyurethane. Single-seal construction depends on a single sealant to provide adhesion of the glass to the spacer as well as minimizing moisture and hydrocarbon transmission. Single-seal construction is generally more cost-efficient than dual-seal systems. A third type of sealant used in IGU construction takes advantage of advanced cross-linking polymers that provide both low moisture transmission and equivalent structural properties to dual-seal systems. These sealants are typically referred to as dual seal equivalent (DSE) materials.

Desiccants. Typical desiccants include molecular sieve, silica gel, or a matrix of both materials. Desiccants are used to absorb moisture that was initially trapped in the IGU during assembly or that gradually diffused through the seals after construction.

Gas Fill. The hermetically sealed space between glass panes in an IGU is most often filled with air. In some cases, argon and krypton gas are used in lieu of air in the space between the panes to further reduce the energy transfer.

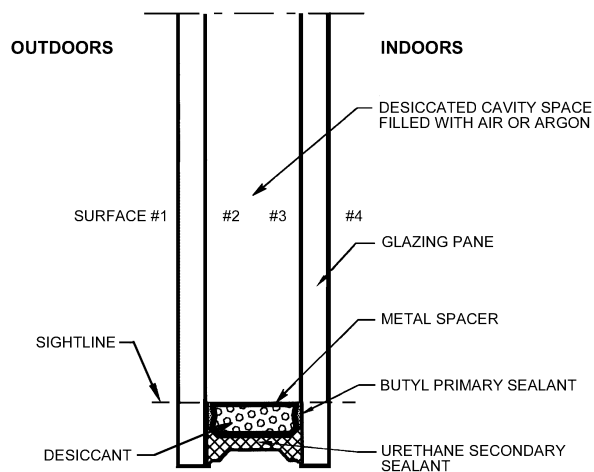


Fig. 1 Insulating Glazing Unit (IGU) Construction Detail

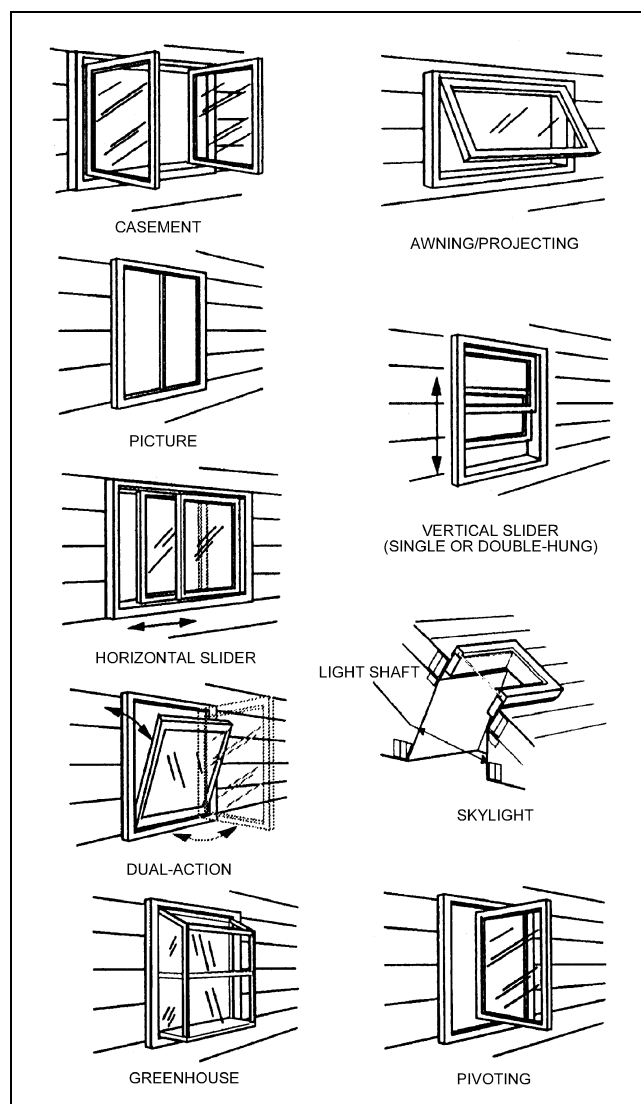


Fig. 2 Types of Residential Windows

Framing

The three main categories of window framing materials are wood, metal, and polymers. **Wood** has good structural integrity and insulating value but low resistance to weather, moisture, warpage, and organic degradation (from mold and insects). **Metal** is durable and has excellent structural characteristics, but it has very poor thermal performance. The metal of choice in windows is almost exclusively aluminum, due to ease of manufacture, low cost, and low mass, but aluminum has a thermal conductivity roughly 1000 times that of wood or polymers. The poor thermal performance of metal-frame windows can be improved with a thermal break (a nonmetal component that separates the metal frame exposed to the outside from the surfaces exposed to the inside). **Polymer** frames are made of extruded vinyl or poltruded fiberglass (glass-reinforced polyester). Their thermal and structural performance is similar to that of wood, although vinyl frames for large windows must be reinforced.

Manufacturers sometimes combine these materials as clad units (e.g., vinyl-clad aluminum, aluminum-clad wood, vinyl-clad wood) to increase durability, improve thermal performance, or improve aesthetics. In addition, curtain wall systems for commercial buildings may be structurally glazed, and the exterior “framing” is simply rubber gaskets or silicone.

Residential windows can be categorized by operator type, as shown in Figure 2. Traditionally there are several basic window types: casements, fixed picture windows, horizontal and vertical sliders, pivoting, awning, or projecting windows, dual acting windows, and special applications such as skylights and greenhouse or garden window inserts. The glazing system can be mounted either directly in the frame (a direct-glazed or direct-set window, which is not operable) or in a sash that moves in the frame (for an operating window). In operable windows, a weather-sealing system between the frame and sash reduces air and water leakage.

Shading

Shading devices are available in a wide range of products that differ greatly in their appearance and energy performance. Shading devices include interior and exterior blinds, integral blinds, interior and exterior screens, shutters, draperies, and roller shades. Shading devices on the exterior of the glazing reduce solar heat gain more effectively than interior devices. However, interior devices are easier to operate and adjust. Some products help insulate the indoors from the outdoors, while others redirect incoming solar radiation to minimize visual and thermal discomfort. Overhangs and vegetation can be effective shading too.

DETERMINING FENESTRATION ENERGY FLOW

Energy flows through fenestration via (1) conductive and convective heat transfer caused by the temperature difference between outdoor and indoor air, (2) net long-wave (above 2500 nm) radiative exchange between the fenestration and its surrounding and between glazing layers, and (3) short-wave (below 2500 nm) solar radiation incident on the fenestration product, either directly from the sun or reflected from the ground or adjacent objects. Simplified calculations are based on the observation that the temperatures of the sky, ground, and surrounding objects (and hence their radiant emission) correlate with the exterior air temperature. The radiative interchanges are then approximated by assuming that all the radiating surfaces (including the sky) are at the same temperature as the outdoor air. With this assumption, the basic equation for the instantaneous energy flow Q through a fenestration is

$$Q = UA_{pf}(t_{out} - t_{in}) + (SHGC)A_{pf}E_t \quad (1)$$

where

Q = instantaneous energy flow, W
 U = overall coefficient of heat transfer (U-factor), W/(m²·K)
 t_{in} = interior air temperature, °C
 t_{out} = exterior air temperature, °C
 A_{pf} = total projected area of fenestration, m²
 SHGC = solar heat gain coefficient, nondimensional
 E_t = incident total irradiance, W/m²

The quantities U and SHGC are instantaneous performance indices. The principal justification for Equation (1) is its simplicity, achieved by collecting all the linked radiative, conductive, and convective energy transfer processes into U and SHGC. These quantities vary because (1) convective heat transfer rates vary as fractional powers of temperature differences or free-stream speeds, (2) variations in temperature due to the weather or climate are small on the absolute temperature scale (°R) that controls radiative heat transfer rates, (3) fenestration systems always involve at least two thermal resistances in series, and (4) solar heat gain coefficients depend on solar incident angle and spectral distribution.

In the discussion of this chapter, Q is divided into two parts:

$$Q = Q_{th} + Q_{sol} \quad (2)$$

where

Q_{th} = instantaneous energy flow due to indoor-outdoor temperature difference (thermal energy flow)
 Q_{sol} = instantaneous energy flow due to solar radiation (solar energy flow)

The section on U-Factor (Thermal Transmittance) deals with Q_{th} , while the section on Solar Heat Gain and Visible Transmittance discusses Q_{sol} . In the latter section, both the effects of direct solar radiation and those of solar radiation scattered by the sky or ground are included.

Equation (1) presents a fenestration as it might appear on a building plan: a featureless, planar object filling an opening in the building envelope. Real fenestrations, however, are composite three-dimensional objects that may consist of frames, sashes, mullions, and other structural elements, as well as glazing systems. The latter in turn may contain structural spacers as well as glazing layers. There may in addition be shading elements, either as separate attachments or integrated into the glazing system.

The heat transfer through such an assembly of elements is calculated by dividing the fenestration area into parts, each of which has an energy flow that is more simply calculated than the total:

$$Q = \sum_v A_v q_v \quad (3)$$

where

q_v = energy flux (energy flow per unit area) of the v th part
 A_v = area of the v th part

This subdivision is applied to each of the terms in Equation (2) separately; for example, the thermal heat transfer through glazings and frames is frequently different, so that it is useful to make the following separation:

$$Q_{th} = A_f q_f + A_g q_g \quad (4)$$

where the subscript f refers to the frame, and g refers to the glazing (both for thermal energy flow). Similarly, solar radiation will have a different effect on the frame and the glazed area of a fenestration (since the former is generally opaque), so that

$$Q_{sol} = A_{op} q_{op} + A_s q_s \quad (5)$$

where the subscript *op* refers to the (opaque) frame (for solar energy flow), and *s* refers to the (solar-transmitting) glazing. This division into frame and glazing areas can be and usually is different for the solar and thermal energy flows. Subdivisions of this sort, when Equation (3) is compared with Equation (1), effectively make the overall U-factor and solar heat gain coefficient area-averaged quantities. This area averaging is described explicitly in the appropriate sections below. Note that in more complicated fenestrations, where the glazing portion may contain opaque shading elements, the opaque portion is that part that can never under any conditions admit solar radiation in any form other than heat. A window with a closed, perfectly opaque blind would not be considered an opaque element because sometimes the blind may be open. A section of curtain wall consisting of wall or frame elements with an exterior cover of glass (for uniform appearance) would be an opaque element in spite of its transparent covering.

A second type of subdivision occurs when, for a given part of the fenestration system, energy flow is driven by physical processes that are more complicated than those assumed in Equation (1). For example, the heat transfer through a glazing consists of a "contact" (i.e., glass-to-air) part and a radiative part, and the latter (q_R) may depend on radiant temperatures that are different from the air temperatures in Equation (1):

$$q = q_C + q_R \quad (6)$$

U-FACTOR (THERMAL TRANSMITTANCE)

In the absence of sunlight, air infiltration, and moisture condensation, the first term in Equation (1) represents the rate of thermal heat transfer through a fenestration system. Most fenestration systems consist of transparent multipane glazing units and opaque elements comprising the sash and frame (hereafter called **frame**). The glazing unit's heat transfer paths include a one-dimensional center-of-glass contribution and a two-dimensional edge contribution. The frame contribution is primarily two-dimensional.

Consequently, the total rate of heat transfer through a fenestration system can be calculated knowing the separate heat transfer contributions of the center glass, edge glass, and frame. (When present, glazing dividers, such as decorative grilles and muntins, also affect heat transfer, and their contribution must be considered.) The overall U-factor is estimated using area-weighted U-factors for each contribution by

$$U_o = \frac{U_{cg}A_{cg} + U_{eg}A_{eg} + U_fA_f}{A_{pf}} \quad (7)$$

where the subscripts *cg*, *eg*, and *f* refer to the center-of-glass, edge-of-glass, and frame, respectively. A_{pf} is the area of the fenestration product's rough opening in the wall or roof less installation clearances. When a fenestration product has glazed surfaces in only one direction (typical windows), the sum of the areas equals the projected area. Skylights, greenhouse/garden windows, bay/bow windows, etc., because they extend beyond the plane of the wall/roof, have greater surface area for heat loss than a window with a similar glazing option and frame material; consequently, U-factors for such products are expected to be greater.

DETERMINING FENESTRATION U-FACTORS

Center-of-Glass U-Factor

Heat flow across the central glazed portion of a multipane unit must consider both convective and radiative transfer in the gas space. Convective heat transfer is estimated based on high-aspect-

ratio, natural convection correlations for vertical and inclined air layers (El Sherbiny et al. 1982, Shewen 1986, Wright 1996). Radiative heat transfer (ignoring gas absorption) is quantified using a more fundamental approach. Computational methods solving the combined heat transfer problem have been devised (Rubin 1982a, 1982b, Hollands and Wright 1982).

Especially for single glass, U-factors depend strongly on indoor and outdoor film coefficients. The U-factor for single glass is

$$U = \frac{1}{1/h_o + 1/h_i + L/1000k} \quad (8)$$

where

h_o, h_i = outdoor and indoor respective glass surface heat transfer coefficients, $W/(m^2 \cdot K)$
 L = glass thickness, mm
 k = thermal conductivity, $W/(m \cdot K)$

Values for U_{cg} at standard indoor and outdoor conditions depend on such glazing construction features as the number of glazing lights, the gas-space dimensions, the orientation relative to vertical, the emissivity of each surface, and the composition of the fill gas. Several computer programs can be used to estimate glazing unit heat transfer for a wide range of glazing construction (Arasteh et al. 1994, Finlayson and Arasteh 1993, Wright 1995c). The National Fenestration Rating Council calls for WINDOW 4.1 (LBL 1994) as a standard calculation method for the center glazing. In Canada, the VISION program (Wright 1995b) is used to determine center-glazing properties for the Canadian Standards Association (CSA *Standard* A440.2).

[Figure 3](#) shows the effect of gas space width on U_{cg} for vertical double- and triple-pane glazing units. U-factors are plotted for air, argon, and krypton fill gases and for high (uncoated) and low (coated) values of surface emissivity. Gas space widths greater than 13 mm have no significant effect on U_{cg} , but greater glazing unit thicknesses decrease U_o since the length of the shortest heat flow path through the frame increases. A low-emissivity coating combined with krypton gas fill offers significant potential for reducing heat transfer in narrow gap-width glazing units.

Edge-of-Glass U-Factor

Insulating glazing units usually have continuous spacer members around the glass perimeter to separate the glazing and provide an edge seal. Aluminum spacers greatly increase conductive heat transfer between the contacted inner and outer glazing, thereby degrading the thermal performance of the glazing unit locally. The edge-of-glass area is typically taken to be a band 65 mm wide around the sightline. The width of this area is determined from the extent of two-dimensional heat transfer effects in current computer models, which are based on conduction-only analysis. In reality, due to convective and radiative effects, this area may extend beyond 65 mm (Beck et al. 1995, Curcija and Goss 1994, Wright and Sullivan 1995b), and it will depend on the type of insulating glazing unit and its thickness.

In low-conductivity frames, the heat flow at the edge-of-glass and frame area is through the spacer, and so the type of spacer has a greater impact on the edge-of-glass and frame U-factor. In metal frames, the edge-of-glass and frame U-factor varies little with the type of spacer (metal or insulating) because there is a significant heat flow through the highly conductive frame near the edge-of-glass area.

Frame U-Factor

Fenestration frame elements consist of all structural members exclusive of the glazing units and include sash, jamb, head, and sill members; meeting rails and stiles; mullions; and other glazing dividers. Estimating the rate of heat transfer through the frame is

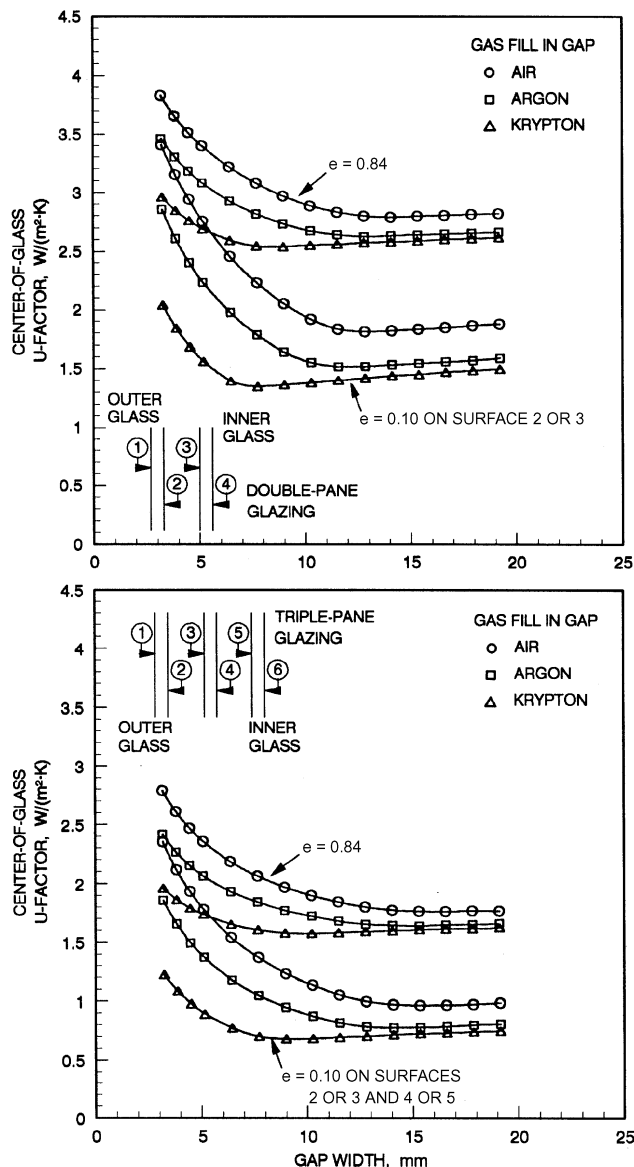


Fig. 3 Center of Glass U-Factor for Vertical Double- and Triple-Pane Glazing Units

complicated by (1) the variety of fenestration products and frame configurations, (2) the different combinations of materials used for frames, (3) the different sizes available, and, to a lesser extent, (4) the glazing unit width and spacer type. Internal dividers or grilles have little impact on the fenestration U-factor, provided there is at least a 3 mm gap between the divider and each panel of glass.

Computer simulations found that frame heat loss in most fenestration is controlled by a single component or controlling resistance, and only changes in this component significantly affect frame heat loss (EEL 1990). For example, the frame U-factor for thermally broken aluminum fenestration products is largely controlled by the depth of the thermal break material in the heat flow direction. For aluminum frames without a thermal break, the inside film coefficient provides most of the resistance to heat flow. For vinyl- and wood-framed fenestrations, the controlling resistance is the shortest distance between the inside and outside surfaces, which usually depends on the thickness of the sealed glazing unit.

Carpenter and McGowan (1993) experimentally validated frame U-factors for a variety of fixed and operable fenestration product

types, sizes, and materials using computer modeling techniques. Table 1 lists frame U-factors for a variety of frame and spacer materials and glazing unit thicknesses. Frame and edge U-factors are normally determined by two-dimensional computer simulation. The National Fenestration Rating Council requires that frame and edge U-factors be determined using the THERM (Arasteh et al. 2000) and FRAME (EEL 1995) computer programs. The Canadian Standards Association requires that frame and edge U-factors be determined using FRAME.

Curtain Wall Construction

A curtain wall is an exterior building wall that carries no roof or floor loads and consists entirely or principally of glass and other surfacing materials supported by a framework. A curtain wall typically has a metal frame. To improve the thermal performance of standard metal frames, manufacturers provide both traditional thermal breaks as well as thermally improved products. The traditional thermal break type is poured and debridged, where urethane is poured into a metal U-channel in the frame and then the bottom of the channel is removed by machine. For this system to work well, there must be a thermal break between the interior and the exterior for all of the frame components, including those in any operable sash. Skip debridging (incomplete pour and debridging used for increased structural strength) can significantly degrade the U-factor. Bolts that penetrate the thermal break also degrade performance, but to a lesser degree. Griffith et al. (1998) showed that stainless steel bolts spaced 300 mm on center increased the frame U-factor by 18%. The paper also concluded that, in general, the isothermal planes method referenced in Chapter 25 provides a conservative approach to determining U-factors.

Thermally improved curtain wall products are a more recent development. In these products, most of the metal frame tends to be located on the interior with only a metal cap exposed on the exterior. Plastic spacers isolate the glazing assembly from both the metal cap on the exterior and the metal frame on the interior. These products can have significantly better thermal performance than standard metal frames, but it is important to minimize the number and area of the bolts that penetrate from exterior to interior.

INDOOR AND OUTDOOR SURFACE HEAT TRANSFER COEFFICIENTS

Part of the overall thermal resistance of a fenestration system is due to the convective and radiative heat transfer between the exposed surfaces and the environment. Surface heat transfer coefficients h_o and h_i at the outer and inner glazing surfaces, respectively, combine the effects of radiation and convection.

The wind speed and orientation of the building are important in determining h_o . This relationship has long been studied, and many correlations have been proposed for h_o as a function of wind speed. However, no universal relationship has been accepted, and limited field measurements at low wind speeds by Klems (1989) show significant difference with values used by others.

Convective heat transfer coefficients are usually determined at standard temperature and air velocity conditions on each side. Wind speed can vary from less than 0.2 m/s for calm weather, free convection conditions, to over 29 m/s for storm conditions. A standard value of 29 $W/(m^2 \cdot K)$ corresponding to a 6.7 m/s wind is often used to represent winter design conditions. At near-zero wind speed, h_o varies with outside air and surface temperature, orientation to vertical, and air moisture content. At low wind speeds, the overall surface heat transfer coefficient can be as low as 6.8 $W/(m^2 \cdot K)$ (Yazdanian and Klems 1993).

For natural convection at the inner surface of a vertical fenestration product, the inner surface coefficient h_i depends on the indoor air and glass surface temperatures and on the emissivity of the glass inner surface. Table 2 shows the variation of h_i for winter ($t_i = 21^\circ C$)

Table 1 Representative Fenestration Frame U-Factors in W/(m²·K)—Vertical Orientation

Frame Material	Type of Spacer	Product Type/Number of Glazing Layers																
		Operable			Fixed			Garden Window		Plant-Assembled Skylight			Curtain Wall ^e			Sloped/Overhead Glazing ^e		
		Single ^b	Double ^c	Triple ^d	Single ^b	Double ^c	Triple ^d	Single ^b	Double ^c	Single ^b	Double ^c	Triple ^d	Single ^f	Double ^g	Triple ^h	Single ^f	Double ^g	Triple ^h
Aluminum without thermal break	All	13.51	12.89	12.49	10.90	10.22	9.88	10.67	10.39	44.57	39.86	39.01	17.09	16.81	16.07	17.32	17.03	16.30
Aluminum with thermal break ^a	Metal	6.81	5.22	4.71	7.49	6.42	6.30			39.46	28.67	26.01	10.22	9.94	9.37	10.33	9.99	9.43
	Insulated	n/a	5.00	4.37	n/a	5.91	5.79			n/a	26.97	23.39	n/a	9.26	8.57	n/a	9.31	8.63
Aluminum-clad wood/reinforced vinyl	Metal	3.41	3.29	2.90	3.12	2.90	2.73			27.60	22.31	20.78						
	Insulated	n/a	3.12	2.73	n/a	2.73	2.50			n/a	21.29	19.48						
Wood /vinyl	Metal	3.12	2.90	2.73	3.12	2.73	2.38	5.11	4.83	14.20	11.81	10.11						
	Insulated	n/a	2.78	2.27	n/a	2.38	1.99	n/a	4.71	n/a	11.47	9.71						
Insulated fiberglass/vinyl	Metal	2.10	1.87	1.82	2.10	1.87	1.82											
	Insulated	n/a	1.82	1.48	n/a	1.82	1.48											
Structural glazing	Metal												10.22	7.21	5.91	10.33	7.27	5.96
	Insulated												n/a	5.79	4.26	n/a	5.79	4.26

Note: This table should only be used as an estimating tool for the early phases of design.

^aDepends strongly on width of thermal break. Value given is for 9.5 mm.

^bSingle glazing corresponds to individual glazing unit thickness of 3 mm (nominal).

^cDouble glazing corresponds to individual glazing unit thickness of 19 mm (nominal).

^dTriple glazing corresponds to individual glazing unit thickness of 34.9 mm (nominal).

^eGlass thickness in curtainwall and sloped/overhead glazing is 6.4 mm.

^fSingle glazing corresponds to individual glazing unit thickness of 6.4 mm (nominal).

^gDouble glazing corresponds to individual glazing unit thickness of 25.4 mm (nominal).

^hTriple glazing corresponds to individual glazing unit thickness of 44.4 mm (nominal).

n/a Not applicable

Table 2 Indoor Surface Heat Transfer Coefficient h_i in W/(m²·K)—Vertical Orientation (Still Air Conditions)

Glazing ID	Glazing Type	Glazing Height, m	Winter Conditions			Summer Conditions		
			Glass Temp., °C	Temp. Diff., °C	h_i , W/(m ² ·K)	Glass Temp., °C	Temp. Diff., °C	h_i , W/(m ² ·K)
1	Single glazing	0.6	−9	30	8.04	33	9	4.12
		1.2	−9	30	7.42	33	9	3.66
		1.8	−9	30	7.10	33	9	3.43
5	Double glazing with 12.7 mm air space	0.6	7	14	7.72	35	11	4.28
		1.2	7	14	7.21	35	11	3.80
		1.8	7	14	6.95	35	11	3.55
23	Double glazing with $e = 0.1$ on surface 2 and 12.7 mm argon space	0.6	13	8	7.44	34	10	4.20
		1.2	13	8	7.00	34	10	3.73
		1.8	13	8	6.77	34	10	3.49
43	Triple glazing with $e = 0.1$ on surfaces 2 and 5 and 12.7 mm argon spaces	0.6	17	4	7.09	40	16	4.61
		1.2	17	4	6.72	40	16	4.08
		1.8	17	4	6.53	40	16	3.81

Notes:

Glazing ID refers to fenestration assemblies in Table 4.

Winter conditions: room air temperature $t_i = 21^\circ\text{C}$, outdoor air temperature $t_o = -18^\circ\text{C}$, no solar radiation

Summer conditions: room air temperature $t_i = 24^\circ\text{C}$, outdoor air temperature $t_o = 32^\circ\text{C}$, direct solar irradiance $E_D = 748 \text{ W/m}^2$

$h_i = h_{ic} + h_{ir} = 1.46(\Delta T/L)^{0.25} + e\Gamma(T_g^4 - T_i^4)/\Delta T$

where $\Delta T = T_g - T_i$, K; L = glazing height, m; T_g = glass temperature, K

and summer ($t_i = 24^\circ\text{C}$) design conditions, for a range of glass types and heights. Designers often use $h_i = 8.3 \text{ W/(m}^2\cdot\text{K)}$, which corresponds to $t_i = 21^\circ\text{C}$, glass temperature of -9°C , and uncoated glass with $e_g = 0.84$. For summer conditions, the same value [$h_i = 8.3 \text{ W/(m}^2\cdot\text{K)}$] is normally used, and it corresponds approximately to glass temperature of 35°C , $t_i = 24^\circ\text{C}$, and $e_g = 0.84$. For winter conditions, this most closely approximates single glazing with clear glass that is 600 mm tall, but it overestimates the value as the glazing unit conductance decreases and height increases. For summer conditions, this value approximates all types of glass that are 600 mm tall but, again, is less accurate as the glass height increases. If the room surface of the glass has a low-e coating, the h_i values are about halved at both winter and summer conditions.

Heat transfer between the glazing surface and its environment is driven not only by the local air temperatures but also by the radiant temperatures to which the surface is exposed. The radiant temperature of the indoor environment is generally assumed to be equal to the indoor air temperature. While this is a safe assumption where a

small fenestration product is exposed to a large room with surface temperatures equal to the air temperature, it is not valid in rooms where the fenestration product is exposed to other large areas of glazing surfaces (e.g., greenhouse, atrium) or to other cooled or heated surfaces (Parmelee and Huebscher 1947).

The radiant temperature of the outdoor environment is frequently assumed to be equal to the outdoor air temperature. This assumption may be in error, since additional radiative heat loss occurs between a fenestration and the clear sky (Duffie and Beckman 1980). Therefore, for clear-sky conditions, some effective outdoor temperature $t_{o,e}$ should replace t_o in Equation (1). For methods for determining $t_{o,e}$, see, for example, work by AGSL (1992). Note that a fully cloudy sky is assumed in ASHRAE design conditions.

The air space in an insulating glass panel made up of glass with no reflective coating on the air space surfaces has a coefficient h_s of $7.4 \text{ W/(m}^2\cdot\text{K)}$. When a reflective coating is applied to an air space surface, h_s can be selected from Table 3 by first calculating the effective air space emissivity $e_{s,e}$ by Equation (9):

Table 3 Air Space Coefficients for Horizontal Heat Flow

Air Space Thickness, mm	Air Space Temp., °C	Air Temp. Diff., °C	Air Space Coefficient h_s , W/(m ² ·K)					
			Effective Emissivity $e_{s,e}$					
			0.82	0.72	0.40	0.20	0.10	0.05
13	-15	5	5.0	4.6	3.3	2.6	2.2	2.0
		15	5.1	4.7	3.5	2.7	2.3	2.1
		30	5.7	5.3	4.0	3.2	2.8	2.7
		40	6.0	5.6	4.3	3.6	3.2	3.0
		50	6.3	5.9	4.6	3.8	3.4	3.2
	0	5	5.7	5.2	3.7	2.8	2.3	2.1
		15	5.7	5.3	3.8	2.9	2.4	2.2
		30	6.1	5.7	4.2	3.3	2.8	2.6
		40	6.4	6.0	4.5	3.5	3.1	2.8
		50	6.7	6.2	4.7	3.8	3.3	3.1
	10	5	6.1	5.6	4.0	3.0	2.4	2.2
		15	6.2	5.7	4.0	3.0	2.5	2.2
		30	6.5	6.0	4.3	3.3	2.8	2.5
		40	6.8	6.2	4.6	3.5	3.0	2.8
		50	7.0	6.5	4.8	3.8	3.3	3.0
	30	5	7.2	6.6	4.6	3.3	2.7	2.4
		15	7.3	6.6	4.6	3.3	2.7	2.4
		30	7.4	6.8	4.7	3.5	2.8	2.5
		40	7.6	6.9	4.9	3.6	3.0	2.7
		50	7.8	7.2	5.1	3.9	3.2	2.9
	50	5	8.4	7.7	5.2	3.7	2.9	2.5
		15	8.5	7.7	5.2	3.7	2.9	2.6
		30	8.5	7.8	5.3	3.8	3.0	2.6
		40	8.6	7.9	5.4	3.9	3.1	2.7
		50	8.8	8.0	5.5	4.0	3.2	2.8
10	-15	5	5.5	5.1	3.9	3.1	2.7	2.5
		30	5.7	5.3	4.0	3.2	2.9	2.7
		50	6.1	5.7	4.4	3.6	3.2	3.1
	0	5	6.2	5.7	4.3	3.3	2.9	2.6
		30	6.3	5.8	4.4	3.4	3.0	2.7
		50	6.6	6.1	4.6	3.7	3.2	3.0
	10	5	6.7	6.2	4.6	3.5	3.0	2.8
		30	6.8	6.3	4.6	3.6	3.1	2.8
		50	7.0	6.5	4.8	3.8	3.2	3.0
	30	5	7.8	7.2	5.2	3.9	3.3	3.0
		30	7.9	7.2	5.2	4.0	3.3	3.0
		50	8.0	7.3	5.3	4.0	3.4	3.1
	50	5	9.1	8.3	5.9	4.3	3.6	3.2
		30	9.1	8.4	5.9	4.4	3.6	3.2
		50	9.2	8.4	6.0	4.4	3.6	3.3
7	-15	<50	6.5	6.1	4.9	4.1	3.7	3.5
	0	<50	7.3	6.8	5.3	4.4	3.9	3.7
	10	<50	7.8	7.3	5.6	4.6	4.1	3.8
	30	<50	9.0	8.4	6.3	5.1	4.4	4.1
	50	<50	10.3	9.5	7.1	5.6	4.8	4.4
6	-15	<50	7.1	6.7	5.4	4.6	4.2	4.0
	0	<50	7.9	7.4	5.9	5.0	4.5	4.3
	10	<50	8.4	7.9	6.2	5.2	4.7	4.4
	30	<50	9.6	9.0	7.0	5.7	5.1	4.7
	50	<50	11.0	10.2	7.8	6.2	5.5	5.1
5	-15	<50	7.8	7.4	6.2	5.4	5.0	4.8
	0	<50	8.7	8.2	6.7	5.8	5.3	5.1
	10	<50	9.2	8.7	7.1	6.0	5.5	5.2
	30	<50	10.5	9.9	7.8	6.6	5.9	5.6
	50	<50	11.9	11.2	8.7	7.2	6.4	6.0

$$e_{s,e} = \frac{1}{1/e_o + 1/e_i - 1} \quad (9)$$

where e_o and e_i are the hemispherical emissivities of the two air space surfaces. Hemispherical emissivity of ordinary uncoated glass is 0.84 over a wavelength range of 0.4 to 40 μm .

REPRESENTATIVE U-FACTORS FOR FENESTRATION PRODUCTS

Table 4 lists computed U-factors for a variety of generic fenestration products. The table is based on ASHRAE-sponsored research involving laboratory testing and computer simulation of various fenestration products. In the past, test data were used to provide more accurate results for specific products (Hogan 1988). Computer simulations (with validation by testing) are now accepted as the standard method for accurate product-specific U-factor determination. The simulation methodologies are specified in the National Fenestration Rating Council's NFRC 100 or Canadian Standards Association (CSA) *Standard* A440.2 and are based on algorithms published in ISO *Standard* 15099. The *International Energy Conservation Code* (ICC 2000) and various state energy codes in the United States, the *National Energy Code* in Canada, and ASHRAE *Standards* 90.1 and 90.2 all cite these standards. Fenestration needs to be rated in accordance with the NFRC or CSA standards for code compliance. The use of Table 4 should be limited to that of an estimating tool for the early phases of design.

Values in Table 4 are listed at winter design conditions for vertical installation and for skylights and other sloped installations with glazing surfaces that are sloped 20° from the horizontal. Data are based on center-of-glass and edge-of-glass component U-factors and assume that there are no dividers. However, they apply only to the specific design conditions described in the footnotes in the table, and they are typically used only to determine peak load conditions for sizing heating equipment. While these U-factors have been determined for winter conditions, they can also be used to estimate heat gain during peak cooling conditions, since conductive gain, which is one of several variables, is usually a small portion of the total heat gain for fenestration in direct sunlight. Glazing designs and framing materials may be compared in choosing a fenestration system that needs a specific winter design U-factor.

Table 4 lists 48 glazing types. (A subset of these types is included in Table 13, which lists solar heat gain coefficients and visible light transmittance.) The multiple glazing categories are appropriate for sealed glazing units and the addition of storm sash to other glazing units. No distinction is made between flat and domed units such as skylights. For acrylic domes, use an average gas-space width to determine the U-factor. Note that garden window and sloped/pyramid/barrel vault skylight U-factors are approximately twice those of other similar products. While this is partially due to the difference in slope in the case of the sloped/pyramid/barrel vault skylights, it is largely because these products project out from the surface of the wall or roof. For instance, the skylight surface area, which includes the curb, can vary from 13 to 240% greater than the rough opening area, depending on the size and mounting method. Unless otherwise noted, all multiple-glazed units are filled with dry air. Argon units are assumed to be filled with 90% argon (Elmahdy and Yusuf 1995). U-factors for CO₂-filled units are similar to argon fills. For spaces up to 13 mm, argon/SF₆ (sulfur hexafluoride) mixtures up to 70% SF₆ are generally the same as argon fills. The use of krypton gas can provide U-factors lower than those for argon for glazing spaces less than 13 mm.

Table 4 provides data for six values of hemispherical emissivity and for 6.4 and 12.7 mm gas space widths. The emissivity of various low-e glasses varies considerably between manufacturers and processes. When the emissivity is between the listed values, interpolation may be used. When manufacturers' data are not available for

Table 4 U-Factors for Various Fenestration Products in W/(m²·K)

Product Type			Glass Only		Vertical Installation								
					Operable (including sliding and swinging glass doors)					Fixed			
Frame Type	Center of Glass	Edge of Glass	Aluminum Without Thermal Break	Aluminum With Thermal Break	Reinforced Vinyl/ Aluminum Clad Wood	Wood/ Vinyl	Insulated Fiberglass/ Vinyl	Aluminum Without Thermal Break	Aluminum With Thermal Break	Reinforced Vinyl/ Aluminum Clad Wood	Wood/ Vinyl	Insulated Fiberglass/ Vinyl	
Single Glazing													
1	3.2 mm glass	5.91	5.91	7.24	6.12	5.14	5.05	4.61	6.42	6.07	5.55	5.55	5.35
2	6.4 mm acrylic/polycarbonate	5.00	5.00	6.49	5.43	4.51	4.42	4.01	5.60	5.25	4.75	4.75	4.58
3	3.2 mm acrylic/polycarbonate	5.45	5.45	6.87	5.77	4.82	4.73	4.31	6.01	5.66	5.15	5.15	4.97
Double Glazing													
4	6.4 mm air space	3.12	3.63	4.93	3.70	3.25	3.13	2.77	3.94	3.56	3.19	3.17	3.04
5	12.7 mm air space	2.73	3.36	4.62	3.42	3.00	2.87	2.53	3.61	3.22	2.86	2.84	2.72
6	6.4 mm argon space	2.90	3.48	4.75	3.54	3.11	2.98	2.63	3.75	3.37	3.00	2.98	2.85
7	12.7 mm argon space	2.56	3.24	4.49	3.30	2.89	2.76	2.42	3.47	3.08	2.73	2.70	2.58
Double Glazing, e = 0.60 on surface 2 or 3													
8	6.4 mm air space	2.95	3.52	4.80	3.58	3.14	3.02	2.67	3.80	3.41	3.05	3.03	2.90
9	12.7 mm air space	2.50	3.20	4.45	3.26	2.85	2.73	2.39	3.42	3.03	2.68	2.66	2.54
10	6.4 mm argon space	2.67	3.32	4.58	3.38	2.96	2.84	2.49	3.56	3.17	2.82	2.80	2.67
11	12.7 mm argon space	2.33	3.08	4.31	3.13	2.74	2.62	2.28	3.28	2.89	2.54	2.52	2.40
Double Glazing, e = 0.40 on surface 2 or 3													
12	6.4 mm air space	2.78	3.40	4.66	3.46	3.03	2.91	2.56	3.66	3.27	2.91	2.89	2.76
13	12.7 mm air space	2.27	3.04	4.27	3.09	2.70	2.58	2.25	3.23	2.84	2.49	2.47	2.35
14	6.4 mm argon space	2.44	3.16	4.40	3.21	2.81	2.69	2.35	3.37	2.98	2.63	2.61	2.49
15	12.7 mm argon space	2.04	2.88	4.09	2.93	2.55	2.43	2.10	3.04	2.65	2.31	2.29	2.17
Double Glazing, e = 0.20 on surface 2 or 3													
16	6.4 mm air space	2.56	3.24	4.49	3.30	2.89	2.76	2.42	3.47	3.08	2.73	2.70	2.58
17	12.7 mm air space	1.99	2.83	4.05	2.89	2.52	2.39	2.07	2.99	2.60	2.26	2.24	2.13
18	6.4 mm argon space	2.16	2.96	4.18	3.01	2.63	2.51	2.17	3.13	2.74	2.40	2.38	2.26
19	12.7 mm argon space	1.70	2.62	3.83	2.68	2.33	2.21	1.89	2.75	2.36	2.03	2.01	1.90
Double Glazing, e = 0.10 on surface 2 or 3													
20	6.4 mm air space	2.39	3.12	4.36	3.17	2.78	2.65	2.32	3.32	2.93	2.59	2.56	2.45
21	12.7 mm air space	1.82	2.71	3.92	2.77	2.41	2.28	1.96	2.84	2.45	2.12	2.10	1.99
22	6.4 mm argon space	1.99	2.83	4.05	2.89	2.52	2.39	2.07	2.99	2.60	2.26	2.24	2.13
23	12.7 mm argon space	1.53	2.49	3.70	2.56	2.22	2.10	1.79	2.60	2.21	1.89	1.86	1.76
Double Glazing, e = 0.05 on surface 2 or 3													
24	6.4 mm air space	2.33	3.08	4.31	3.13	2.74	2.62	2.28	3.28	2.89	2.54	2.52	2.40
25	12.7 mm air space	1.70	2.62	3.83	2.68	2.33	2.21	1.89	2.75	2.36	2.03	2.01	1.90
26	6.4 mm argon space	1.87	2.75	3.96	2.81	2.44	2.32	2.00	2.89	2.50	2.17	2.15	2.03
27	12.7 mm argon space	1.42	2.41	3.61	2.48	2.15	2.02	1.71	2.50	2.11	1.79	1.77	1.67
Triple Glazing													
28	6.4 mm air space	2.16	2.96	4.11	2.89	2.51	2.45	2.16	3.10	2.73	2.38	2.33	2.25
29	12.7 mm air space	1.76	2.67	3.80	2.60	2.25	2.19	1.91	2.76	2.39	2.05	2.01	1.93
30	6.4 mm argon space	1.93	2.79	3.94	2.73	2.36	2.30	2.01	2.90	2.54	2.19	2.15	2.07
31	12.7 mm argon space	1.65	2.58	3.71	2.52	2.17	2.12	1.84	2.66	2.30	1.96	1.91	1.84
Triple Glazing, e = 0.20 on surface 2,3,4, or 5													
32	6.4 mm air space	1.87	2.75	3.89	2.69	2.32	2.27	1.98	2.86	2.49	2.15	2.10	2.03
33	12.7 mm air space	1.42	2.41	3.54	2.36	2.02	1.97	1.70	2.47	2.10	1.77	1.73	1.66
34	6.4 mm argon space	1.59	2.54	3.67	2.48	2.13	2.08	1.80	2.61	2.25	1.91	1.87	1.80
35	12.7 mm argon space	1.25	2.28	3.40	2.23	1.91	1.86	1.59	2.32	1.96	1.63	1.59	1.52
Triple Glazing, e = 0.20 on surfaces 2 or 3 and 4 or 5													
36	6.4 mm air space	1.65	2.58	3.71	2.52	2.17	2.12	1.84	2.66	2.30	1.96	1.91	1.84
37	12.7 mm air space	1.14	2.19	3.31	2.15	1.84	1.78	1.52	2.23	1.86	1.54	1.49	1.43
38	6.4 mm argon space	1.31	2.32	3.45	2.27	1.95	1.90	1.62	2.37	2.01	1.68	1.63	1.56
39	12.7 mm argon space	0.97	2.05	3.18	2.03	1.72	1.67	1.41	2.08	1.71	1.39	1.35	1.29
Triple Glazing, e = 0.10 on surfaces 2 or 3 and 4 or 5													
40	6.4 mm air space	1.53	2.49	3.63	2.44	2.10	2.05	1.77	2.57	2.20	1.86	1.82	1.75
41	12.7 mm air space	1.02	2.10	3.22	2.07	1.76	1.71	1.45	2.13	1.76	1.44	1.40	1.33
42	6.4 mm argon space	1.19	2.23	3.36	2.19	1.87	1.82	1.55	2.27	1.91	1.58	1.54	1.47
43	12.7 mm argon space	0.80	1.92	3.05	1.90	1.61	1.56	1.30	1.93	1.57	1.25	1.21	1.15
Quadruple Glazing, e = 0.10 on surfaces 2 or 3 and 4 or 5													
44	6.4 mm air spaces	1.25	2.28	3.40	2.23	1.91	1.86	1.59	2.32	1.96	1.63	1.59	1.52
45	12.7 mm air spaces	0.85	1.96	3.09	1.94	1.65	1.60	1.34	1.98	1.62	1.30	1.26	1.19
46	6.4 mm argon spaces	0.97	2.05	3.18	2.03	1.72	1.67	1.41	2.08	1.71	1.39	1.35	1.29
47	12.7 mm argon spaces	0.68	1.83	2.96	1.82	1.54	1.48	1.23	1.84	1.47	1.16	1.11	1.05
48	6.4 mm krypton spaces	0.68	1.83	2.96	1.82	1.54	1.48	1.23	1.84	1.47	1.16	1.11	1.05

Notes:

1. All heat transmission coefficients in this table include film resistances and are based on winter conditions of -18°C outdoor air temperature and 21°C indoor air temperature, with 6.7 m/s outdoor air velocity and zero solar flux. With the exception of single glazing, small changes in the indoor and outdoor temperatures will not significantly affect overall U-factors. The coefficients are for vertical position except skylight values, which are for 20° from horizontal with heat flow up.

2. Glazing layer surfaces are numbered from the outdoor to the indoor. Double, triple, and quadruple refer to the number of glazing panels. All data are based on 3 mm glass, unless otherwise noted. Thermal conductivities are: 0.917 W/(m·K) for glass, and 0.19 W/(m·K) for acrylic and polycarbonate.

3. Standard spacers are metal. Edge-of-glass effects assumed to extend over the 65 mm band around perimeter of each glazing unit.

Table 4 U-Factors for Various Fenestration Products in W/(m²·K) (Concluded)

Vertical Installation					Sloped Installation									ID
Garden Windows		Curtain Wall			Glass Only (Skylights)		Manufactured Skylight				Site-Assembled Sloped/Overhead Glazing			
Aluminum Without Thermal Break	Wood/Vinyl	Aluminum Without Thermal Break	Aluminum With Thermal Break	Structural Glazing	Center of Glass	Edge of Glass	Aluminum Without Thermal Break	Aluminum With Thermal Break	Reinforced Vinyl/Aluminum Clad	Wood/Vinyl	Aluminum Without Thermal Break	Aluminum With Thermal Break	Structural Glazing	
14.76	13.13	6.93	6.30	6.30	6.76	6.76	11.24	10.73	9.96	8.34	7.73	7.09	7.09	1
13.23	11.71	6.11	5.48	5.48	5.85	5.85	10.33	9.82	9.07	7.45	6.90	6.26	6.26	2
14.00	12.42	6.52	5.89	5.89	6.30	6.30	10.79	10.27	9.52	7.89	7.31	6.67	6.67	3
10.30	9.16	4.47	3.84	3.59	3.29	3.75	7.44	6.32	5.94	4.79	4.64	3.99	3.74	4
9.72	8.68	4.14	3.51	3.26	3.24	3.71	7.39	6.27	5.90	4.74	4.59	3.95	3.70	5
9.97	8.88	4.28	3.65	3.40	3.01	3.56	7.19	6.06	5.70	4.54	4.40	3.75	3.50	6
9.47	8.47	3.99	3.36	3.11	3.01	3.56	7.19	6.06	5.70	4.54	4.40	3.75	3.50	7
10.05	8.95	4.33	3.70	3.45	3.07	3.60	7.24	6.11	5.75	4.59	4.45	3.80	3.55	8
9.38	8.40	3.94	3.31	3.06	3.01	3.56	7.19	6.06	5.70	4.54	4.40	3.75	3.50	9
9.63	8.61	4.09	3.46	3.21	2.78	3.40	6.98	5.86	5.49	4.34	4.20	3.56	3.31	10
9.13	8.19	3.80	3.17	2.92	2.78	3.40	6.98	5.86	5.49	4.34	4.20	3.56	3.31	11
9.80	8.75	4.18	3.55	3.30	2.90	3.48	7.09	5.96	5.59	4.44	4.30	3.66	3.41	12
9.05	8.12	3.75	3.12	2.87	2.84	3.44	7.03	5.91	5.54	4.39	4.25	3.61	3.36	13
9.30	8.33	3.89	3.26	3.01	2.50	3.20	6.73	5.60	5.24	4.09	3.96	3.32	3.07	14
8.71	7.83	3.55	2.92	2.67	2.61	3.28	6.83	5.70	5.34	4.19	4.06	3.41	3.16	15
9.47	8.47	3.99	3.36	3.11	2.61	3.28	6.83	5.70	5.34	4.19	4.06	3.41	3.16	16
8.62	7.76	3.50	2.87	2.63	2.61	3.28	6.83	5.70	5.34	4.19	4.06	3.41	3.16	17
8.88	7.98	3.65	3.02	2.77	2.22	3.00	6.47	5.34	4.99	3.84	3.72	3.07	2.83	18
8.19	7.40	3.26	2.63	2.38	2.27	3.04	6.52	5.39	5.04	3.89	3.77	3.12	2.87	19
9.21	8.26	3.84	3.22	2.97	2.50	3.20	6.73	5.60	5.24	4.09	3.96	3.32	3.07	20
8.36	7.55	3.36	2.73	2.48	2.50	3.20	6.73	5.60	5.24	4.09	3.96	3.32	3.07	21
8.62	7.76	3.50	2.87	2.63	2.04	2.88	6.31	5.18	4.84	3.69	3.57	2.93	2.68	22
7.94	7.18	3.11	2.48	2.23	2.16	2.96	6.41	5.29	4.94	3.79	3.67	3.03	2.78	23
9.13	8.19	3.80	3.17	2.92	2.39	3.12	6.62	5.50	5.14	3.99	3.87	3.22	2.97	24
8.19	7.40	3.26	2.63	2.38	2.44	3.16	6.67	5.55	5.19	4.04	3.91	3.27	3.02	25
8.45	7.62	3.41	2.78	2.53	1.93	2.79	6.21	5.08	4.73	3.58	3.48	2.83	2.58	26
7.76	7.04	3.01	2.39	2.14	2.04	2.88	6.31	5.18	4.84	3.69	3.57	2.93	2.68	27
see note 7	see note 7	3.58	2.97	2.65	2.22	3.00	6.38	5.07	4.77	3.63	3.65	3.02	2.71	28
		3.24	2.63	2.31	2.04	2.88	6.22	4.92	4.62	3.48	3.51	2.88	2.56	29
		3.39	2.77	2.46	1.99	2.83	6.17	4.86	4.56	3.43	3.46	2.83	2.51	30
		3.14	2.53	2.21	1.87	2.75	6.07	4.76	4.46	3.33	3.36	2.73	2.41	31
see note 7	see note 7	3.34	2.73	2.41	1.93	2.79	6.12	4.81	4.51	3.38	3.41	2.78	2.46	32
		2.95	2.33	2.02	1.76	2.67	5.96	4.65	4.36	3.22	3.26	2.63	2.32	33
		3.09	2.48	2.16	1.59	2.54	5.81	4.50	4.21	3.07	3.11	2.49	2.17	34
		2.80	2.19	1.87	1.53	2.49	5.75	4.44	4.15	3.02	3.07	2.44	2.12	35
see note 7	see note 7	3.14	2.53	2.21	1.65	2.58	5.86	4.55	4.26	3.12	3.16	2.53	2.22	36
		2.70	2.09	1.77	1.53	2.49	5.75	4.44	4.15	3.02	3.07	2.44	2.12	37
		2.85	2.24	1.92	1.36	2.36	5.60	4.29	4.00	2.86	2.92	2.29	1.97	38
		2.55	1.94	1.62	1.25	2.28	5.49	4.18	3.90	2.76	2.82	2.19	1.87	39
see note 7	see note 7	3.05	2.43	2.11	1.53	2.49	5.75	4.44	4.15	3.02	3.07	2.44	2.12	40
		2.60	1.99	1.67	1.42	2.41	5.65	4.34	4.05	2.91	2.97	2.34	2.02	41
		2.75	2.14	1.82	1.19	2.23	5.44	4.13	3.84	2.71	2.77	2.14	1.82	42
		2.40	1.79	1.47	1.14	2.19	5.38	4.07	3.79	2.66	2.72	2.09	1.78	43
see note 7	see note 7	2.80	2.19	1.87	1.25	2.28	5.49	4.18	3.90	2.76	2.82	2.19	1.87	44
		2.45	1.84	1.52	1.08	2.14	5.33	4.02	3.74	2.60	2.67	2.04	1.73	45
		2.55	1.94	1.62	1.02	2.10	5.28	3.97	3.69	2.55	2.62	1.99	1.68	46
		2.31	1.69	1.38	0.91	2.01	5.17	3.86	3.59	2.45	2.52	1.90	1.58	47
		2.31	1.69	1.38	0.74	1.87	5.01	3.70	3.43	2.29	2.38	1.75	1.43	48

4. Product sizes are described in Figure 4, and frame U-factors are from Table 1.

5. Use $U = 3.40$ W/(m²·K) for glass block with mortar but without reinforcing or framing.

6. The use of this table should be limited to that of an estimating tool for the early phases of design.

7. Values for triple- and quadruple-glazed garden windows are not listed as these are not common products.

8. Minor differences exist between the data in this table and U-factors determined using NFRC 100-91 because the data in this table are generated using modified heat transfer correlations for glazing cavities (Wright 1996) and indoor fenestration surfaces (Curcija and Goss 1995b).

low-e glass, assume that glass with a pyrolytic (hard) coating has an emissivity of 0.40 and that glass with a sputtered (soft) coating has an emissivity as low as 0.36. Tinted glass does not change the winter U-factor. Also, some reflective glass may have an emissivity less than 0.84. Values listed are for insulating glass units using aluminum edge spacers. If an insulated or nonmetallic spacer is used, the U-factors are approximately $0.17 \text{ W}/(\text{m}^2 \cdot \text{K})$ lower.

Fenestration product types are subdivided first by vertical versus sloped installation and then into two general categories—manufactured and site-assembled. “Manufactured” is intended to represent products delivered as a complete unit to the site. These products are typically installed in low-rise residential and small commercial/institutional/industrial buildings. For vertical sliders, horizontal sliders, casement, awning, pivoted, and dual-action windows, and for sliding and swinging glass doors, use the operable category. For picture windows, use the fixed category. For products that project out from the surface of the wall, use the garden window category. For skylights, use the sloped skylight category.

“Site-assembled” is intended to represent products where frame extrusions are assembled on site into a fenestration product and then glazing is added on site. These products are typically installed in high-rise residential and larger commercial/institutional/industrial buildings. Curtain walls are typically made up of vision (transparent portion) and spandrel (opaque portion) panels. Table 4 contains representative U-factors for the vision panel (including mullions) for these assemblies. The spandrel portion of curtain walls usually consists of a metal pan filled with insulation and covered with a sheet of glass or other weatherproof covering. Although the U-factor in the center of the spandrel panel can be quite low, the metal pan is a thermal bridge, significantly increasing the U-factor of the assembly. Two-dimensional simulation validated by testing of a curtain wall having an aluminum frame with a thermal break found that the U-factor for the edge of the spandrel panel (the 65 mm band around the perimeter adjacent to the frame) was 40% of the way toward the U-factor of the frame. The U-factor was $0.34 \text{ W}/(\text{m}^2 \cdot \text{K})$ for the center of the spandrel, 2.56 for the edge of the spandrel, and 6.02 for the

frame (Carpenter and Elmahdy 1994). Two-dimensional heat transfer analysis or physical testing is recommended to determine the U-factor of spandrel panels. Use the sloped/overhead glazing category for sloped glazing panels comparable to curtain walls.

Physical testing of double-glazed units showed U-factors of $5.7 \text{ W}/(\text{m}^2 \cdot \text{K})$ for a thermally broken aluminum pyramidal skylight and $7.4 \text{ W}/(\text{m}^2 \cdot \text{K})$ for an aluminum-frame half-round barrel vault (both normalized to a rough opening of 2.4 m by 2.4 m). Until more conclusive results are available, U-factors for these systems can be estimated by multiplying the “site-assembled sloped/overhead glazing” values in Table 4 by the ratio of total product surface area (including curbs) to rough opening area. These ratios range from 1.2 to 2.0 for low-slope skylights, 1.4 to 2.1 for pyramid assemblies sloped at 45° , and 1.7 to 2.9 for semicircular barrel vault assemblies. An example calculation is provided in Example 4.

The U-factors in Table 4 are based on the definitions of the six product types, frame sizes, and proportion of frame to glass area shown in Figure 4. Four of the products are manufactured fenestration products. The operable category glazing units are 1.35 m^2 in area, and the overall size corresponds to a 900 mm by 1500 mm fenestration product. The fixed (nonoperable) category is about 1.44 m^2 in area, and the overall size corresponds to a 1200 mm by 1200 mm window. The garden window category is 1.35 m^2 in projected area (3.15 m^2 in surface area) and 1500 mm wide by 900 mm high by 380 mm deep. The manufactured skylight category is a nominal 0.72 m^2 in area, corresponding to a 600 mm by 1200 mm skylight. The nominal dimensions of a roof-mounted skylight correspond to centerline spacing of roof framing members; consequently, the rough opening dimensions are 570 mm by 1180 mm. The curtain wall and sloped/overhead glazing categories are a nominal 1.44 m^2 in area, representing repeating 1200 mm by 1200 mm panels. The nominal dimensions correspond to centerline spacing of the head and sill and vertical mullions.

Six frame types are listed (although not all for any one category) in order of improving thermal performance. The most conservative assumption is to use the frame category of aluminum frame without

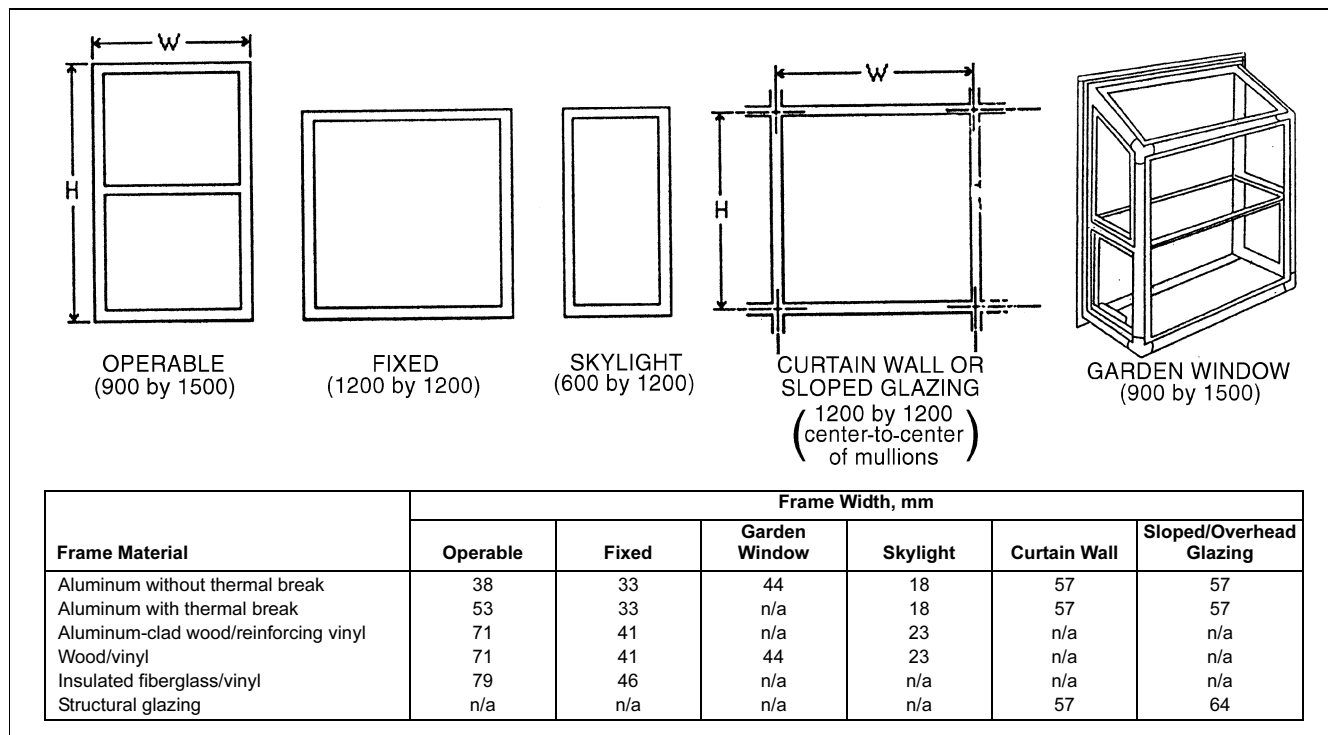


Fig. 4 Standard Fenestration Units

Table 5 Glazing U-Factors for Various Wind Speeds

Wind Speed, km/h		
24	12	0
U-Factor, W/(m ² ·K)		
0.5	0.46	0.42
1.0	0.92	0.85
1.5	1.33	1.27
2.0	1.74	1.69
2.5	2.15	2.12
3.0	2.56	2.54
3.5	2.98	2.96
4.0	3.39	3.38
4.5	3.80	3.81
5.0	4.21	4.23
5.5	4.62	4.65
6.0	5.03	5.08
6.5	5.95	5.50

a thermal break (although there are products on the market that have higher U-factors). The aluminum frame with a thermal break is for frames having at least a 10 mm thermal break between the inside and outside for all members including both the frame and the operable sash, if applicable. (Products are available with significantly wider thermal breaks, which achieve considerable improvement.) The reinforced vinyl/aluminum clad wood category represents vinyl-frame products, such as sliding glass doors or large windows that have extensive metal reinforcing within the frame and wood products with extensive metal, usually on the exterior surface of the frame. Both of these factors provide short circuits, which degrade the thermal performance of the frame material. The wood/vinyl frame is meant to represent the improved thermal performance that is possible if the thermal short circuits from the previous frame category do not exist. Insulated fiberglass/vinyl represents fiberglass or vinyl frames that do not have metal reinforcing and whose frame cavities are filled with insulation. For several site-assembled product types, there is a structural glazing frame category that is intended to represent products where sheets of glass are butt-glazed to each other using a sealant only, and none of the framing members is exposed to the exterior. For glazing with a steel frame, use aluminum frame values. For aluminum window with wood trim or vinyl cladding, use the values for aluminum. Frame type refers to the primary unit. Thus, when storm sash is added over another fenestration product, use the values given for the nonstorm product.

To estimate the overall U-factor of a fenestration product that differs significantly from the assumptions given in Table 4 and/or Figure 4, first determine the area that is frame/sash, center-of-glass, and edge-of-glass (based on a 65 mm band around the perimeter of each glazing unit). Next, determine the appropriate component U-factors. These can be taken either from the standard values listed in italics in Table 4 for glass, from the values in Table 1 for frames, or from some other source such as test data or computed factors. Finally, multiply the area and the component U-factors, sum these products, and then divide by the rough opening in the building envelope where this product will fit to obtain the overall U-factor U_o .

Table 5 provides approximate data to convert the overall U-factor at one wind condition to a U-factor at another.

REPRESENTATIVE U-FACTORS FOR DOORS

Doors are often an overlooked component in the thermal integrity of the building envelope. Although swinging and revolving doors represent a small portion of the shell in residential, commercial, and institutional buildings, their U-factor is usually many times higher than that of the walls or ceilings. In some storage and

Table 6 U-Factors of Doors in W/(m²·K)

			Double Glazing with 12.7 mm	Double Glazing with 12.7 mm <i>e</i> = 0.10, Argon
Door Type	No Glazing	Single Glazing	Air Space	
SWINGING DOORS (Rough Opening—970 mm × 2080 mm)				
<i>Slab Doors</i>				
Wood slab in wood frame ^a	2.61			
6% glazing (560 × 200 lite)	—	2.73	2.61	2.50
25% glazing (560 × 910 lite)	—	3.29	2.61	2.38
45% glazing (560 × 1620 lite)	—	3.92	2.61	2.21
More than 50% glazing	Use Table 5 (operable)			
Insulated steel slab with wood edge in wood frame ^a	0.91			
6% glazing (560 × 200 lite)	—	1.19	1.08	1.02
25% glazing (560 × 910 lite)	—	2.21	1.48	1.31
45% glazing (560 × 1630 lite)	—	3.29	1.99	1.48
More than 50% glazing	Use Table 5 (operable)			
Foam insulated steel slab with metal edge in steel frame ^b	2.10			
6% glazing (560 × 200 lite)	—	2.50	2.33	2.21
25% glazing (560 × 910 lite)	—	3.12	2.73	2.50
45% glazing (560 × 1630 lite)	—	4.03	3.18	2.73
More than 50% glazing	Use Table 5 (operable)			
Cardboard honeycomb slab with metal edge in steel frame	3.46			
<i>Stile- and -Rail Doors</i>				
Sliding glass doors/ French doors	Use Table 5 (operable)			
<i>Site-Assembled Stile- and -Rail Doors</i>				
Aluminum in aluminum frame	—	7.49	5.28	4.49
Aluminum in aluminum frame with thermal break	—	6.42	4.20	3.58
REVOLVING DOORS (Rough Opening—2080 mm × 2130 mm)				
Aluminum in aluminum frame				
Open	—	7.49	—	—
Closed	—	3.69	—	—
SECTIONAL OVERHEAD DOORS (Nominal—3050 mm × 3050 mm)				
Uninsulated steel				
(nominal <i>U</i> = 6.53)	6.53	—	—	—
Insulated steel				
(nominal <i>U</i> = 0.62)	1.36	—	—	—
Insulated steel with thermal break				
(nominal <i>U</i> = 0.45)	0.74	—	—	—

Note: All dimensions are in millimetres.

^a Thermally broken sill [add 0.17 W/(m²·K) for non-thermally broken sill]

^b Non-thermally broken sill

^c Nominal U-factors are through the center of the insulated panel before consideration of thermal bridges around the edges of the door sections and due to the frame.

industrial buildings, loading bay doors (overhead doors) represent a significant area of high heat loss. Table 6 contains representative U-factors for swinging, overhead, and revolving doors determined through computer simulation (Carpenter and Hogan 1996). These are generic values, and product-specific values determined in accordance with standards should be used whenever available. NFRC 100, Section B, and CSA Standard A453 give procedures for evaluating the performance of swinging doors. Overhead doors are often evaluated in accordance with National Association of Garage Door Manufacturers (NAGDM) Standard 105. Where these standards are cited in codes, they must be used for compliance.

Swinging doors can be divided into two categories: slab and stile-and-rail. A stile-and-rail door is a swinging door with a full-glass insert supported by horizontal rails and vertical stiles. The stiles and rails are typically either solid wood members or extruded aluminum or vinyl, as shown in Figure 5. Most residential doors are slab type with either solid wood, steel, or fiberglass skin over foam insulation in a wood frame with aluminum sill. The edges of the

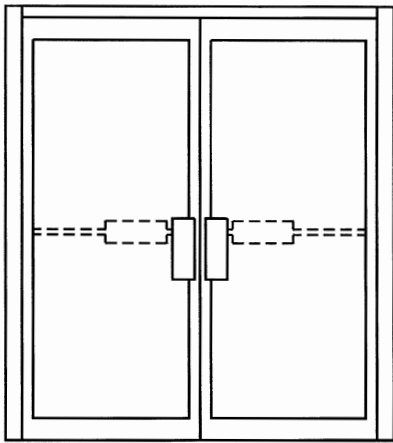


Fig. 5 Details of Stile-and-Rail Door

steel skin door are normally wood to provide a thermal break. In commercial construction, doors are either steel skin over foam insulation in a steel frame (i.e., utility doors) or a full glass door made up of aluminum stiles, rails, and frame (i.e., entrance doors). The most important factors affecting door U-factor are material construction, glass size, and glass type. Frame depth, slab width, and number of panels have a minor effect on door performance. Sidelites and double doors have U-factors similar to a single door of the same construction. For wood slab doors in a wood frame, the glazing area does not have much effect on the U-factor. For the insulated steel slab in a wood frame, however, glazing area has a strong effect on U-factor. Typical commercial insulated slab doors have a U-factor approximately twice that of residential insulated doors, the prime reason being thermal bridging of the slab edge and the steel frame. Stile-and-rail doors, even if thermally broken, have U-factors 50% higher than a full-glass commercial steel slab door.

There are three generic types of overhead doors: roll-up, uninsulated sectional, and insulated sectional. Metal roll-up doors consist of small metal plates of approximately 65 mm in height that “roll up” around a metal rod to open. Sectional doors consist of a series of 600 mm high sections that travel in a track to open. There is a wide range in the design of insulated overhead doors. Factors affecting heat transfer include width of insulation, thermal break design (if any), and design of interior skin. For the uninsulated sectional door, there is very little difference between the center value and the total value: essentially the value of single glazing. The center of the insulated door has low U-factors, but thermal bridging at the door and section edges significantly increases the total U-factor. For doors without thermally broken edges, the total value is 2.5 to 3.3 times greater than the center value. The addition of a good thermal break design reduces this increase to a 1.6 multiplier.

Many commercial buildings use revolving entrance doors. Most of these doors are of similar design: single glazing in an aluminum frame without thermal break. The door, however, can be in two positions: closed (X shaped as viewed from above) or open (+ shaped). At nighttime, these doors are locked in the X position, effectively creating a double-glazed system. During the daytime, the door revolves and is often left positioned so that there is only one glazing between the inside and outside (+ position). U-factors are given in Table 6 for both positions.

EXAMPLES

Example 1. Estimate the U-factor for a manufactured fixed fenestration product with a reinforced vinyl frame and double-glazing with a sputter-type low-e coating ($e = 0.10$). The gap is 13 mm wide and argon-filled, and the spacer is metal.

Solution: Locate the glazing system type in the first column of Table 4 (ID = 23), then find the appropriate product type (fixed) and frame type (reinforced vinyl). The U-factor listed (in the tenth column of U-factors) is $1.89 \text{ W}/(\text{m}^2 \cdot \text{K})$.

Example 2. Estimate a representative U-factor for a wood-framed, 970 mm by 2080 mm swinging French door with eight 280 mm by 400 mm panes (true divided panels), each consisting of clear double-glazing with a 6.5 mm air space and a metal spacer.

Solution: Without more detailed information, assume that the dividers have the same U-factor as the frame and that the divider edge has the same U-factor as the edge-of-glass. Calculate the center-of-glass, edge-of-glass, and frame areas:

$$A_{cg} = 8[(280 - 130)(400 - 130)]/10^6 = 0.324 \text{ m}^2$$

$$A_{eg} = 8(280 \times 400)/10^6 - 0.324 = 0.572 \text{ m}^2$$

$$A_f = (970 \times 2080)/10^6 - 8(280 \times 400)/10^6 = 1.122 \text{ m}^2$$

Select the center-of-glass, edge-of-glass, and frame U-factors. These component U-factors are 3.29 and $3.63 \text{ W}/(\text{m}^2 \cdot \text{K})$ (from Table 4, glazing ID = 4, U-factor columns 1 and 2) and $2.90 \text{ W}/(\text{m}^2 \cdot \text{K})$ (from Table 1, wood frame, metal spacer, operable, double-glazing), respectively. From Equation (7),

$$U_o = \frac{(3.12 \times 0.324) + (3.63 \times 0.572) + (2.90 \times 1.122)}{(0.97 \times 2.08)} \\ = 3.14 \text{ W}/(\text{m}^2 \cdot \text{K})$$

Example 3. Estimate the overall average U-factor for a multifloor curtain wall assembly that is part vision glass and part opaque spandrel. The typical floor-to-floor height is 3.6 m, and the building module is 1.2 m as reflected in the spacing of the mullions both horizontally and vertically. For a representative section 1.2 m wide and 3.6 m tall, one of the modules is glazed and the other two are opaque. The mullions are aluminum frame with a thermal break 80 mm wide and centered on the module. The IGU is double glazing with a pyrolytic low-e coating ($e = 0.40$) and has a 13 mm gap filled with air and a metal spacer. The spandrel panel has a metal pan backed by $R = 3.5 \text{ m}^2 \cdot \text{K}/\text{W}$ insulation and no intermediate reinforcing members.

Solution: It is necessary to calculate the U-factor for the glazed module and for the opaque spandrel modules and then to do an area-weighted average to determine the average U-factor for the overall curtain wall assembly.

First, calculate the overall U-factor for the glazed module. Calculate the center-of-glass, edge-of-glass, and frame areas. The glazed area is 1120 mm by 1120 mm (1200 mm module, 1200 mm of mullions on each edge).

$$A_{cg} = (1120 - 130)(1120 - 130)/10^6 = 0.9801 \text{ m}^2$$

$$A_{eg} = (1120 \times 1120)/10^6 - 0.9801 = 0.2743 \text{ m}^2$$

$$A_f = [(1200 \times 1200)/10^6 - (1120 \times 1120)]/10^6 = 0.1856 \text{ m}^2$$

Select the center-of-glass, edge-of-glass, and frame U-factors. These component U-factors are 2.27 and $3.04 \text{ W}/(\text{m}^2 \cdot \text{K})$ (from Table 4, ID = 13, columns 1 and 2) and $9.94 \text{ W}/(\text{m}^2 \cdot \text{K})$ (from Table 1, aluminum frame with a thermal break, metal spacer, curtain wall, double glazing), respectively. From Equation (7),

$$U_{\text{glazing module}} = \frac{(2.27 \times 0.9801) + (3.04 \times 0.2743) + (9.94 \times 0.1856)}{(1.2 \times 1.2)} \\ = 3.41 \text{ W}/(\text{m}^2 \cdot \text{K})$$

Then, calculate the overall U-factor for the two opaque spandrel modules. The center-of-spandrel, edge-of-spandrel, and frame areas are the same as the glazed module. The frame U-factor is the same. Calculate the center-of-spandrel U-factor. In this particular case, the R-value of the insulation does not need to be rated as there are no intermediate framing members penetrating it and providing thermal short circuits. When the resistance of the insulation ($3.5 \text{ m}^2 \cdot \text{K}/\text{W}$) is

added to the exterior air film resistance of $0.03 \text{ m}^2 \cdot \text{K}/\text{W}$ and the interior air film resistance of $0.12 \text{ m}^2 \cdot \text{K}/\text{W}$ (from [Table 1, Chapter 25](#)), the total resistance is $3.65 \text{ m}^2 \cdot \text{K}/\text{W}$ and the U-factor is $1/3.65 = 0.274 \text{ W}/(\text{m}^2 \cdot \text{K})$. The edge-of-spandrel U-factor is 40% of the way to the frame U-factor, which is $0.274 + [0.40(9.94 - 0.274)] = 4.14 \text{ W}/(\text{m}^2 \cdot \text{K})$.

$$\begin{aligned} U_{\text{opaque spandrel module}} &= \frac{(0.274 \times 0.9801) + (4.14 \times 0.2743) + (9.94 \times 0.1856)}{(1.2 \times 1.2)} \\ &= 2.26 \text{ W}/(\text{m}^2 \cdot \text{K}) \end{aligned}$$

Finally, calculate the overall average U-factor for the curtain wall assembly, including the one module of vision glass and the two modules of opaque spandrel.

$$\begin{aligned} U_{\text{curtain wall}} &= \frac{[3.41 \times (1.2 \times 1.2)] + [2.26 \times 2 \times (1.2 \times 1.2)]}{3 \times (1.2 \times 1.2)} \\ &= 2.64 \text{ W}/(\text{m}^2 \cdot \text{K}) \end{aligned}$$

Note that even with double glazing having a low-e coating and with R-20 in the opaque areas, this curtain wall with metal pans only has an overall R-value of approximately $0.38 \text{ m}^2 \cdot \text{K}/\text{W}$.

Example 4. Estimate the U-factor for a semicircular barrel vault that is 6 m wide (3 m tall) and 10 m long mounted on a 150 mm curb. The barrel vault has an aluminum frame without a thermal break. The glazing is double with a 13 mm gap width filled with air and a low-e coating ($e = 0.20$).

Solution: An approximation can be made by multiplying the U-factor for a site-assembled sloped/overhead glazing product having the same frame and glazing features by the ratio of the surface area (including the curb) of the barrel vault to the rough opening area in the roof that the barrel vault fits over. First, determine the surface area (including the curb) of the barrel vault:

$$\begin{aligned} \text{Area of the curved portion of the barrel vault} &= (\pi \times \text{diameter}/2) \times \text{length} \\ &= (3.14 \times 6/2) \times 10 = 94.25 \text{ m}^2 \end{aligned}$$

$$\begin{aligned} \text{Area of the two ends of the barrel vault} &= 2\pi(\text{radius})^2/2 = \pi r^2 \\ &= 3.14 \times 3^2 = 28.27 \text{ m}^2 \end{aligned}$$

$$\begin{aligned} \text{Area of the curb} &= \text{perimeter} \times \text{curb height} \\ &= (6 + 10 + 6 + 10) \times 0.150 = 4.8 \text{ m}^2 \end{aligned}$$

$$\begin{aligned} \text{Total surface area of the barrel vault} &= 94.25 + 28.27 + 4.8 = 127.3 \text{ m}^2 \end{aligned}$$

Second, determine the rough opening area in the roof that the barrel vault fits over:

$$\begin{aligned} &= \text{length} \times \text{width} \\ &= 6 \times 10 = 60 \text{ m}^2 \end{aligned}$$

Third, determine the ratio of the surface area to the rough opening area:

$$= 127.3/60 = 2.12$$

Fourth, determine the U-factor from [Table 4](#) of a site-assembled sloped/overhead glazing product having the same frame and glazing features. The U-factor is $4.06 \text{ W}/(\text{m}^2 \cdot \text{K})$ (ID = 17, 12th column on the second page of [Table 4](#)).

Fifth, determine the estimated U-factor of the barrel vault.

$$\begin{aligned} U_{\text{barrel vault}} &= U_{\text{sloped overhead glazing}} \times \text{surface area/rough opening for the barrel vault} \\ &= 4.06 \times 2.12 = 8.61 \text{ W}/(\text{m}^2 \cdot \text{K}) \end{aligned}$$

SOLAR HEAT GAIN AND VISIBLE TRANSMITTANCE

Fenestration solar heat gain has two components. First is directly transmitted solar radiation. The quantity of radiation entering the fenestration directly is governed by the solar transmittance of the glazing system. Multiplying the incident irradiance by the glazing area and its solar transmittance yields the solar heat enter-

ing the fenestration directly. The second component is the absorbed solar radiation, radiation that is removed from the main beam and absorbed in the glazing and framing materials of the window, some of which is subsequently conducted to the interior of the building.

DETERMINING INCIDENT SOLAR FLUX

Solar Radiation

The flux of solar radiation on a surface normal (perpendicular) to the sun's rays above the earth's atmosphere at the mean earth-sun distance of $149.5 \times 10^6 \text{ km}$ (Allen 1973) is defined as the solar constant E_{sc} . The currently accepted value is $1367 \text{ W}/\text{m}^2$ (Iqbal 1983). Because the earth's orbit is slightly elliptical, the extraterrestrial radiant flux E_o varies from a maximum of $1413 \text{ W}/\text{m}^2$ on January 3, when the earth is closest to the sun (aphelion), to a minimum of $1332 \text{ W}/\text{m}^2$ on July 4, when the earth-sun distance reaches its maximum (perihelion).

The earth's orbital velocity also varies throughout the year, so **apparent solar time**, as determined by a solar time sundial, varies somewhat from the **mean time** kept by a clock running at a uniform rate. This variation, called the **equation of time**, is given in [Table 7](#). The conversion between local standard time and solar time involves two steps. First the equation of time is added to the local standard time, and then a longitude correction is added. This longitude correction is four minutes of time per degree difference between the local (site) longitude and the longitude of the **local standard meridian** for that time zone. Standard meridians are found every 15° from 0° at Greenwich, England (Greenwich Meridian). In the United States and Canada, these values are 60° for Atlantic Standard Time, 75° for Eastern Standard Time, 90° for Central Standard Time, 105° for Mountain Standard Time, 120° for Pacific Standard Time, 135° for Alaska Standard Time, and 150° for Hawaii-Aleutian Standard Time.

Equation (10) relates apparent solar time (AST) to local standard time (LST) as follows:

$$\text{AST} = \text{LST} + \text{ET}/60 + (\text{LSM} - \text{LON})/15 \quad (10)$$

where

AST = apparent solar time, decimal hours

LST = local solar time, decimal hours

ET = equation of time, decimal minutes

LSM = local standard time meridian, decimal $^\circ$ of arc

LON = local longitude, decimal $^\circ$ of arc

Because the earth's equatorial plane is tilted at an angle of 23.45° to the orbital plane, the **solar declination** δ (the angle between the

Table 7 Extraterrestrial Solar Irradiance and Related Data

	E_o , W/m^2	Equation of Time, min	Declination, degrees	A , W/m^2	B (Dimensionless Ratios)	C
Jan	1416	-11.2	-20.0	1230	0.142	0.058
Feb	1401	-13.9	-10.8	1215	0.144	0.060
Mar	1381	-7.5	0.0	1186	0.156	0.071
Apr	1356	1.1	11.6	1136	0.180	0.097
May	1336	3.3	20.0	1104	0.196	0.121
June	1336	-1.4	23.45	1088	0.205	0.134
July	1336	-6.2	20.6	1085	0.207	0.136
Aug	1338	-2.4	12.3	1107	0.201	0.122
Sep	1359	7.5	0.0	1151	0.177	0.092
Oct	1380	15.4	-10.5	1192	0.160	0.073
Nov	1405	13.8	-19.8	1221	0.149	0.063
Dec	1417	1.6	-23.45	1233	0.142	0.057

Note: Data are for 21st day of each month during the base year of 1964.

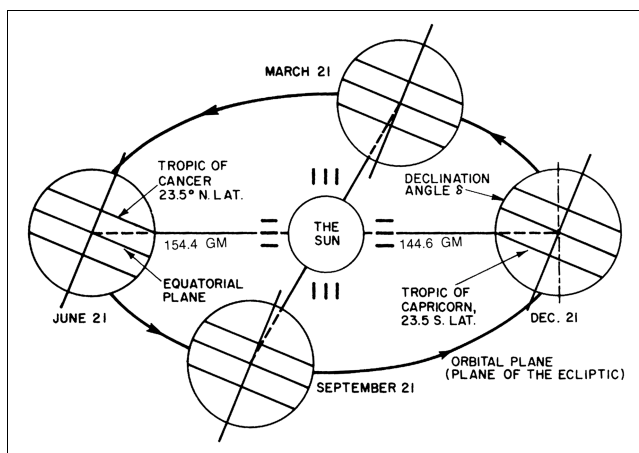


Fig. 6 Motion of Earth around Sun

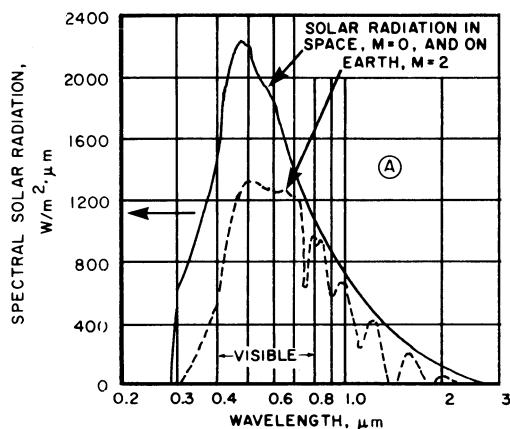


Fig. 7 Terrestrial and Extraterrestrial Solar Spectral Irradiances

earth-sun line and the equatorial plane) varies through out the year, as shown in Figure 6, Table 7, and Equation (11). This variation causes the changing seasons with their unequal periods of daylight and darkness. The following equation can be used to estimate the declination from the day of year η , but it is more accurate to look up the actual declination in an astronomical or nautical almanac for the actual year and date in question.

$$\delta = 23.45 \sin \{ [360(284 + \eta)] / 365 \} \quad (11)$$

The spectral distribution of solar radiation beyond the earth's atmosphere (Figure 7) resembles the radiant energy emitted by a blackbody at about 6000 K. The peak solar spectral irradiance of $2130 \text{ W}/(\text{m}^2 \cdot \mu\text{m})$ is reached at $0.451 \mu\text{m}$ (451 nm) in the green portion of the visible spectrum.

In passing through the earth's atmosphere, the sun's radiation is reflected, scattered, and absorbed by dust, gas molecules, ozone, water vapor, and water droplets (fog and clouds). The extent of this depletion at any given time is determined by atmospheric composition and length of the atmospheric path traversed by the sun's rays. This length is expressed in terms of the air mass m , which is the ratio of the mass of atmosphere in the actual earth-sun path to the mass that would exist if the sun were directly overhead at sea level ($m = 1.0$). For most purposes, the air mass at any time equals the cosecant of the solar altitude multiplied by the ratio of the existing barometric pressure to standard pressure. Beyond the atmosphere, $m = 0$.

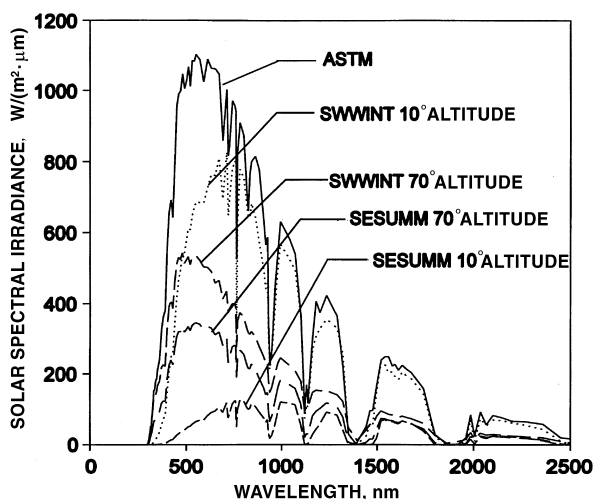


Fig. 8 Comparison of Standard Air Mass $m = 1.5$ Solar Spectrum with Direct Beam Spectra Through Atmospheres Characteristic of southwest in winter (SWWINT) and southeast U.S. in summer (SESUMM) for two solar altitude angles (McCluney 1996)

Table 8 Portions of Total Solar Spectral Irradiance Contained in Portions of Visible Spectrum

Wavelength, nm		Percent Irradiance	Percent Illuminance
Start	End		
370	770	54.4	100.0
380	760	52.2	100.0
390	750	50.2	99.9
400	740	47.4	99.9
410	730	44.9	99.8
420	720	41.9	99.8
430	710	39.5	99.8
440	700	36.7	99.8
450	690	35.3	99.5
460	680	31.1	99.1

Note: The integrated total irradiance = $950 \text{ W}/\text{m}^2$ and illuminance = 100 klx.

Most ultraviolet solar radiation is absorbed by the ozone in the upper atmosphere, while part of the radiation in the short-wave portion of the spectrum is scattered by air molecules, imparting the blue color to the sky. Water vapor in the lower atmosphere causes the characteristic absorption bands observed in the solar spectrum at sea level (Figure 7). For a solar altitude β of 41.8° (air mass $m = 1.5$), the total solar direct beam flux on a clear day at sea level can be divided into spectral regions as follows. Less than 3% of the total is in the ultraviolet, 47% is in the visible region, and the remaining 50% is in the infrared (ASTM Standard E 891). The maximum spectral irradiance occurs at $0.61 \mu\text{m}$, and little solar energy (less than 5% of the spectrum) exists at wavelengths beyond $2.1 \mu\text{m}$.

It is interesting to see what fraction of the total solar irradiance lies in the visible part of the spectrum. Since the limits of the visible portion vary from observer to observer (and because the eye is not very sensitive to radiation at the spectral limits of vision), the fractions of total irradiance and illuminance found between different spectral limits at the edge of the visible portion of the spectrum can be calculated. The results are shown in Table 8 for the ASTM air mass $m = 1.5$ terrestrial spectrum shown in Figure 8.

The solar spectral distribution shown in Figure 7 for $m = 0$ is the World Radiation Center's 1985 standard extraterrestrial spectrum for a solar constant of $1367 \text{ W}/\text{m}^2$ (Wehrli 1985). The one for $m = 1.5$ in Figure 8 is from ASTM Standard E 891. This latter takes no account of monthly variations in irradiance caused by changes in the

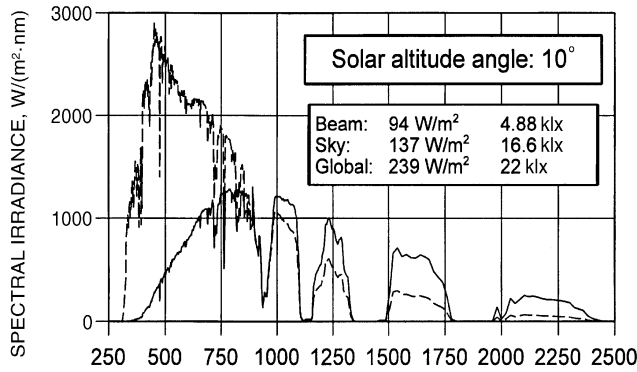


Fig. 9 Comparison of Direct and Diffuse Solar Spectra for Low Solar Altitude Angle

earth-sun distance and by variations in the atmosphere's constituent particulates and gases.

When variations in atmospheric constituents and air mass are considered, the solar spectral distribution is seen to vary, as illustrated in Figure 8, for two different atmospheric conditions and for two solar altitude angles, and in Figure 9 for both direct and diffuse radiation components and a low sun angle. It is clear that the spectral distribution for low sun angle beam radiation is significantly shifted toward longer wavelengths. This shift can be seen visually as a reddening of the sun near to the horizon. Clear sky diffuse radiation is generally shifted toward the blue end of the spectrum.

Upon passage through the atmosphere, extraterrestrial solar radiation is reduced in magnitude due to absorption by atmospheric gases and particulates. The strength of this absorption varies with wavelength, and the terrestrial solar spectrum exhibits definite "dips" in regions of strong absorption, called **absorption bands**. The most prominent atmospheric gases contributing to this effect are listed below:

- **Ozone.** Strongest absorption in the ultraviolet, some in the visible. Concentration variable.
- **H₂O.** Strongest absorption in near and far IR. Highly variable.
- **CO₂.** Strongest absorption in near and far IR. Slightly variable.
- **O₂, CH₄, N₂O, CFCs.** Strongest absorption mostly in the IR. Concentration almost constant.
- **NO₂.** Strongest absorption in the visible. Highly variable in polluted areas.

The effect of aerosols and other particulates on terrestrial solar radiation can be significant. Diffuse sky radiation is solar beam radiation that has been multiply scattered out of the direct beam and downward through the atmosphere to the earth's surface. This scattering is produced by 30 different atmospheric molecules (of which the above are the most significant optically) and by larger particles of different types, including aerosols of water, dust, smoke, and particulates of other kinds.

More information on atmospheric optics can be found in Chapter 44 of the Optical Society of America's *Handbook of Optics* (Bass 1995) and in Iqbal (1983).

Glazing systems exhibiting strong spectral selectivity (strong changes in their optical properties over the solar spectrum) will selectively pass more or less radiation in different parts of the spectrum. This effect can cause substantial changes in the solar heat gain coefficient of the glazing system when the shape of the solar spectrum shifts appreciably. This in turn can cause errors in solar heat gain predictions when the actual solar radiation on a fenestration system has a spectrum that is different from the standard spectrum used to determine the solar heat gain coefficient of that system

(McCluney 1996). These errors are typically 5 to 10% but can be substantially greater in special cases.

Some short-wavelength radiation scattered by air molecules, dust, and other particulates in the atmosphere reaches the earth in the form of diffuse sky radiation E_d . Since this diffuse radiation comes from all parts of the sky, its irradiance is difficult to predict and varies as moisture and particulate content and sun angle change throughout any given day. For completely overcast conditions, the diffuse component accounts for all solar radiant heat gain of fenestrations.

The total short-wavelength irradiance E_t reaching a terrestrial surface is the sum of the direct solar radiation E_D , the diffuse sky radiation E_d , and the solar radiation E_r reflected from surrounding surfaces. The irradiance on the fenestration aperture of the direct beam component E_D is the product of the direct normal irradiance E_{DN} and the cosine of the angle of incidence θ between the incoming solar rays and a line normal (perpendicular) to the surface:

$$E_t = E_{DN} \cos \theta + E_d + E_r \quad (12)$$

A method for computing all the factors on the right side of Equation (12) is presented in the sections on Direct Normal Irradiance and Diffuse and Ground-Reflected Radiation. Perez et al. (1986), Gueymard (1987), *Solar Energy* (1988), and Gueymard (1993) give more detailed models, which separate the diffuse sky radiation into different components. Gueymard (1995) provides a comprehensive spectrally based model for calculating the spectral and broadband totals of all three terms in Equation (12), for cloudless sky conditions. The Gueymard model allows user input of the concentrations of a variety of atmospheric constituents, including particulates.

The importance of the diffuse component is illustrated in Figure 9, which shows that at low sun angles the diffuse component contains more radiant flux than the direct beam component, even on a clear day, and that the spectral distributions of the two components are quite different. Although the total irradiances are relatively modest for both of these components, they are not insignificant for annual energy performance calculations.

Vertical windows receive considerable quantities of diffuse sky radiation over the course of a year. The diffuse component is an important part of solar radiant heat gain.

Determining Solar Angle

The sun's position in the sky is conveniently expressed in terms of the solar altitude β above the horizontal and the solar azimuth ϕ measured from the south (Figure 10). These angles, in turn, depend on the local latitude L ; the solar declination δ , which is a function of the date [Table 7 or Equation (11)]; and the apparent solar time, expressed as the hour angle H , where

$$H = 15(\text{AST} - 12) \quad (13)$$

Equations (14) and (15) relate β and ϕ to the three angles just mentioned:

$$\sin \beta = \cos L \cos \delta \cos H + \sin L \sin \delta \quad (14)$$

$$\cos \phi = \frac{\sin \beta \sin L - \sin \delta}{\cos \beta \cos L} \quad (15)$$

Figure 10 shows the solar position angles and incident angles for horizontal and vertical surfaces. Line OQ leads to the sun, the north-south line is NOS, and the east-west line is EOW. Line OV is perpendicular to the horizontal plane in which the solar azimuth ϕ (angle HOS) and the surface azimuth Ψ (angle POS) are located. Angle HOP is the surface solar azimuth γ , defined as

$$\gamma = \phi - \Psi \quad (16)$$

The solar azimuth ϕ is positive for afternoon hours and negative for morning hours. Likewise, surfaces that face west have a positive

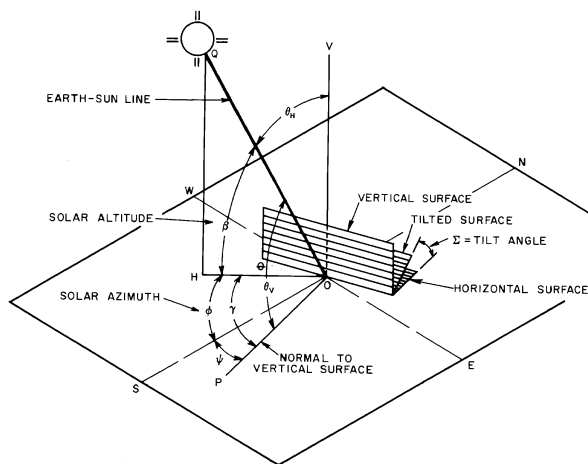


Fig. 10 Solar Angles for Vertical and Horizontal Surfaces

Table 9 Surface Orientations and Azimuths, Measured from South

Orientation	N	NE	E	SE	S	SW	W	NW
Surface azimuth ψ	180°	-135°	-90°	-45°	0	45°	90°	135°

surface azimuth ψ ; those facing east have a negative surface azimuth (Table 9). If γ is greater than 90° or less than -90°, the surface is in the shade. Table 9 gives values in degrees for the surface azimuth ψ , applicable to the orientations of interest.

The angle of incidence θ for any surface is defined as the angle between the incoming solar rays and a line normal to that surface. For the horizontal surface shown in Figure 10, the incident angle θ_H is QOV; for the vertical surface, the incident angle θ_V is QOP.

For any surface, the incident angle θ is related to β , γ , and the tilt angle of the surface Σ by

$$\cos\theta = \cos\beta \cos\gamma \sin\Sigma + \sin\beta \cos\Sigma \quad (17)$$

where Σ = tilt angle of surface from horizontal.

When the surface is horizontal, $\Sigma = 0^\circ$ and

$$\cos\theta_H = \sin\beta \quad (18)$$

For a vertical surface, $\Sigma = 90^\circ$ and

$$\cos\theta_V = \cos\beta \cos\gamma \quad (19)$$

Direct Normal Irradiance

At the earth's surface on a clear day, direct normal irradiance, or solar irradiance E_{DN} , is represented by

$$E_{DN} = \frac{A}{\exp(B/\sin\beta)} \quad (20)$$

where

A = apparent solar irradiation at air mass $m = 0$ (Table 7)

B = atmospheric extinction coefficient (Table 7)

Values of A and B vary during the year because of seasonal changes in the dust and water vapor content of the atmosphere and because of the changing earth-sun distance. Equation (20) does not give the maximum value of E_{DN} that can occur in each month but yields values that are representative of conditions on cloudless days for a relatively dry and clear atmosphere. For very clear atmospheres, E_{DN} can be 15% higher than indicated by Equation (20), using values of A and B in Table 7.

For locations where clear, dry skies predominate (e.g., at high elevations) or, conversely, where hazy and humid conditions are frequent, values found by using Equation (20) and Table 7 should be

Table 10 Solar Reflectances of Foreground Surfaces

Foreground Surface	Incident Angle					
	20°	30°	40°	50°	60°	70°
New concrete	0.31	0.31	0.32	0.32	0.33	0.34
Old concrete	0.22	0.22	0.22	0.23	0.23	0.25
Bright green grass	0.21	0.22	0.23	0.25	0.28	0.31
Crushed rock	0.20	0.20	0.20	0.20	0.20	0.20
Bitumen and gravel roof	0.14	0.14	0.14	0.14	0.14	0.14
Bituminous parking lot	0.09	0.09	0.10	0.10	0.11	0.12

Adapted from Threlkeld (1962)

multiplied by the Clearness Numbers in Threlkeld and Jordan (1958), reproduced as Figure 5 in Chapter 33 of the *ASHRAE Handbook—Applications*. This broadband model should only be used for determining fenestration solar gain when the glazing system is not strongly spectrally selective and when its angular selectivity closely matches that of single-pane glass.

Diffuse and Ground-Reflected Radiation

The following equations can be used to generate E_d and E_r , where all angles are in degrees. The solar azimuth ϕ and the surface azimuth ψ are measured in degrees from south; angles to the east of south are negative, and angles to the west of south are positive. Values of A , B , and C are given in Table 7 for the 21st day of each month. Values for other dates can be obtained by interpolation.

The ratio Y of sky diffuse radiation on a vertical surface to sky diffuse radiation on a horizontal surface is given by

$$Y = 0.55 + 0.437 \cos\theta + 0.313 \cos^2\theta \quad \text{for } \cos\theta > -0.2$$

$$Y = 0.45 \quad \text{for } \cos\theta \leq -0.2 \quad (21)$$

Diffuse irradiance E_d is given by

$$E_d = C Y E_{DN} \quad \text{for vertical surfaces} \quad (22)$$

$$E_d = C E_{DN} \frac{1 + \cos\Sigma}{2} \quad \text{for surfaces other than vertical} \quad (23)$$

Ground-reflected irradiance E_r is given by

$$E_r = E_{DN}(C + \sin\beta) \rho_g \frac{1 - \cos\Sigma}{2} \quad \text{for surfaces at all orientations} \quad (24)$$

where ρ_g is ground reflectivity, often taken to be 0.2 for typical mixture of ground surfaces. For other surfaces, Table 10 lists angle-dependent solar reflectances.

Example 5. Find the solar azimuth and altitude at 3:00 P.M. central daylight time on June 21 in St. Louis, MO.

Solution: Central daylight time of 3:00 P.M. re-expressed in decimal hours at local standard time is LST = 14.0. The latitude and longitude of St. Louis, MO, are 38.6°N and 90.2°W, respectively. The local standard meridian of the central time zone is 90°W. The equation of time (Table 7) is -1.4 min. From Equation (10), apparent solar time (AST) = 14.0 - 1.4/60 + (90 - 90.2)/15 = 13.9633. From Equation (13), $H = 15 \times (13.9633 - 12) = 29.45^\circ$. Table 7 gives the solar declination δ on June 21 as 23.45°.

Thus, by Equation (14),

$$\sin\beta = \cos(38.6^\circ) \cos(23.45^\circ) \cos(29.45^\circ) + \sin(38.6^\circ) \sin(23.45^\circ) = 0.873$$

$$\beta = 60.76^\circ$$

Using Equation (15),

$$\cos\phi = \frac{\sin(60.76^\circ) \sin(38.6^\circ) - \sin(23.45^\circ)}{\cos(60.76^\circ) \cos(38.6^\circ)} = 0.384$$

$$\phi = 67.4^\circ$$

Example 6. For the conditions of Example 5, find the incident angle at a window facing west.

Solution: From Example 5, $\phi = 67.4^\circ$. From Table 9, $\psi = 90^\circ$. From Equation (16), $\gamma = 67.4^\circ - 90^\circ = -22.6^\circ$.

A negative surface solar azimuth γ indicates that the sun is south of the normal to the surface. Thus, using Equation (19),

$$\cos\theta = \cos(60.76^\circ) \cos(-22.6^\circ) = 0.451$$

$$\theta = 63.2^\circ$$

Example 7. Find the direct, diffuse, and ground-reflected components of the solar irradiation on the window in Example 6.

Solution: From Example 5, $\sin\beta = 0.873$, and from Table 7, $A = 1088 \text{ W/m}^2$ and $B = 0.205$. Therefore, from Equation (20),

$$E_{DN} = 1088 / [\exp(0.205/0.873)] = 860.3 \text{ W/m}^2$$

$$E_{DN} \cos(\theta) = 860.3 \times 0.451 = 388 \text{ W/m}^2$$

From Table 7, $C = 0.134$. From Equation (21), $Y = 0.55 + 0.437 \times 0.451 + 0.313 \times (0.451)^2 = 0.811$. From Equation (22),

$$E_d = (0.134)(0.811)(860.3) = 93.5 \text{ W/m}^2$$

From Equation (24), assuming a ground reflectivity ρ_g of 0.2,

$$E_r = (860.3)(0.134 + 0.873)(0.2)/2 = 86.6 \text{ W/m}^2$$

Thermal Infrared Radiation

Any material above a temperature of absolute zero emits electromagnetic radiation. The rate of emission depends upon the temperature of the material and can be expressed in a simple equation, called the Stefan-Boltzmann law:

$$E_b = \sigma T^4 \quad (25)$$

where

E_b = hemispherical total emissive power of black body, W/m^2

T = temperature, K

σ = Stefan-Boltzmann constant, $\text{W}/(\text{m}^2 \cdot \text{K}^4)$

The **emissivity** e of a surface is the ratio of the emission of thermal radiant flux from the surface to the flux that would be emitted by a blackbody emitter at the same temperature. Given the temperature and emissivity of a surface, the emitted irradiance spectrum can be computed from

$$E = e\sigma T^4$$

where E is the emitted irradiance in units of flux per unit area, e is the emissivity of the surface, σ is the Stefan-Boltzmann constant, and T is the absolute temperature of the surface.

The maximum value of **hemispherical emissivity** e for any material is 1.0, in which case the surface emits the theoretical maximum amount of radiation possible. In this case, the surface is called a **blackbody**, and the radiation emitted by the surface is called **blackbody radiation**.

Occasionally, a related quantity called **normal emissivity** is used. The relationship between them is illustrated in Figure 11. The spectral distribution of blackbody radiation is illustrated in Figure 12 for temperatures ranging from 300 K (room temperature) to 20 000 K.

OPTICAL PROPERTIES

Solar radiation (including both direct rays from the sun and diffuse rays from the sky, clouds, and surrounding objects) incident on a fenestration system is partly transmitted and partly reflected by the

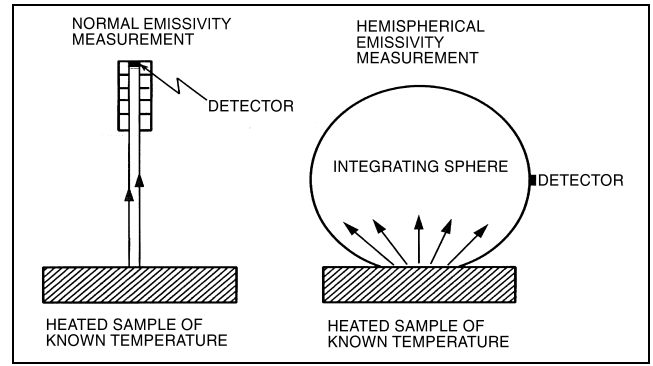


Fig. 11 Illustration of Difference Between Normal and Hemispherical Emissivity

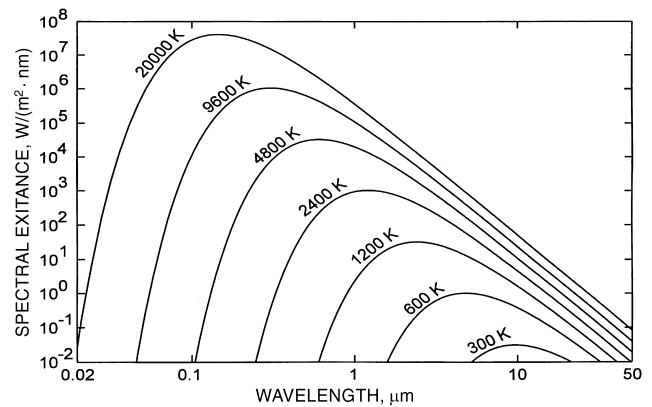


Fig. 12 Spectral Distributions of Blackbody Radiation at Different Source Temperatures

glazings of that system. An additional fraction is absorbed within the glazings and/or the coatings on their surfaces. The fraction of incident flux that is reflected is called the **reflectance** R , the fraction absorbed is called the **absorptance** A , and the fraction transmitted is the **transmittance** T . The sum of the transmittance T , absorptance A , and reflectance R of a glazing layer is unity:

$$T + R + A = 1 \quad (26)$$

However, this is complicated by the fact that radiation incident on a surface can have nonconstant distributions over the directions of incidence and over the wavelength (or frequency) scale. Thus, when measuring one or more of the optical properties, the wavelength distribution and direction of incident (and emerging) radiation must be specified.

Angular Dependence

The concept of solid angle is needed to understand angular dependence. A solid angle is defined and enclosed by all rays joining a point to a closed curve. For a closed curve on a sphere of radius R , the solid angle ϖ is the ratio of the projected area A on the sphere to the square of R . A sphere has a solid angle of 4π steradians ($4\pi \text{ sr}$); a hemisphere has a $2\pi \text{ sr}$ solid angle.

Radiation incident on a point in a surface comes to that point from many directions in some solid angle. For a cone of half angle α , the solid angle defined by the circular top and point bottom of that cone is given by

$$\varpi = 2\pi (1 - \cos \alpha) \quad (27)$$

In measuring transmittance or reflectance, a sample is illuminated over a specified solid angle. The reflected or transmitted flux is then collected within another solid angle. The size of a conical solid angle and the direction of its axis need to be specified to obtain meaningful results. A conical solid angle is bounded by a right circular cone.

ASTM *Standards* E 903, E 1084, E 971, and E 972, as well as NFRC 300, which refers to ASTM *Standard* E 971, refer to **conical-hemispherical** measurements of optical properties. The reason is that for most thermal or HVAC design calculations, only the total flux transmitted into a **hemispherical** solid angle, due to the direct solar beam incident in a small **conical** solid angle, is of interest. All transmitted solar irradiance is considered heat gain in these applications, regardless of the directional distribution of the transmitted radiation.

For complex fenestrations (those with nonspecular components), for many daylighting applications, and for some passive solar space-heating applications, the directional distribution of transmitted radiation is of interest. In such cases, it is important to know what is called the **biconical transmittance and reflectance** of fenestration systems, defined for conical solid angles of incidence and emergence (see Figure 13).

Biconical optical properties are needed (1) to treat diffuse sky as well as direct beam radiation, (2) to handle the directional distribution of the flux entering a room through a window, and (3) to calculate the angle-dependent optical and solar gain properties of multiple-pane window systems and complex glazing systems, including those with integral or attached shading devices.

Spectral Dependence

Frequency and wavelength are related through

$$\lambda f = c \quad (28)$$

where

- λ = wavelength, m
- f = frequency, Hz
- c = speed of light = 3.0×10^8 m/s in air at standard atmospheric pressure

The wavelength dependence of radiometric quantities is denoted with a subscript λ attached to the optical quantity, thus ϕ_λ , E_λ , and L_λ . The wavelength dependency of optical properties is denoted by the functional notation, thus $\alpha(\lambda)$, $\rho(\lambda)$, $\tau(\lambda)$, and $e(\lambda)$.

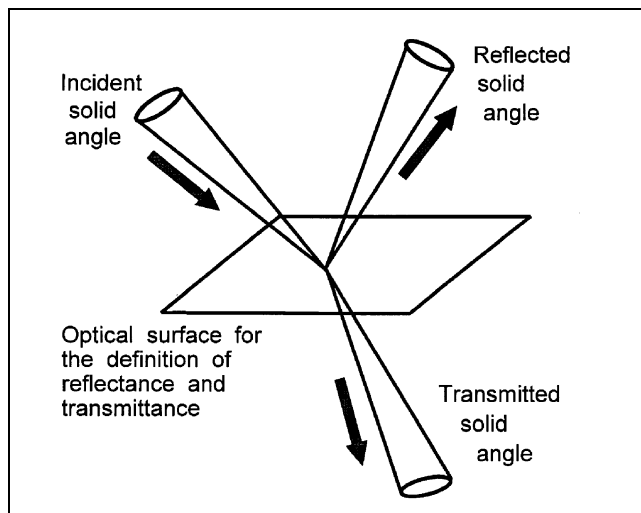


Fig. 13 Geometry for Definition of Biconical Transmittance and Reflectance

All solar radiant flux becomes heat when it is absorbed by materials such as glazings, window frames, and room surfaces. This includes radiation in the UV, visible, and IR portions of the spectrum. Recall from Equation (26) that the sum of the transmittance, reflectance, and absorptance is 1.0.

There is an additional relationship among the optical properties that is of interest and importance. It is called Kirchhoff's law (McCluney 1994a):

$$A(\lambda, \theta, \phi) = e(\lambda, \theta, \phi) \quad (29)$$

where θ and ϕ are angles defining the directional dependence of the spectral absorptance $A(\lambda)$ and the spectral emissivity $e(\lambda)$. A consequence of Equations (26) and (29) is that for opaque materials a good absorber is a good emitter and a poor reflector, and vice versa, but only on a wavelength-by-wavelength basis or over a defined wavelength interval. A surface appearing to be an excellent reflector in the visible portion of the spectrum may have a high emissivity (and low reflectance) over most of the infrared spectrum, or vice versa.

Source Spectra. Radiation incident on a surface has a distribution not only over direction within some solid angle but also over a range of wavelengths. The latter distribution is called a **spectrum**. For terrestrial applications, it is only after the extraterrestrial solar spectrum has been modified by passage through the atmosphere that it is of interest (Figures 8 and 9).

SOLAR-OPTICAL PROPERTIES OF GLAZING

The solar-optical properties of a glazing are the wavelength-integrated (or total) transmittance, reflectance, and absorptance of the glazing to incident solar radiation. If the spectral optical properties [$T(\lambda)$, $R(\lambda)$, $A(\lambda)$] of the glazing and the spectral irradiance $E(\lambda)$ incident on the glazing are known, the solar optical properties can be calculated from

$$p = \frac{\int_{\lambda_{min}}^{\lambda_{max}} p(\lambda) E(\lambda) d\lambda}{\int_{\lambda_{min}}^{\lambda_{max}} E(\lambda) d\lambda} \quad (30)$$

where p stands for transmittance, reflectance, or absorptance, and the limits of integration are those values of wavelength outside of which the solar spectral irradiance is negligibly small.

If $E(\lambda)$ in Equation (30) is a standard solar spectral irradiance distribution, then the optical property resulting from this equation is called the **solar optical property**. If the spectral properties $p(\lambda)$ are available only at a set of discrete wavelengths λ_k (e.g., measured data), then the following discrete sum approximation of Equation (30) can be calculated:

$$p = \sum_{k=1}^M w_k p(\lambda_k) \quad (31)$$

where $w_k = \frac{E(\lambda_k)}{\sum_{k=1}^M E(\lambda_k) \Delta\lambda_k}$ is the spectral weight for the wavelength

λ_k and where $\Delta\lambda_k = 1/2(\lambda_{k+1} - \lambda_{k-1})$.

Unless explicitly stated otherwise, solar-optical properties used in this chapter are calculated using the tabulated ASTM *Standard* E 891 solar spectrum and Equation (31).

Many window glazings do not have strong spectral selectivity over the solar spectrum, so their spectral optical properties can be

considered constant, even if the source spectrum changes substantially. In these cases, the transmitted spectral irradiance can be determined by multiplying the incident irradiance by the solar transmittance.

Figure 14 shows the spectral transmittance at normal incidence of typical architectural glasses. The approximate transmittance of total incident solar radiation through clear float glass at an incident angle of 0° ranges from 86% for 2.4 mm thick glass to 84% for 3.2 mm thick glass to 78% for 6.4 mm thick glass. Actual transmittance varies with the amount of iron or other absorbers in the glass. Low iron content glass has a relatively constant spectral transmittance over the entire solar spectrum.

Figure 15 shows the normal incidence spectral transmittances of several common commercially available glazings. Figure 16 shows the normal incidence spectral transmittances and exterior reflectances of a variety of additional coated and tinted glasses, indicating the strong spectral selectivity that is now available from some glass and window manufacturers.

Angular Dependence of Glazing Optical Properties

As Figure 17 shows, the optical properties of a single sheet of clear glass depend on the angle of incidence. This variation is small for incident angles below 40° but becomes significant at larger angles.

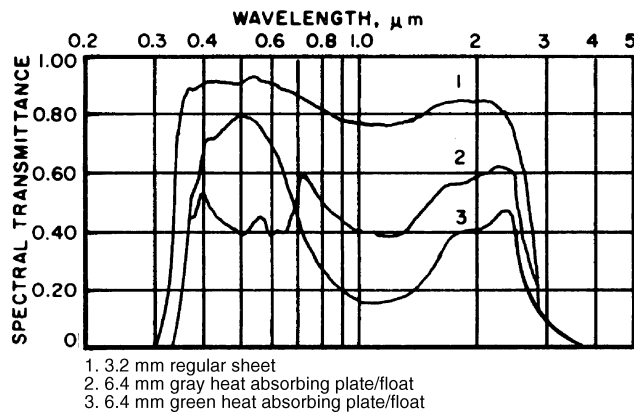


Fig. 14 Spectral Transmittance for Typical Architectural Glass

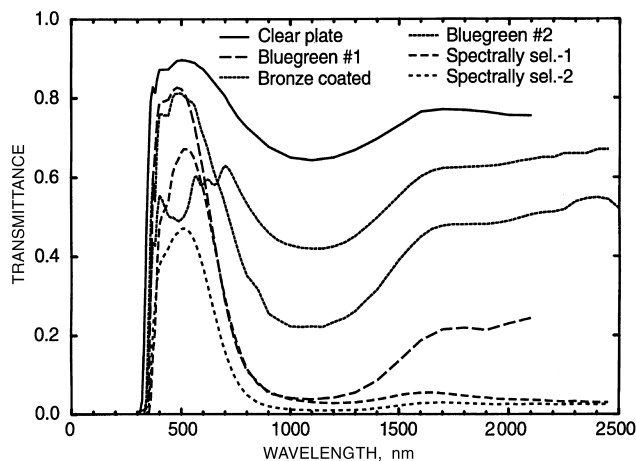


Fig. 15 Spectral Transmittances of Commercially Available Glazings (McCluney 1993)

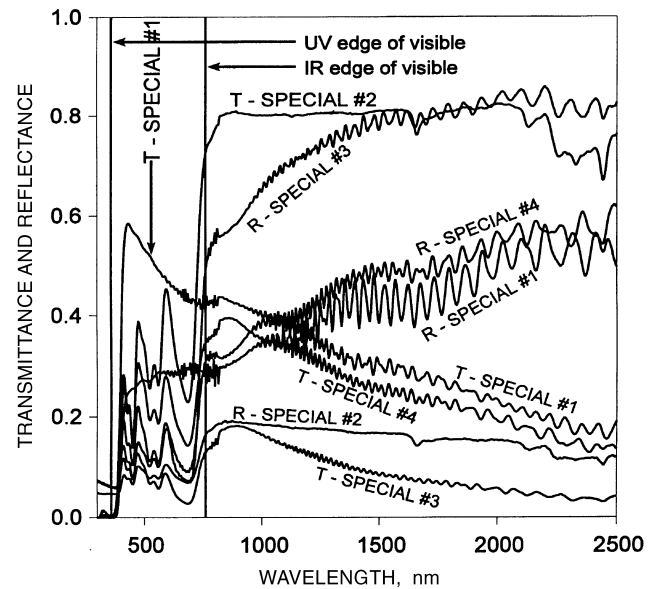


Fig. 16 Spectral Transmittances and Reflectances of Strongly Spectrally Selective Commercially Available Glazings (McCluney 1996)

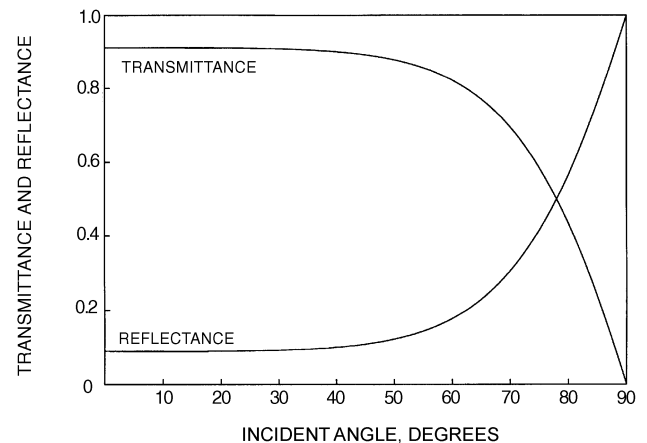


Fig. 17 Transmittance and Reflectance of Plane, Parallel, Glass Plate
refractive index $n = 1.55$, thickness $t = 3.2$ mm, absorptivity $\alpha = 0.01/m$

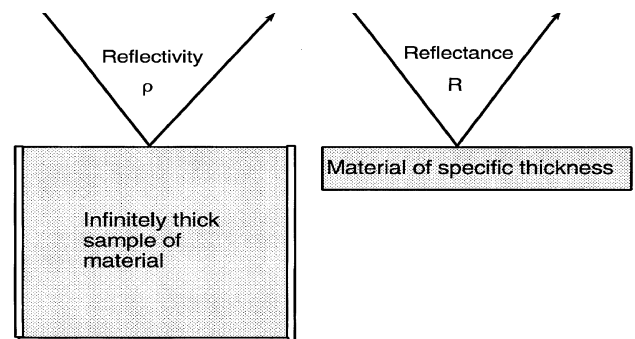


Fig. 18 Variations with Incident Angle of Solar-Optical Properties for (A) Double-Strength Sheet Glass, (B) Clear Plate Glass, and (C) Heat-Absorbing Plate Glass

Figure 18 compares the properties of glasses of different thickness and composition. As the incident angle increases from zero, transmittance diminishes, reflectance increases, and absorptance first increases because of the lengthened optical path and then decreases as more incident radiation is reflected. While the shapes of the property curves are superficially similar, note that both the magnitude of the transmittance at normal incidence and the angle at which the transmittance changes significantly vary with glass type and thickness. The three curves all have slightly different shapes. For coated glasses or for multiple-pane glazing systems, this difference is more pronounced. One cannot assume that all glazings or glazing systems have a universal angular dependence. This is one of the inadequacies of the shading coefficient methodology for determining solar heat gain that led to its elimination from this edition.

In North America, peak summertime solar gains occur with east- and west-facing vertical windows at angles of incidence ranging from about 25 to 55°. The peak solar gain for horizontal glazings occurs typically at small angles of incidence. For north- and south-facing vertical glazings, peak summertime solar gains occur at angles of incidence greater than about 40° (McCluney 1994b).

Angles of incidence important for annual energy performance calculations range from 5° to over 80° for east- and west-facing vertical windows and for horizontal glazings. This range is only slightly diminished for south-facing windows. For north-facing windows, the direct beam solar gains are small and their angles of incidence range from 62 to 86° (McCluney 1994b).

Optical Properties of Single Glazing Layers

The optical properties of a single layer of glazing material are outlined in Figure 19. The layer has a thickness d and is characterized by a surface reflectivity and transmissivity, ρ and τ , for each of the two surfaces (denoted f and b in the figure) and an absorptivity, α , which is a volumetric property of the material (assumed of uniform composition). In general, τ and ρ are characteristics of the interface between the material and the adjacent medium; they may in principle be different for the two surfaces (e.g., for a coated surface, or where a material layer is adjacent to another material rather than air). All three properties, transmissivity, reflectivity, and absorptivity, depend on the wavelength of the incident radiation, and τ and ρ also depend on the incident angle θ of the radiation incident on the layer.

The transmittance T and the front reflectance R^f of a layer (as opposed to a surface) contain the effects of multiple reflections between the two surfaces of the layer, as indicated in Figure 19, as well as the effects of absorption during the passage through the layer

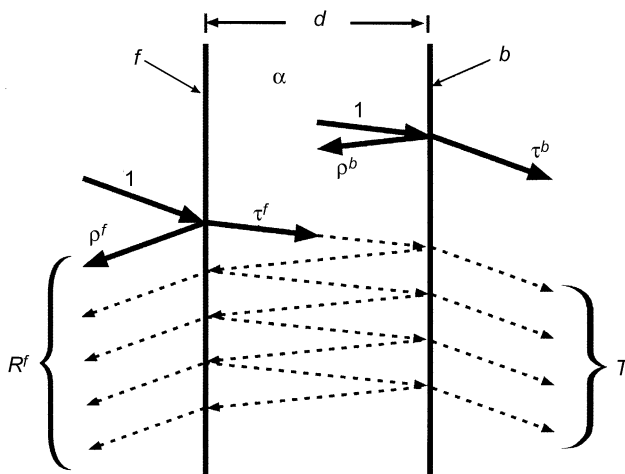


Fig. 19 Optical Properties of a Single Glazing Layer

(one or more times), due to the volume absorptivity α . The same is true of the back reflectance R^b , which is the reflectance of the layer for radiation incident on back side b and which is not illustrated in the figure. For non-normal incidence, surface reflectances are in general different for the two possible polarizations of light, conventionally denoted s (TE) and p (TM). We distinguish these below by a subscript μ ($= s, p$) on the surface reflectance. [A pre-subscript is used where there is a possibility of confusion with later notational additions.] The transmittance and reflectances are given by

$${}_{\mu}T(\theta, \lambda) = \frac{\tau_{\mu}^f(\theta, \lambda)\tau_{\mu}^b(\theta, \lambda)e^{-\frac{\alpha(\lambda)d}{\cos\zeta}}}{1 - \rho_{\mu}^f(\theta, \lambda)\rho_{\mu}^b(\theta, \lambda)e^{-\frac{2\alpha(\lambda)d}{\cos\zeta}}} \quad (32)$$

$${}_{\mu}R^f(\theta, \lambda) = \rho_{\mu}^f(\theta, \lambda) + \rho_{\mu}^b(\theta, \lambda){}_{\mu}T(\theta, \lambda)e^{-\frac{\alpha(\lambda)d}{\cos\zeta}} \quad (33)$$

$${}_{\mu}R^b(\theta, \lambda) = \rho_{\mu}^b(\theta, \lambda) + \rho_{\mu}^f(\theta, \lambda){}_{\mu}T(\theta, \lambda)e^{-\frac{\alpha(\lambda)d}{\cos\zeta}} \quad (34)$$

where ζ is the angle at which radiation incident at angle θ propagates within the glazing layer (the refracted angle). Since sunlight is unpolarized, the transmittance and reflectances of an isolated glazing layer are then calculated from

$$T(\theta, \lambda) = \frac{1}{2}[{}_sT(\theta, \lambda) + {}_pT(\theta, \lambda)] \quad (35)$$

$$R^f(\theta, \lambda) = \frac{1}{2}[{}_sR^f(\theta, \lambda) + {}_pR^f(\theta, \lambda)] \quad (36)$$

$$R^b(\theta, \lambda) = \frac{1}{2}[{}_sR^b(\theta, \lambda) + {}_pR^b(\theta, \lambda)] \quad (37)$$

The transmittance is the same for incident radiation incident (of a given polarization) on either surface, as can be seen from the symmetry of Equation (32) in the indices f and b . Front and back reflectances, however, may differ. The angular and wavelength dependence of these quantities is emphasized in the equations through explicit function reference [e.g., $T(\theta, \lambda)$]. This dependence will not always be made explicit (in the interest of brevity of equations) but should not be forgotten.

The transmittance and reflectances are the basic measurable quantities for an isolated glazing layer in air. Measurements on glazing layers are typically made at normal incidence, and the properties at other angles must be inferred from these measurements. A systematic compilation of these measured properties for most glazings manufactured in the United States is maintained by the National Fenestration Rating Council, Silver Spring, MD, and is available on the World Wide Web at <http://www.nfrc.org> or at <http://windows.lbl.gov/software/> [see also LBL (1994) and NFRC (2000a)].

It follows from conservation of energy that the average absorptance of the layer must be defined as the fraction of the incident radiation that is neither transmitted nor reflected by the layer. Note that when the layer surfaces have different properties, this results in different absorptances for front and back incidence. It also produces an angular dependence in the layer absorptance a that is not present in the absorptivity α :

$${}_{\mu}a^f(\theta, \lambda) = 1 - {}_{\mu}T(\theta, \lambda) - {}_{\mu}R^f(\theta, \lambda) \quad (38a)$$

$${}_{\mu}a^b(\theta, \lambda) = 1 - {}_{\mu}T(\theta, \lambda) - {}_{\mu}R^b(\theta, \lambda) \quad (38b)$$

and, since these are linear relations,

$$d^f(\theta, \lambda) = 1 - T(\theta, \lambda) - R^f(\theta, \lambda) \quad (38c)$$

$$a^b(\theta, \lambda) = 1 - T(\theta, \lambda) - R^b(\theta, \lambda) \quad (38d)$$

for the unpolarized quantities. A lowercase symbol is used here in anticipation of the discussion of multilayer glazing systems below.

Uncoated Glazings

For uncoated glazings, the interface reflectivities ρ of the two surfaces are the same and may be determined from the Fresnel equations:

$$\rho_s(\theta, \lambda) = \left(\frac{\sin(\theta - \zeta)}{\sin(\theta + \zeta)} \right)^2 \quad (39a)$$

$$\rho_p(\theta, \lambda) = \left(\frac{\tan(\theta - \zeta)}{\tan(\theta + \zeta)} \right)^2 \quad (39b)$$

where ζ is the refracted angle and may be calculated from Snell's law and the real part of the refractive index n relative to air:

$$\sin \theta = n \sin \zeta \quad \text{and} \quad \zeta = \arcsin\left(\frac{\sin \theta}{n}\right) \quad (40)$$

At normal incidence, the two polarizations are indistinguishable, and Equation (39) reduces to

$$\rho(0, \lambda) = \frac{[n(\lambda) - 1]^2}{[n(\lambda) + 1]^2} \quad \text{and} \quad n(\lambda) = \frac{1 + \sqrt{\rho(0, \lambda)}}{1 - \sqrt{\rho(0, \lambda)}} \quad (41)$$

and since

$$\tau_\mu(\theta, \lambda) + \rho_\mu(\theta, \lambda) = 1 \quad (42)$$

for any surface, a measurement of the spectral transmittance and reflectance at normal incidence may be used with Equations (32) and (33) to determine the refractive index and absorptance as a function of wavelength. Note that n is also wavelength-dependent, although for most glazing materials the dependence is weak over the solar spectrum. Once these quantities are known, the equations may be used to calculate the properties at all angles.

ASHRAE “Standard” Glass

In the discussion of single glazing, and historically in the context of the solar heat gain factor and shading coefficient methodology, ASHRAE has used as a calculation standard the properties of “one-eighth inch [3.2 mm], clear double-strength glass” (DSG). The wavelength-averaged properties of this standard glazing are calculated from the following equations:

$$T_{\text{DSG}}(\theta) = \sum_{n=0}^5 (ts)_n \cos^n \theta \quad (43)$$

$$a_{\text{DSG}}^f(\theta) = a_{\text{DSG}}^b(\theta) = \sum_{n=0}^5 (as)_n \cos^n \theta \quad (44)$$

where the coefficients $(ts)_n$ and $(as)_n$ are given in Table 11. The hemispherical average quantities may be calculated by averaging Equations (43) and (44), which yields

$$\langle T_{\text{DSG}} \rangle_D = 2 \sum_{n=0}^5 \frac{(ts)_n}{n+2} \quad (45)$$

Table 11 Coefficients for Double-Strength Glass (DSG) for Calculation of Transmittance and Absorptance

n	$(as)_n$	$(ts)_n$
0	0.01154	-0.00885
1	0.77674	2.71235
2	-3.94657	-0.62062
3	8.57881	-7.07329
4	-8.38135	9.75995
5	3.01188	-3.89922

$$\langle a_{\text{DSG}}^f \rangle_D = \langle a_{\text{DSG}}^b \rangle_D = 2 \sum_{n=0}^5 \frac{(as)_n}{n+2} \quad (46)$$

Determining the Properties of Uncoated Glazing Layers from Normal Incidence Measurements

For uncoated glazings, the front and back transmissivities, reflectivities, transmittances, reflectances, and isolated-layer absorptances are equal, the two polarizations are indistinguishable, and at normal incidence Equations (32) and (33) become

$$T(0, \lambda) = \frac{[\tau(0, \lambda)]^2 e^{-\alpha(\lambda)d}}{1 - [\rho(0, \lambda)]^2 e^{-2\alpha(\lambda)d}} \quad (47)$$

$$R(0, \lambda) = \rho(0, \lambda)[1 + T(0, \lambda)e^{-\alpha(\lambda)d}] \quad (48)$$

while Equation (42) becomes

$$\tau(0, \lambda) + \rho(0, \lambda) = 1 \quad (49)$$

These three equations can be solved to yield $\rho(0, \lambda)$ and $\alpha(\lambda)$:

$$\rho(0, \lambda) = \frac{P - \sqrt{P^2 - 4[2 - R(0, \lambda)]R(0, \lambda)}}{2[2 - R(0, \lambda)]} \quad (50)$$

where

$$P = [T(0, \lambda)]^2 - [R(0, \lambda)]^2 + 2R(0, \lambda) \quad (51)$$

$$\alpha(\lambda) = -\frac{1}{d} \ln \left[\frac{R(0, \lambda) - \rho(0, \lambda)}{\rho(0, \lambda)T(0, \lambda)} \right] \quad (52)$$

The real part of the refractive index (relative to air) is then calculated by solving Equation (41):

$$n(\lambda) = \frac{1 + \sqrt{\rho(0, \lambda)}}{1 - \sqrt{\rho(0, \lambda)}} \quad (53)$$

Thus, given spectroscopic measurements of the transmittance and reflectance at normal incidence of an uncoated glazing layer, one can determine the basic parameters needed for a complete calculation of the optical properties of that layer.

Example 8. Construct an approximate model of the optical properties of a single layer of uncoated 3 mm clear glass, suitable for use in calculations involving selective glazings that have different properties in the visible and NIR regions. Use this model to calculate the properties under the conditions of Example 5.

Solution: The spectral transmittance and reflectance of clear 3 mm glass are shown in Figure 20. [The source of these data is “generic” clear glass in the NFRC (2000b) spectral data library.] It can be seen

that the variation with wavelength is not very great, and although a single average transmittance and reflectance would be adequate, for use with spectrally selective glazings it is better to construct the “2-band” model also shown in the figure, which characterizes the properties separately for the visible region (320 to 780 nm wavelength) and the NIR region (780 to 2500 nm). About 99% of the ASTM solar spectrum lies within these two regions. The corresponding normal incidence properties are $T(0, \text{vis}) = 0.876$, $R(0, \text{vis}) = 0.081$, $T(0, \text{NIR}) = 0.791$, and $R(0, \text{NIR}) = 0.069$.

From Equation (51), one then calculates $P(\text{vis}) = 1.922$ and $P(\text{NIR}) = 1.758$. Equation (50) yields surface reflectances of $\rho(0, \text{vis}) = 0.44$ and $\rho(0, \text{NIR}) = 0.041$, and Equation (53) gives refractive indices for the two wavelength regions of $n(\text{vis}) = 1.530$ and $n(\text{NIR}) = 1.507$. From Equation (52), we obtain the values $\alpha(\text{vis}) = 0.0149$ and $\alpha(\text{NIR}) = 0.0508$. These are the parameters necessary for calculating the optical properties.

For the conditions of Example 5, the incident angle is found in Example 6 to be 63.2° . At this incident angle, Equation (40) gives refracted angles of $\zeta(\text{vis}) = 35.7^\circ$ and $\zeta(\text{NIR}) = 36.3^\circ$. For polarization s , Equation (39a) gives $\rho_s(63.2^\circ, \text{vis}) = 0.218$, $\rho_s(63.2^\circ, \text{NIR}) = 0.210$, and for polarization p , Equation (39b) gives $\rho_p(63.2^\circ, \text{vis}) = 0.0066$, and $\rho_p(63.2^\circ, \text{NIR}) = 0.0072$. Putting these values into Equations (32) through (34) gives for the transmittances and reflectances for each polarization: ${}_sT(63.2^\circ, \text{vis}) = 0.604$, ${}_sR(63.2^\circ, \text{vis}) = 0.343$, ${}_sT(63.2^\circ, \text{NIR}) = 0.533$, ${}_sR(63.2^\circ, \text{NIR}) = 0.303$, ${}_pT(63.2^\circ, \text{vis}) = 0.934$, ${}_pR(63.2^\circ, \text{vis}) = 0.012$, ${}_pT(63.2^\circ, \text{NIR}) = 0.816$, and ${}_pR(63.2^\circ, \text{NIR}) = 0.012$.

Note that the reflected radiation is almost completely polarized. The unpolarized quantities are then calculated from Equations (35) and (36): $T(63.2^\circ, \text{vis}) = 1/2(0.604 + 0.934) = 0.769$ and $R(63.2^\circ, \text{vis}) = 1/2(0.343 + 0.012) = 0.178$, and, similarly, $T(63.2^\circ, \text{NIR}) = 0.674$ and $R(63.2^\circ, \text{NIR}) = 0.157$.

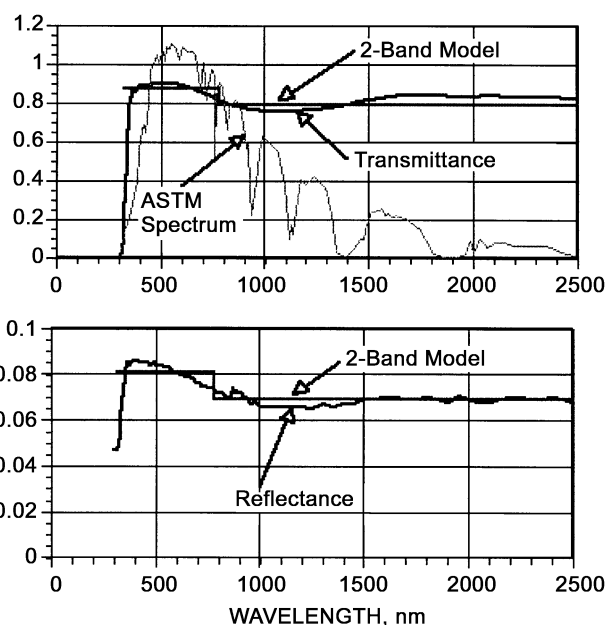


Fig. 20 Transmittance and Reflectance of Clear 3 mm Glass Approximated by a 2-Band Model of Spectrally Weighted Transmittance and Reflectance

Table 12 Polynomial Coefficients for Calculation of Reference Angular Functions for Coated Glazings

Condition		m				
		0	1	2	3	4
$T(0) > 0.645$	TA	-0.0015	3.355	-3.840	1.460	0.0288
	RA	0.999	-0.563	2.043	-2.532	1.054
$T(0) \leq 0.645$	TA	-0.002	2.813	-2.341	-0.05725	0.599
	RA	0.997	-1.868	6.513	-7.862	3.225

Coated Glazings

While in principle the equations in the preceding sections could be used to calculate the properties of coated glazings, this is not currently practical. To obtain the necessary basic information about the structure of complex coatings would require spectrophotometric measurements at angles other than normal incidence. The instruments for making such measurements are not widely available nor are there yet standardized procedures for making the measurements and extracting coating properties from them.

Until such capabilities are available, the following approximate procedure should be used to model coated glazings (Finlayson and Arasteh 1993). Coated glazing properties should vary from these estimates by no more than $\pm 20\%$ at 60° incidence (Rubin et al. 1999).

The spectral transmittance and reflectances at any incident angle are approximated from those at normal incidence by

$$T(\theta, \lambda) = T(0, \lambda)T_{REF}(\theta) \quad (54)$$

$$R^i(\theta, \lambda) = R^i(0, \lambda)[1 - R_{REF}(\theta)] + R_{REF}(\theta) \quad (i = f, b) \quad (55)$$

where

$$T_{REF}(\theta) = \sum_{m=0}^4 (TA)_m \cos^m \theta \quad (56)$$

and

$$R_{REF}(\theta) = \sum_{m=0}^4 (RA)_m \cos^m \theta - T_{REF}(\theta) \quad (57)$$

The constants in Equations (56) and (57) are selected from the entries in Table 12 appropriate to the value of the spectrally averaged transmittance at normal incidence, $T(0)$. Since Equations (54) and (55) make wavelength-independent modifications to the properties at normal incidence, the spectral averaging may be done first, yielding

$$T(\theta) = T(0)[T_{REF}(\theta)] \quad (58)$$

$$R^i(\theta) = R^i(0)[1 - R_{REF}(\theta)] + R_{REF}(\theta) \quad (i = f, b) \quad (59)$$

Example 9. Construct an approximate model of the optical properties of a single layer of 3 mm clear glass with a selective low-emissivity coating on surface 2. Use this model to calculate the properties under the conditions of Example 5.

Solution: The spectral transmittance and reflectances of selective 3 mm glass at normal incidence are shown in Figure 21. [The source of these data is “EE-170-3.CIG” glass in the NFRC (2000b) spectral data library.] The 2-band model shown in the figure has the following normal-incidence spectral properties: $T(0, \text{vis}) = 0.657$, $R^f(0, \text{vis}) = 0.132$, $R^b(0, \text{vis}) = 0.122$, $T(0, \text{NIR}) = 0.088$, $R^f(0, \text{NIR}) = 0.614$, and $R^b(0, \text{NIR}) = 0.830$. It can be seen from Figure 21 that this model crudely represents the difference in glazing optical properties for the two spectral regions.

For the crude optical model available for coated glass, the angular dependence enters only through T_{REF} and R_{REF} . Following the method of Example 11 to average the spectral properties, one finds that the spectral average transmittance at normal incidence for this glazing, $T(0)$, is 0.379. Since this is less than 0.645, constants for computing these two functions using Equations (56) and (57) are taken from the lower two rows of Table 12. At an incident angle of 63.2° (from Example 6), these functions are $T_{REF}(63.2^\circ) = 0.810$ and $R_{REF}(63.2^\circ) = 0.081$. The transmittance and reflectances are then calculated for each wavelength region using Equations (58) and (59):

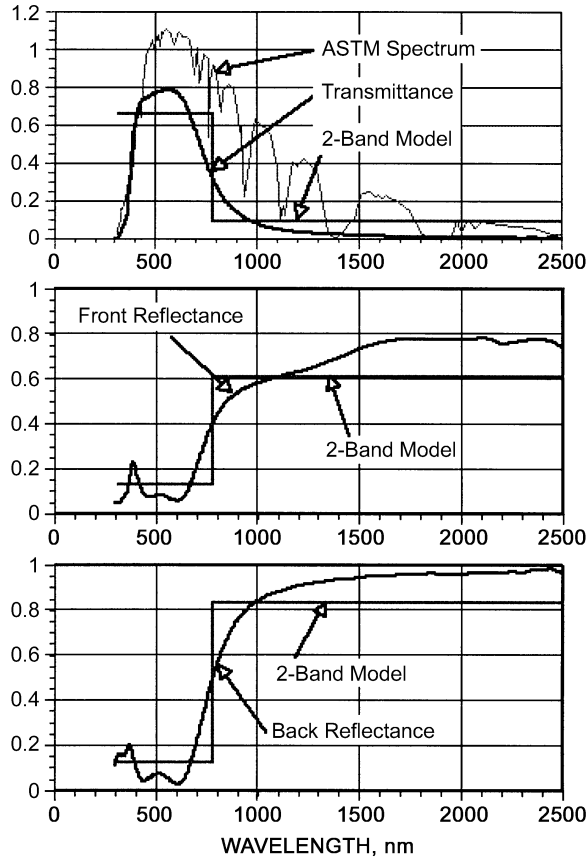


Fig. 21 Transmittance and Reflectance at Normal Incidence of a Selective Low-e Glass Approximated by a 2-Band Model of Spectrally Weighted Transmittance and Reflectance

$$T(63.2^\circ, \text{vis}) = 0.532, R^f(63.2^\circ, \text{vis}) = 0.202, R^b(63.2^\circ, \text{vis}) = 0.193, \\ T(63.2^\circ, \text{NIR}) = 0.071, R^f(63.2^\circ, \text{NIR}) = 0.646, \text{ and} \\ R^b(63.2^\circ, \text{NIR}) = 0.844$$

Optical Properties of Multiple-Layer Glazing Systems

For the optical properties of glazing systems consisting of multiple glazing layers, interreflections may occur between layers, which means that the effect of a particular layer on the overall properties may depend on its position within the assembly as well as on the transmittance and reflectances of the particular layer. We must therefore expand the glazing layer considerations above to apply to the overall properties of systems and subsystems of glazing layers. The notation for doing this is illustrated in [Figure 22](#).

In the following section, polarization indices are omitted from the equations. In principle, these equations should be used to make separate calculations of the optical properties of the glazing system for each of the two polarizations, *s* and *p*, and the results should be averaged using Equations (35) through (37). This should be done if a highly accurate result is desired (and data are available). However, since accurate data on coated glazings are lacking and polarization effects are relatively small, the polarization-averaged quantities will be used for each layer. This is the approximation used in commonly available computer calculations such as Wright (1995b) and LBL (1994).

The position of each layer in a multilayer glazing system consisting of *L* layers is characterized by its layer number *n* as shown in [Figure 22](#). (By convention, layer 1 is the layer closest to the sun.) The individual layer transmittances, reflectances, and absorptances for the *n*th layer (the properties of the layer when isolated in air) are

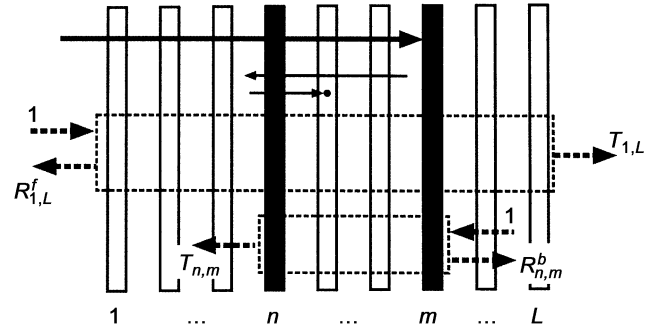


Fig. 22 Multilayer Glazings Considered as Systems and Subsystems

denoted by adding a single subscript to the property symbol: T_n , R_n^f , R_n^b , a_n^f and a_n^b . The properties of a subsystem consisting of the layers *n* through *m*, inclusive (*n* and *m* may be written as capital letters *N* and *M* to avoid confusion and emphasize their role in specifying a subsystem), are denoted by symbols with two indices for transmittances and reflectances and by script capital letters for absorptances (*A*):

$T_n(\theta, \lambda)$ = isolated-layer transmittance of the *n*th layer (in an *L*-layer system)

$T_{N,M}(\theta, \lambda)$ = transmittances of the subsystem consisting of layers *N* through *M* (in an *L*-layer system)

and similarly for reflectances, while

$a_n^f(\theta, \lambda)$ = isolated-layer front absorptance for the *n*th layer (in an *L*-layer system)

$A_{n:(N,M)}^f(\theta, \lambda)$ = actual front absorptance for the *n*th layer in the subsystem consisting of layers *N* through *M* (in an *L*-layer system); the fraction of the radiation incident on layer *N* that is absorbed in layer *n*, including effects of multiple reflections from layers *N* through *M*

$A_{n:(N,M)}^b(\theta, \lambda)$ = actual back absorptance for the *n*th layer in the subsystem consisting of layers *N* through *M* (in an *L*-layer system); the fraction of the (backward-going) radiation incident on layer *M* that is absorbed in layer *n*, including effects of multiple reflections from layers *N* through *M*.

A quantity such as $T_{1,L}(\theta, \lambda)$ refers to the total overall system property. Note that $A_{n:(n,n)}^f(\theta, \lambda) = a_n^f$ and $A_{n:(n,n)}^b(\theta, \lambda) = a_n^b$. (A subsystem consisting of one layer is the same as an isolated layer.)

The properties of any subsystem can be calculated by use of the following recursion relations and proceeding from left to right in [Figure 22](#) (Finlayson and Arasteh 1993):

$$T_{n,m+1}(\theta, \lambda) = \frac{T_{n,m}(\theta, \lambda) T_{m+1}(\theta, \lambda)}{1 - R_{n,m}^b(\theta, \lambda) R_{m+1}^f(\theta, \lambda)} \quad (60)$$

$$R_{n,m+1}^f(\theta, \lambda) = R_{n,m}^f(\theta, \lambda) + \frac{[T_{n,m}(\theta, \lambda)]^2 R_{m+1}^b(\theta, \lambda)}{1 - R_{n,m}^b(\theta, \lambda) R_{m+1}^f(\theta, \lambda)} \quad (61)$$

$$R_{n,m+1}^b(\theta, \lambda) = R_{m+1}^b(\theta, \lambda) + \frac{[T_{m+1}(\theta, \lambda)]^2 R_{n,m}^b(\theta, \lambda)}{1 - R_{n,m}^b(\theta, \lambda) R_{m+1}^f(\theta, \lambda)} \quad (62)$$

where it is always the case that $m \geq n$, and a subsystem consisting of one layer is the same as an isolated layer [e.g., $T_{n,n}(\theta, \lambda) \equiv T_n(\theta, \lambda)$]. These equations allow one to build up the properties of the *L*-layer system by beginning with the isolated properties of the first layer and successively adding additional layers. The absorptance of the *n*th layer in the system is then calculated from

$$A_{n:(1,L)}^f(\theta, \lambda) = \frac{T_{1,n-1}(\theta, \lambda) a_n^f(\theta, \lambda)}{1 - R_{1,n-1}^b(\theta, \lambda) R_{n,L}^f(\theta, \lambda)} + \frac{T_{1,n}(\theta, \lambda) R_{n+1,L}^f(\theta, \lambda) a_n^b(\theta, \lambda)}{1 - R_{1,n}^b(\theta, \lambda) R_{n+1,L}^f(\theta, \lambda)} \quad (63)$$

or

$$A_{n:(1,L)}^b(\theta, \lambda) = \frac{T_{n+1,L}(\theta, \lambda) a_n^b(\theta, \lambda)}{1 - R_{1,n}^b(\theta, \lambda) R_{n+1,L}^f(\theta, \lambda)} + \frac{T_{n,L}(\theta, \lambda) R_{1,n-1}^f(\theta, \lambda) a_n^f(\theta, \lambda)}{1 - R_{1,n}^f(\theta, \lambda) R_{n+1,L}^b(\theta, \lambda)} \quad (64)$$

Note that in Equations (63) and (64), combinations of subscripts will arise for the first and last layer absorptances that refer to non-existent layers (the layer before the first or after the last). Rather than write separate equations for these special cases, we define the nonexistent layers to have transmittance of one and reflectance of zero:

$$T_{1,0} = T_{L+1,L} = 1$$

$$R_{L+1,L}^f = R_{L+1,L}^b = R_{1,0}^f = R_{1,0}^b = 0 \quad (65)$$

Example 10. Calculate the properties of a double-glazed unit having the coated glass of Example 9 as an outer glass and the clear glass of Example 8 as an inner glass, under the conditions of Example 5.

Solution: From Example 9, the optical properties of the outer glazing, which is layer 1, at 63.2° (Example 6) are $T_1(63.2^\circ, \text{vis}) = 0.532$, $R_1^f(63.2^\circ, \text{vis}) = 0.202$, and $R_1^b(63.2^\circ, \text{vis}) = 0.193$ for the visible region and $T_1(63.2^\circ, \text{NIR}) = 0.071$, $R_1^f(63.2^\circ, \text{NIR}) = 0.646$, and $R_1^b(63.2^\circ, \text{NIR}) = 0.844$ for the NIR region. From Example 8, the corresponding (unpolarized) values for the inner glazing (layer 2) are $T_2(63.2^\circ, \text{vis}) = 0.769$ and $R_2^f(63.2^\circ, \text{vis}) = R_2^b(63.2^\circ, \text{vis}) = 0.178$ for the visible region, and $T_2(63.2^\circ, \text{NIR}) = 0.674$ and $R_2^f(63.2^\circ, \text{NIR}) = R_2^b(63.2^\circ, \text{NIR}) = 0.157$ for the NIR region.

Inserting these values into Equation (60) gives the following for the glazing system's overall transmittance:

$$T_{1,2}(63.2^\circ, \text{vis}) = \frac{T_1(63.2^\circ, \text{vis}) T_2(63.2^\circ, \text{vis})}{1 - R_1^b(63.2^\circ, \text{vis}) R_2^f(63.2^\circ, \text{vis})} = \frac{(0.532)(0.769)}{1 - (0.193)(0.178)} = 0.424$$

and

$$T_{1,2}(63.2^\circ, \text{NIR}) = \frac{T_1(63.2^\circ, \text{NIR}) T_2(63.2^\circ, \text{NIR})}{1 - R_1^b(63.2^\circ, \text{NIR}) R_2^f(63.2^\circ, \text{NIR})} = \frac{(0.071)(0.674)}{1 - (0.844)(0.157)} = 0.055$$

Similarly, Equation (61) gives $R_{1,2}^f(63.2^\circ, \text{vis}) = 0.202 + (0.532)^2 \times (0.178) / [1 - (0.193)(0.178)] = 0.254$ and $R_{1,2}^f(63.2^\circ, \text{NIR}) = 0.446$ for the front reflectances in the two spectral regions, and Equation (62) gives the back reflectances, $R_{1,2}^b(63.2^\circ, \text{vis}) = 0.178 + (0.769)^2 \times (0.193) / [1 - (0.193)(0.178)] = 0.296$ and $R_{1,2}^b(63.2^\circ, \text{NIR}) = 0.600$. In order to calculate the layer absorptances in the glazing system, we must first calculate the isolated-layer absorptances for both glazings using Equations (38c) and (38d):

$$a_1^f(63.2^\circ, \text{vis}) = 1 - 0.532 - 0.202 = 0.266$$

$$a_1^b(63.2^\circ, \text{vis}) = 0.275$$

$$a_1^f(63.2^\circ, \text{NIR}) = 0.283$$

$$a_1^b(63.2^\circ, \text{NIR}) = 0.085$$

$$a_2^f(63.2^\circ, \text{vis}) = a_2^b(63.2^\circ, \text{vis}) = 0.053$$

$$a_2^f(63.2^\circ, \text{NIR}) = a_2^b(63.2^\circ, \text{NIR}) = 0.165$$

We then use Equations (63) and (65) to calculate the layer front absorptances in the glazing system:

$$A_{1:(1,2)}^f(63.2^\circ, \text{vis}) = a_1^f(63.2^\circ, \text{vis}) + \frac{T_1(63.2^\circ, \text{vis}) R_2^f(63.2^\circ, \text{vis}) a_1^b(63.2^\circ, \text{vis})}{1 - R_1^b(63.2^\circ, \text{vis}) R_2^f(63.2^\circ, \text{vis})} = 0.266 + \frac{(0.532)(0.178)(0.275)}{1 - (0.193)(0.178)} = 0.293$$

$$A_{2:(1,2)}^f(63.2^\circ, \text{vis}) = \frac{T_1(63.2^\circ, \text{vis}) a_2^b(63.2^\circ, \text{vis})}{1 - R_1^b(63.2^\circ, \text{vis}) R_2^f(63.2^\circ, \text{vis})} = \frac{(0.532)(0.053)}{1 - (0.193)(0.178)} = 0.029$$

$$A_{1:(1,2)}^f(63.2^\circ, \text{NIR}) = 0.285$$

$$A_{2:(1,2)}^f(63.2^\circ, \text{NIR}) = 0.014$$

and Equations (64) and (65) to calculate the back absorptances: $A_{1:(1,2)}^b(63.2^\circ, \text{vis}) = 0.219$, $A_{2:(1,2)}^b(63.2^\circ, \text{vis}) = 0.061$, $A_{1:(1,2)}^b(63.2^\circ, \text{NIR}) = 0.066$, and $A_{2:(1,2)}^b(63.2^\circ, \text{NIR}) = 0.279$.

Spectral Averaging of Glazing Properties

For calculating fenestration heat transfer, it is generally sufficient to use spectrally averaged glazing system properties as defined in Equation (30) or (31). While for special combinations of climate and location it may be desirable to carry out this averaging using variant solar spectra as weighting functions in these equations, as discussed in the section on Solar Radiation under Determining Incident Solar Flux, it is seldom either feasible or necessary to carry out heat transfer calculations using a detailed, time-dependent solar spectrum and the spectral glazing properties.

For multiple-layer glazing systems, the spectral averaging of Equation (30) or (31) should in general be applied to the system spectral properties at each angle [Equations (60) through (64)]. Since all glazing layer properties are to some extent both angle and wavelength dependent, and since these equations are nonlinear in the glazing properties, this is the only procedure that is valid in principle. In general, when a glazing property is used without a specific function reference to wavelength, it assumes that this averaging procedure has been carried out. For example, for a multiple-layer glazing,

$$T_{n,m}(\theta) = \frac{\int_{\lambda_{\min}}^{\lambda_{\max}} E_{STD}(\lambda) T_{n,m}(\theta, \lambda) d\lambda}{\int_{\lambda_{\min}}^{\lambda_{\max}} E_{STD}(\lambda) d\lambda} \quad (66)$$

where $T_{n,m}(\theta, \lambda)$ has been obtained from the individual layer properties and the application of Equation (60). The analogous definitions apply for $R_{n,m}^f(\theta)$, $R_{n,m}^b(\theta)$, $A_{n:(1,L)}^f(\theta)$, and $A_{n:(1,L)}^b(\theta)$ and the other wavelength-dependent quantities appearing in the

section on Optical Properties of Multiple-Layer Glazing Systems. Unless otherwise stated, the standard spectrum, $E_{STD}(\lambda)$, used in the calculation is the ASTM *Standard E 891* spectrum.

However, as explained in this section, many glazings have properties that vary little over the wavelength region spanned by the solar spectrum. For systems containing only these glazings, much computational labor can be saved by calculating the wavelength-averaged properties (as a function of incident angle) for each isolated glazing layer and using these properties in Equations (60) through (64). While this procedure is less accurate, it may prove adequate for systems involving clear and nearly clear glazings. In using it, one should, however, examine the spectral properties of the glazings to ensure that the potential errors in the approximation are understood. One should particularly note [Figures 15, 16, 23, and 24](#). While clear architectural glazings are generally engineered to have constant spectral properties in the visible region to avoid objectionable coloration, this may not apply to the substantial part of the solar spectrum outside the visible region.

The values of $T_{1,m}(\theta)$, $R_{1,m}^f(\theta)$, and $R_{1,m}^b(\theta)$ are tabulated for a number of common single ($m = 1$), double ($m = 2$), and triple ($m = 3$) glazing systems in [Table 13](#), and these may be used in combination with the wavelength-averaged versions of Equations (63), (64), (38c), and (38d). One obtains the wavelength-averaged equation by simply dropping the references to wavelength in the equations. At the level of accuracy implied by the use of [Table 13](#), it will be sufficient to use the wavelength-averaged properties listed in the table for layers or subsystems in Equations (63) and (64) to calculate the layer absorptances in the system. For example, if one were interested in a double-glazed system with a tinted and a clear glass, the properties listed in [Table 13](#) for single-glazed clear and single-glazed tinted glass could be used for the layer properties in calculating the in-system layer absorptances. A problem arises for some low-e coated glazings, which are not listed in [Table 13](#) as single glazings because they are never utilized that way (due to the fragility of the coating). In this case, one must use the formulas or consult the NFRC (2000b) data library and its associated (free) computer software to obtain the layer properties.

Even when some glazings have a significant spectral dependence, it may be possible to simplify the calculation by evaluating Equation (31) over only a small number of selected wavelengths. For example, a common situation is a glazing system consisting primarily of clear glazing layers but containing one “selective” or “hot climate” low-e glazing layer (see [Figure 24](#) and associated text). This glazing layer will have very different properties in the visible and near-infrared parts of the solar spectrum. One could, therefore, calculate its spectral average separately over the two spectral regions and utilize the center wavelengths of the two regions in Equation (31)—a “two-band” model. If the other glazings in the system have properties that can be considered constant within each of the two spectral regions, a model of this type will generally produce adequate results.

Example 11. Calculate the spectral average properties of the glazings in Examples 8, 9, and 10. How do the results using a 2-band model compare with those for a single-band model? How do the results obtained from the formulas compare with those obtained by linearly interpolating the values in [Table 13](#)?

Solution: One must first calculate the spectral weights to be applied to the 2-band model. This is done by integrating the ASTM spectrum (numerically) to determine the fraction of energy contained in the visible (320 to 780 nm) and NIR (780 to 2500 nm) bands. Energy outside of either band is neglected (about 1.4% of the solar spectrum). These weights are $w_{vis} = 0.512$ and $w_{NIR} = 0.488$. The spectral average properties are then calculated using Equation (31). For the selective glazing of Example 9, the spectral average properties at 63.2° are $T_1(63.2^\circ) = (0.512)(0.532) + (0.488)(0.071) = 0.307$, $R_1^f(63.2^\circ) =$

0.419 , $R_1^b(63.2^\circ) = 0.511$, $a_1^f(63.2^\circ) = 0.274$, and $a_1^b(63.2^\circ) = 0.182$. For the clear glazing of Example 8, the spectral average properties are $T_2(63.2^\circ) = 0.723$, $R_2^f(63.2^\circ) = R_2^b(63.2^\circ) = 0.168$, and $a_2^f(63.2^\circ) = a_2^b(63.2^\circ) = 0.107$. For the double-glazed system of Example 10, the spectral average properties are $T_{1,2}(63.2^\circ) = 0.244$, $R_{1,2}^f(63.2^\circ) = 0.446$, $R_{1,2}^b(63.2^\circ) = 0.444$, $A_{1;(1,2)}^f(63.2^\circ) = 0.289$, $A_{1;(1,2)}^b(63.2^\circ) = 0.144$, $A_{2;(1,2)}^f(63.2^\circ) = 0.022$, and $A_{2;(1,2)}^b(63.2^\circ) = 0.167$.

To obtain the results for a single-band model, we repeat the calculations of Example 10 using the spectral average quantities for the two glazing layers instead of the separate values for the visible and NIR bands. When we do this, we obtain the spectral average properties $T_{1,2}(63.2^\circ) = 0.243$, $R_{1,2}^f(63.2^\circ) = 0.436$, $R_{1,2}^b(63.2^\circ) = 0.460$, $A_{1;(1,2)}^f(63.2^\circ) = 0.285$, $A_{1;(1,2)}^b(63.2^\circ) = 0.144$, $A_{2;(1,2)}^f(63.2^\circ) = 0.037$, and $A_{2;(1,2)}^b(63.2^\circ) = 0.153$. As can be seen, the results for the two methods are not identical but are relatively close together for this glazing system.

The exact glazing system used in this example is not listed in [Table 13](#) (as will frequently be the case in practice), so we must locate the glazing system that is closest in properties. The emissivity of the selective coating on surface 2 of the outer glazing is 0.05, and the transmittance and reflectances for the insulating glass unit at normal incidence are $T(0^\circ) = 0.331$, $R^f(0^\circ) = 0.388$, and $R^b(0^\circ) = 0.396$. The most similar unit listed in [Table 13](#) is ID 25a, which has $T(0^\circ) = 0.37$, $R^f(0^\circ) = 0.35$, and $R^b(0^\circ) = 0.39$ (i.e., slightly lower front reflectance and therefore higher transmittance).

Near the required angle of incidence, the table values listed are $T(60^\circ) = 0.29$, $R^f(60^\circ) = 0.40$, $R^b(60^\circ) = 0.43$ and $T(70^\circ) = 0.22$, $R^f(70^\circ) = 0.47$, and $R^b(70^\circ) = 0.50$. (The subscripts 1,2 are understood from the system description.) Linear interpolation in angle yields the values $[T_{1,2}(63.2^\circ)]_{25a} = 0.27$, $[R_{1,2}^f(63.2^\circ)]_{25a} = 0.42$, and $[R_{1,2}^b(63.2^\circ)]_{25a} = 0.45$.

Since the normal incidence transmittance of ID 25a in the table was about 0.04 higher than that of the glazing system in which we are interested (and the front reflectance correspondingly 0.04 lower), we might correct the above calculation by multiplying by the ratio of the normal incidence value for the desired glazing to that of table entry 25a. When we do this, we obtain the values $[T_{1,2}(63.2^\circ)]_{table} = 0.27 \times 0.331/0.37 = 0.24$, $[R_{1,2}^f(63.2^\circ)]_{table} = 0.42 \times 0.388/0.35 = 0.47$, and $[R_{1,2}^b(63.2^\circ)]_{table} = 0.45 \times 0.396/0.39 = 0.46$. These values are quite close to the ones obtained above from use of the exact formulas.

Angular Averaging of Glazing Properties

As stressed in the previous sections, the solar-optical properties of glazings depend on the incident angle of the radiation passing through the glazing. It is relatively simple to account for this dependence in the case of beam solar radiation, since at any particular time the radiation can be considered to be incident from a single direction, and from this direction the incident angle can be calculated as described in the section on Determining Solar Angle under Determining Solar Incident Flux. However, for the diffuse solar and ground-reflected radiation, the situation is more complicated. In principle, the energy flow through the glazing should be a sum over the individual energy flows resulting from incident radiation from each direction; for example, the radiant flux directly transmitted through an L -layer glazing due to sky and ground radiation would be

$$q_{trans} = \int \int_{\lambda, hem} \int E_{sky, ground}(\theta, \phi, \lambda) T_{1,L}(\theta, \lambda) (\cos \theta) d\omega d\lambda \quad (67)$$

where λ denotes solar wavelengths and hem stands for hemispherical. $E_{sky, ground}(\theta, \phi, \lambda)$ is the spectral radiance of the portion of the sky viewed in the direction (θ, ϕ) from the glazing, and $d\omega$ is the infinitesimal element of solid angle corresponding to this direction. While such calculations can be carried out for specific sky conditions using detailed sky data or models, such as those cited in the text following Equation (12) in the section on Solar Radiation, the labor of such a calculation will be worthwhile only for very specific purposes. More generally, a drastic simplifying assumption, alluded to in Equation (12), is made. Both the sky and ground radiation are assumed to be **ideally diffuse** (i.e., to have a sky radiance that is

Table 13 Visible Transmittance (T_v), Solar Heat Gain Coefficient (SHGC), Solar Transmittance (T_s), Front Reflectance (R^f), Back Reflectance (R^b), and Layer Absorptances (A_n^f) for Glazing and Window Systems

												Total Window SHGC at Normal Incidence				Total Window T_v at Normal Incidence				
												Center-of-Glazing Properties								Aluminum
ID	Glazing System			Center Glazing T_v		Incidence Angles							Operable	Fixed	Operable	Fixed	Operable	Fixed	Operable	Fixed
	Glass Thick., mm					Normal 0.00	40.00	50.00	60.00	70.00	80.00	Hemis., Diffuse								
Uncoated Single Glazing																				
1a	3	CLR	0.90	SHGC	0.86	0.84	0.82	0.78	0.67	0.42	0.78	0.75	0.78	0.64	0.75	0.77	0.80	0.66	0.78	
				T	0.83	0.82	0.80	0.75	0.64	0.39	0.75									
				R^f	0.08	0.08	0.10	0.14	0.25	0.51	0.14									
				R^b	0.08	0.08	0.10	0.14	0.25	0.51	0.14									
				A_{f1}	0.09	0.10	0.10	0.11	0.11	0.11	0.10									
1b	6	CLR	0.88	SHGC	0.81	0.80	0.78	0.73	0.62	0.39	0.73	0.71	0.74	0.60	0.71	0.75	0.79	0.64	0.77	
				T	0.88	0.87	0.85	0.80	0.69	0.43	0.80									
				R^f	0.08	0.09	0.11	0.15	0.27	0.53	0.14									
				R^b	0.08	0.09	0.11	0.15	0.27	0.53	0.14									
				A_{f1}	0.16	0.17	0.18	0.19	0.19	0.17	0.17									
1c	3	BRZ	0.68	SHGC	0.73	0.71	0.68	0.64	0.55	0.34	0.65	0.64	0.67	0.54	0.64	0.58	0.61	0.50	0.59	
				T	0.65	0.62	0.59	0.55	0.46	0.27	0.56									
				R^f	0.06	0.07	0.08	0.12	0.22	0.45	0.12									
				R^b	0.06	0.07	0.08	0.12	0.22	0.45	0.12									
				A_{f1}	0.29	0.31	0.32	0.33	0.33	0.29	0.31									
1d	6	BRZ	0.54	SHGC	0.62	0.59	0.57	0.53	0.45	0.29	0.54	0.54	0.56	0.46	0.54	0.45	0.48	0.39	0.47	
				T	0.49	0.45	0.43	0.39	0.32	0.18	0.41									
				R^f	0.05	0.06	0.07	0.11	0.19	0.42	0.10									
				R^b	0.05	0.68	0.66	0.62	0.53	0.33	0.10									
				A_{f1}	0.46	0.49	0.50	0.51	0.49	0.41	0.48									
1e	3	GRN	0.82	SHGC	0.70	0.68	0.66	0.62	0.53	0.33	0.63	0.62	0.64	0.52	0.61	0.70	0.73	0.60	0.71	
				T	0.61	0.58	0.56	0.52	0.43	0.25	0.53									
				R^f	0.06	0.07	0.08	0.12	0.21	0.45	0.11									
				R^b	0.06	0.07	0.08	0.12	0.21	0.45	0.11									
				A_{f1}	0.33	0.35	0.36	0.37	0.36	0.31	0.35									
1f	6	GRN	0.76	SHGC	0.60	0.58	0.56	0.52	0.45	0.29	0.54	0.53	0.55	0.45	0.53	0.65	0.68	0.55	0.66	
				T	0.47	0.44	0.42	0.38	0.32	0.18	0.40									
				R^f	0.05	0.06	0.07	0.11	0.20	0.42	0.10									
				R^b	0.05	0.06	0.07	0.11	0.20	0.42	0.10									
				A_{f1}	0.47	0.50	0.51	0.51	0.49	0.40	0.49									
1g	3	GRY	0.62	SHGC	0.70	0.68	0.66	0.61	0.53	0.33	0.63	0.62	0.64	0.52	0.61	0.52	0.55	0.45	0.54	
				T	0.61	0.58	0.56	0.51	0.42	0.24	0.53									
				R^f	0.06	0.07	0.08	0.12	0.21	0.44	0.11									
				R^b	0.06	0.07	0.08	0.12	0.21	0.44	0.11									
				A_{f1}	0.33	0.36	0.37	0.37	0.37	0.32	0.35									
1h	6	GRY	0.46	SHGC	0.59	0.57	0.55	0.51	0.44	0.28	0.52	0.53	0.54	0.44	0.52	0.39	0.41	0.34	0.40	
				T	0.46	0.42	0.40	0.36	0.29	0.16	0.38									
				R^f	0.05	0.06	0.07	0.10	0.19	0.41	0.10									
				R^b	0.05	0.06	0.07	0.10	0.19	0.41	0.10									
				A_{f1}	0.49	0.52	0.54	0.54	0.52	0.43	0.51									
1i	6	BLUGRN	0.75	SHGC	0.62	0.59	0.57	0.54	0.46	0.30	0.55	0.55	0.57	0.46	0.54	0.64	0.67	0.55	0.65	
				T	0.49	0.46	0.44	0.40	0.33	0.19	0.42									
				R^f	0.06	0.06	0.07	0.11	0.20	0.43	0.11									
				R^b	0.06	0.06	0.07	0.11	0.20	0.43	0.11									
				A_{f1}	0.45	0.48	0.49	0.49	0.47	0.38	0.48									
Reflective Single Glazing																				
1j	6	SS on CLR 8%	0.08	SHGC	0.19	0.19	0.19	0.18	0.16	0.10	0.18	0.18	0.18	0.15	0.17	0.07	0.07	0.06	0.07	
				T	0.06	0.06	0.06	0.05	0.04	0.03	0.05									
				R^f	0.33	0.34	0.35	0.37	0.44	0.61	0.36									
				R^b	0.50	0.50	0.51	0.53	0.58	0.71	0.52									
				A_{f1}	0.61	0.61	0.60	0.58	0.52	0.37	0.57									
1k	6	SS on CLR 14%	0.14	SHGC	0.25	0.25	0.24	0.23	0.20	0.13	0.23	0.23	0.24	0.19	0.22	0.12	0.12	0.10	0.12	
				T	0.11	0.10	0.10	0.09	0.07	0.04	0.09									
				R^f	0.26	0.27	0.28	0.31	0.38	0.57	0.30									
				R^b	0.44	0.44	0.45	0.47	0.52	0.67	0.46									
				A_{f1}	0.63	0.63	0.62	0.60	0.55	0.39	0.60									

Table 13 Visible Transmittance (T_v), Solar Heat Gain Coefficient (SHGC), Solar Transmittance (T_s), Front Reflectance (R^f), Back Reflectance (R^b), and Layer Absorptances (A^n_f) for Glazing and Window Systems (*Continued*)

													Total Window SHGC at Normal Incidence				Total Window T_v at Normal Incidence			
													Center-of-Glazing Properties							
Glazing System					Incidence Angles								Aluminum		Other Frames		Aluminum		Other Frames	
ID		Glass Thick., mm		Center Glazing T_v	Normal 0.00	40.00	50.00	60.00	70.00	80.00	Hemis., Diffuse	Operable	Fixed	Operable	Fixed	Operable	Fixed	Operable	Fixed	
1l	6	SS on CLR 20%	0.20	SHGC	0.31	0.30	0.30	0.28	0.24	0.16	0.28	0.28	0.29	0.24	0.27	0.17	0.18	0.15	0.17	
				T	0.15	0.15	0.14	0.13	0.11	0.06	0.13									
				R^f	0.21	0.22	0.23	0.26	0.34	0.54	0.25									
				R^b	0.38	0.38	0.39	0.41	0.48	0.64	0.41									
				A_1^f	0.64	0.64	0.63	0.61	0.56	0.40	0.60									
1m	6	SS on GRN 14%	0.12	SHGC	0.25	0.25	0.24	0.23	0.21	0.14	0.23	0.23	0.24	0.19	0.22	0.10	0.11	0.09	0.10	
				T	0.06	0.06	0.06	0.06	0.04	0.03	0.06									
				R^f	0.14	0.14	0.16	0.19	0.27	0.49	0.18									
				R^b	0.44	0.44	0.45	0.47	0.52	0.67	0.46									
				A_1^f	0.80	0.80	0.78	0.76	0.68	0.48	0.75									
1n	6	TI on CLR 20%	0.20	SHGC	0.29	0.29	0.28	0.27	0.23	0.15	0.27	0.27	0.27	0.22	0.26	0.17	0.18	0.15	0.17	
				T	0.14	0.13	0.13	0.12	0.09	0.06	0.12									
				R^f	0.22	0.22	0.24	0.26	0.34	0.54	0.26									
				R^b	0.40	0.40	0.42	0.44	0.50	0.65	0.43									
				A_1^f	0.65	0.65	0.64	0.62	0.57	0.40	0.62									
1o	6	TI on CLR 30%	0.30	SHGC	0.39	0.38	0.37	0.35	0.30	0.20	0.35	0.35	0.36	0.30	0.34	0.26	0.27	0.22	0.26	
				T	0.23	0.22	0.21	0.19	0.16	0.09	0.20									
				R^f	0.15	0.15	0.17	0.20	0.28	0.50	0.19									
				R^b	0.32	0.33	0.34	0.36	0.43	0.60	0.36									
				A_1^f	0.63	0.65	0.64	0.62	0.57	0.40	0.62									
Uncoated Double Glazing																				
5a	3	CLR CLR	0.81	SHGC	0.76	0.74	0.71	0.64	0.50	0.26	0.66	0.67	0.69	0.56	0.66	0.69	0.72	0.59	0.70	
				T	0.70	0.68	0.65	0.58	0.44	0.21	0.60									
				R^f	0.13	0.14	0.16	0.23	0.36	0.61	0.21									
				R^b	0.13	0.14	0.16	0.23	0.36	0.61	0.21									
				A_1^f	0.10	0.11	0.11	0.12	0.13	0.13	0.11									
				A_2^f	0.07	0.08	0.08	0.08	0.07	0.05	0.07									
5b	6	CLR CLR	0.78	SHGC	0.70	0.67	0.64	0.58	0.45	0.23	0.60	0.61	0.63	0.52	0.61	0.66	0.69	0.57	0.68	
				T	0.61	0.58	0.55	0.48	0.36	0.17	0.51									
				R^f	0.11	0.12	0.15	0.20	0.33	0.57	0.18									
				R^b	0.11	0.12	0.15	0.20	0.33	0.57	0.18									
				A_1^f	0.17	0.18	0.19	0.20	0.21	0.20	0.19									
				A_2^f	0.11	0.12	0.12	0.12	0.10	0.07	0.11									
5c	3	BRZ CLR	0.62	SHGC	0.62	0.60	0.57	0.51	0.39	0.20	0.53	0.55	0.57	0.46	0.54	0.53	0.55	0.45	0.54	
				T	0.55	0.51	0.48	0.42	0.31	0.14	0.45									
				R^f	0.09	0.10	0.12	0.16	0.27	0.49	0.15									
				R^b	0.12	0.13	0.15	0.21	0.35	0.59	0.19									
				A_1^f	0.30	0.33	0.34	0.36	0.37	0.34	0.33									
				A_2^f	0.06	0.06	0.06	0.06	0.05	0.03	0.06									
5d	6	BRZ CLR	0.47	SHGC	0.49	0.46	0.44	0.39	0.31	0.17	0.41	0.44	0.46	0.37	0.43	0.40	0.42	0.35	0.41	
				T	0.38	0.35	0.32	0.27	0.20	0.08	0.30									
				R^f	0.07	0.08	0.09	0.13	0.22	0.44	0.12									
				R^b	0.10	0.11	0.13	0.19	0.31	0.55	0.17									
				A_1^f	0.48	0.51	0.52	0.53	0.53	0.45	0.50									
				A_2^f	0.07	0.07	0.07	0.07	0.06	0.04	0.07									
5e	3	GRN CLR	0.75	SHGC	0.60	0.57	0.54	0.49	0.38	0.20	0.51	0.53	0.55	0.45	0.53	0.63	0.66	0.54	0.65	
				T	0.52	0.49	0.46	0.40	0.30	0.13	0.43									
				R^f	0.09	0.10	0.12	0.16	0.27	0.50	0.15									
				R^b	0.12	0.13	0.15	0.21	0.35	0.60	0.19									
				A_1^f	0.34	0.37	0.38	0.39	0.39	0.35	0.37									
				A_2^f	0.05	0.05	0.05	0.04	0.04	0.03	0.04									
5f	6	GRN CLR	0.68	SHGC	0.49	0.46	0.44	0.39	0.31	0.17	0.41	0.43	0.45	0.37	0.43	0.57	0.60	0.49	0.59	
				T	0.39	0.36	0.33	0.29	0.21	0.09	0.31									
				R^f	0.08	0.08	0.10	0.14	0.23	0.45	0.13									
				R^b	0.10	0.11	0.13	0.19	0.31	0.55	0.17									
				A_1^f	0.49	0.51	0.05	0.53	0.52	0.43	0.50									
				A_2^f	0.05	0.05	0.05	0.05	0.04	0.03	0.05									

Table 13 Visible Transmittance (T_v), Solar Heat Gain Coefficient (SHGC), Solar Transmittance (T), Front Reflectance (R^f), Back Reflectance (R^b), and Layer Absorptances (A_n^f) for Glazing and Window Systems (Continued)

												Total Window SHGC at Normal Incidence				Total Window T_v at Normal Incidence			
												Aluminum		Other Frames		Aluminum		Other Frames	
Glazing System				Center Glazing T_v	Incidence Angles								Operable	Fixed	Operable	Fixed	Operable	Fixed	
ID	Glass Thick., mm				Normal 0.00	40.00	50.00	60.00	70.00	80.00	Hemis., Diffuse								
5g	3	GRY CLR	0.56	SHGC	0.60	0.57	0.54	0.48	0.37	0.20	0.51	0.53	0.55	0.45	0.52	0.48	0.50	0.41	0.49
				T	0.51	0.48	0.45	0.39	0.29	0.12	0.42								
				R^f	0.09	0.09	0.11	0.16	0.26	0.48	0.14								
				R^b	0.12	0.13	0.15	0.21	0.34	0.59	0.19								
				A_1^f	0.34	0.37	0.39	0.40	0.41	0.37	0.37								
				A_2^f	0.05	0.06	0.06	0.xx	0.xx	0.xx	0.xx								
5h	6	GRY CLR	0.41	SHGC	0.47	0.44	0.42	0.37	0.29	0.16	0.39	0.42	0.43	0.35	0.41	0.35	0.37	0.30	0.36
				T	0.36	0.32	0.29	0.25	0.18	0.07	0.28								
				R^f	0.07	0.07	0.08	0.12	0.21	0.43	0.12								
				R^b	0.10	0.11	0.13	0.18	0.31	0.55	0.17								
				A_1^f	0.51	0.54	0.56	0.57	0.56	0.47	0.53								
				A_2^f	0.07	0.07	0.07	0.06	0.05	0.03	0.06								
5i	6	BLUGRN CLR	0.67	SHGC	0.50	0.47	0.45	0.40	0.32	0.17	0.43	0.45	0.46	0.38	0.44	0.57	0.60	0.49	0.58
				T	0.40	0.37	0.34	0.30	0.22	0.10	0.32								
				R^f	0.08	0.08	0.10	0.14	0.24	0.46	0.13								
				R^b	0.11	0.11	0.14	0.19	0.31	0.55	0.17								
				A_1^f	0.47	0.49	0.50	0.51	0.50	0.42	0.48								
				A_2^f	0.06	0.06	0.06	0.05	0.04	0.03	0.05								
5j	6	HI-P GRN CLR	0.59	SHGC	0.39	0.37	0.35	0.31	0.25	0.14	0.33	0.35	0.36	0.30	0.34	0.50	0.53	0.43	0.51
				T	0.28	0.26	0.24	0.20	0.15	0.06	0.22								
				R^f	0.06	0.07	0.08	0.12	0.21	0.43	0.11								
				R^b	0.10	0.11	0.13	0.19	0.31	0.55	0.17								
				A_1^f	0.62	0.65	0.65	0.65	0.62	0.50	0.63								
				A_2^f	0.03	0.03	0.03	0.03	0.02	0.01	0.03								
Reflective Double Glazing																			
5k	6	SS on CLR 8%, CLR	0.07	SHGC	0.13	0.12	0.12	0.11	0.10	0.06	0.11	0.13	0.13	0.11	0.12	0.06	0.06	0.05	0.06
				T	0.05	0.05	0.04	0.04	0.03	0.01	0.04								
				R^f	0.33	0.34	0.35	0.37	0.44	0.61	0.37								
				R^b	0.38	0.37	0.38	0.40	0.46	0.61	0.40								
				A_1^f	0.61	0.61	0.60	0.58	0.53	0.37	0.56								
				A_2^f	0.01	0.01	0.01	0.01	0.01	0.01	0.01								
5l	6	SS on CLR 14%, CLR	0.13	SHGC	0.17	0.17	0.16	0.15	0.13	0.08	0.16	0.17	0.17	0.13	0.15	0.11	0.12	0.09	0.11
				T	0.08	0.08	0.08	0.07	0.05	0.02	0.07								
				R^f	0.26	0.27	0.28	0.31	0.38	0.57	0.30								
				R^b	0.34	0.33	0.34	0.37	0.44	0.60	0.36								
				A_1^f	0.63	0.64	0.64	0.63	0.61	0.56	0.60								
				A_2^f	0.02	0.02	0.02	0.02	0.02	0.02	0.02								
5m	6	SS on CLR 20%, CLR	0.18	SHGC	0.22	0.21	0.21	0.19	0.16	0.09	0.20	0.21	0.21	0.17	0.20	0.15	0.16	0.13	0.16
				T	0.12	0.11	0.11	0.09	0.07	0.03	0.10								
				R^f	0.21	0.22	0.23	0.26	0.34	0.54	0.25								
				R^b	0.30	0.30	0.31	0.34	0.41	0.59	0.33								
				A_1^f	0.64	0.64	0.63	0.62	0.57	0.41	0.61								
				A_2^f	0.03	0.03	0.03	0.03	0.02	0.02	0.03								
5n	6	SS on GRN 14%, CLR	0.11	SHGC	0.16	0.16	0.15	0.14	0.12	0.08	0.14	0.16	0.16	0.13	0.14	0.09	0.10	0.08	0.10
				T	0.05	0.05	0.05	0.04	0.03	0.01	0.04								
				R^f	0.14	0.14	0.16	0.19	0.27	0.49	0.18								
				R^b	0.34	0.33	0.34	0.37	0.44	0.60	0.36								
				A_1^f	0.80	0.80	0.79	0.76	0.69	0.49	0.76								
				A_2^f	0.01	0.01	0.01	0.01	0.01	0.01	0.01								
5o	6	TI on CLR 20%, CLR	0.18	SHGC	0.21	0.20	0.19	0.18	0.15	0.09	0.18	0.20	0.20	0.16	0.19	0.15	0.16	0.13	0.16
				T	0.11	0.10	0.10	0.08	0.06	0.03	0.09								
				R^f	0.22	0.22	0.24	0.27	0.34	0.54	0.26								
				R^b	0.32	0.31	0.32	0.35	0.42	0.59	0.35								
				A_1^f	0.65	0.66	0.65	0.63	0.58	0.41	0.62								
				A_2^f	0.02	0.02	0.02	0.02	0.02	0.01	0.02								
5p	6	TI on CLR 30%, CLR	0.27	SHGC	0.29	0.28	0.27	0.25	0.20	0.12	0.25	0.27	0.27	0.22	0.26	0.23	0.24	0.20	0.23
				T	0.18	0.17	0.16	0.14	0.10	0.05	0.15								
				R^f	0.15	0.15	0.17	0.20	0.29	0.51	0.19								
				R^b	0.27	0.27	0.28	0.31	0.40	0.58	0.31								
				A_1^f	0.64	0.64	0.63	0.62	0.58	0.43	0.61								
				A_2^f	0.04	0.04	0.04	0.04	0.03	0.02	0.04								

Table 13 Visible Transmittance (T_v), Solar Heat Gain Coefficient (SHGC), Solar Transmittance (T_s), Front Reflectance (R^f), Back Reflectance (R^b), and Layer Absorptances (A_n^f) for Glazing and Window Systems (*Continued*)

													Total Window SHGC at Normal Incidence				Total Window T_v at Normal Incidence			
													Aluminum		Other Frames		Aluminum		Other Frames	
ID	Glazing System			Center Glazing T_v	Incidence Angles								Operable	Fixed	Operable	Fixed	Operable	Fixed	Operable	Fixed
	Glass Thick., mm				Normal 0.00	40.00	50.00	60.00	70.00	80.00	Hemis., Diffuse									
Low-e Double Glazing, $e = 0.2$ on surface 2																				
17a	3	LE CLR	0.76	SHGC	0.65	0.64	0.61	0.56	0.43	0.23	0.57	0.57	0.59	0.49	0.57	0.65	0.68	0.55	0.66	
				T	0.59	0.56	0.54	0.48	0.36	0.18	0.50									
				R^f	0.15	0.16	0.18	0.24	0.37	0.61	0.22									
				R^b	0.17	0.18	0.20	0.26	0.38	0.61	0.24									
				A_1^f	0.20	0.21	0.21	0.21	0.20	0.16	0.20									
				A_2^f	0.07	0.07	0.08	0.08	0.07	0.05	0.07									
17b	6	LE CLR	0.73	SHGC	0.60	0.59	0.57	0.51	0.40	0.21	0.53	0.53	0.55	0.45	0.53	0.62	0.65	0.53	0.64	
				T	0.51	0.48	0.46	0.41	0.30	0.14	0.43									
				R^f	0.14	0.15	0.17	0.22	0.35	0.59	0.21									
				R^b	0.15	0.16	0.18	0.23	0.35	0.57	0.22									
				A_1^f	0.26	0.26	0.26	0.26	0.25	0.19	0.25									
				A_2^f	0.10	0.11	0.11	0.11	0.10	0.07	0.10									
Low-e Double Glazing, $e = 0.2$ on surface 3																				
17c	3	CLR LE	0.76	SHGC	0.70	0.68	0.65	0.59	0.46	0.24	0.61	0.62	0.64	0.52	0.61	0.65	0.68	0.55	0.66	
				T	0.59	0.56	0.54	0.48	0.36	0.18	0.50									
				R^f	0.17	0.18	0.20	0.26	0.38	0.61	0.24									
				R^b	0.15	0.16	0.18	0.24	0.37	0.61	0.22									
				A_1^f	0.11	0.12	0.13	0.13	0.14	0.15	0.12									
				A_2^f	0.14	0.14	0.14	0.13	0.11	0.07	0.13									
17d	6	CLR LE	0.73	SHGC	0.65	0.63	0.60	0.54	0.42	0.21	0.56	0.57	0.59	0.49	0.57	0.62	0.65	0.53	0.64	
				T	0.51	0.48	0.46	0.41	0.30	0.14	0.43									
				R^f	0.15	0.16	0.18	0.23	0.35	0.57	0.22									
				R^b	0.14	0.15	0.17	0.22	0.35	0.59	0.21									
				A_1^f	0.17	0.19	0.20	0.21	0.22	0.22	0.19									
				A_2^f	0.17	0.17	0.17	0.15	0.13	0.07	0.16									
17e	3	BRZ LE	0.58	SHGC	0.57	0.54	0.51	0.46	0.35	0.18	0.48	0.51	0.52	0.43	0.50	0.49	0.52	0.42	0.50	
				T	0.46	0.43	0.41	0.36	0.26	0.12	0.38									
				R^f	0.12	0.12	0.14	0.18	0.28	0.50	0.17									
				R^b	0.14	0.15	0.17	0.23	0.35	0.60	0.21									
				A_1^f	0.31	0.34	0.35	0.37	0.38	0.35	0.34									
				A_2^f	0.11	0.11	0.10	0.10	0.08	0.04	0.10									
17f	6	BRZ LE	0.45	SHGC	0.45	0.42	0.40	0.35	0.27	0.14	0.38	0.40	0.42	0.34	0.40	0.38	0.40	0.33	0.39	
				T	0.33	0.30	0.28	0.24	0.17	0.07	0.26									
				R^f	0.09	0.09	0.10	0.14	0.23	0.44	0.13									
				R^b	0.13	0.14	0.16	0.21	0.34	0.58	0.20									
				A_1^f	0.48	0.51	0.52	0.54	0.53	0.45	0.50									
				A_2^f	0.11	0.11	0.10	0.09	0.07	0.04	0.09									
17g	3	GRN LE	0.70	SHGC	0.55	0.52	0.50	0.44	0.34	0.17	0.46	0.49	0.50	0.41	0.48	0.60	0.62	0.51	0.61	
				T	0.44	0.41	0.38	0.33	0.24	0.11	0.36									
				R^f	0.11	0.11	0.13	0.17	0.27	0.48	0.16									
				R^b	0.14	0.15	0.17	0.23	0.35	0.60	0.21									
				A_1^f	0.35	0.38	0.39	0.41	0.42	0.37	0.38									
				A_2^f	0.11	0.10	0.10	0.09	0.07	0.04	0.09									
17h	6	GRN LE	0.62	SHGC	0.42	0.40	0.38	0.34	0.26	0.13	0.36	0.38	0.39	0.32	0.37	0.53	0.55	0.45	0.54	
				T	0.29	0.26	0.24	0.21	0.15	0.06	0.23									
				R^f	0.08	0.08	0.09	0.13	0.22	0.43	0.13									
				R^b	0.13	0.14	0.16	0.21	0.34	0.58	0.20									
				A_1^f	0.56	0.59	0.61	0.61	0.59	0.48	0.58									
				A_2^f	0.09	0.09	0.09	0.08	0.08	0.04	0.08									
17i	3	GRY LE	0.51	SHGC	0.53	0.50	0.48	0.42	0.33	0.17	0.45	0.47	0.49	0.40	0.47	0.43	0.45	0.37	0.44	
				T	0.43	0.40	0.38	0.33	0.24	0.11	0.35									
				R^f	0.11	0.11	0.13	0.17	0.27	0.48	0.16									
				R^b	0.14	0.15	0.17	0.22	0.35	0.60	0.21									
				A_1^f	0.58	0.60	0.61	0.61	0.59	0.48	0.59									
				A_2^f	0.08	0.08	0.08	0.08	0.07	0.04	0.08									

Table 13 Visible Transmittance (T_v), Solar Heat Gain Coefficient (SHGC), Solar Transmittance (T_s), Reflectance (R^f), Back Reflectance (R^b), and Layer Absorptances (A_n^f) for Glazing and Window Systems

												Total Window SHGC at Normal Incidence				Total Window T_v at Normal Incidence				
												Aluminum		Other Frames		Aluminum		Other Frames		
Glazing System					Incidence Angles															
ID	Glass Thick., mm		Center Glazing T_v		Normal	40.00	50.00	60.00	70.00	80.00	Hemis., Diffuse	Operable	Fixed	Operable	Fixed	Operable	Fixed	Operable	Fixed	
					0.00															
17j	6	GRY LE	0.37	SHGC	0.39	0.37	0.35	0.31	0.24	0.13	0.33	0.35	0.36	0.30	0.34	0.31	0.33	0.27	0.32	
				T	0.27	0.25	0.23	0.20	0.14	0.06	0.21									
				R^f	0.09	0.09	0.11	0.14	0.23	0.44	0.14									
				R^b	0.13	0.14	0.16	0.22	0.34	0.58	0.20									
				A_1^f	0.55	0.58	0.59	0.59	0.58	0.48	0.56									
				A_2^f	0.09	0.09	0.08	0.07	0.06	0.03	0.08									
17k	6	BLUGRN LE	0.62	SHGC	0.45	0.42	0.40	0.36	0.28	0.14	0.38	0.40	0.42	0.34	0.40	0.53	0.55	0.45	0.54	
				T	0.22	0.20	0.18	0.15	0.11	0.07	0.17									
				R^f	0.07	0.07	0.08	0.12	0.20	0.44	0.11									
				R^b	0.13	0.14	0.16	0.21	0.34	0.58	0.20									
				A_1^f	0.48	0.51	0.53	0.54	0.54	0.45	0.51									
				A_2^f	0.11	0.10	0.10	0.09	0.07	0.03	0.09									
17l	6	HI-P GRN LE	0.55	0.241	0.34	0.32	0.30	0.27	0.21	0.11	0.29	0.31	0.32	0.26	0.30	0.47	0.49	0.40	0.48	
				T	0.22	0.19	0.18	0.15	0.10	0.04	0.17									
				R^f	0.07	0.07	0.08	0.11	0.20	0.41	0.11									
				R^b	0.13	0.14	0.16	0.21	0.33	0.58	0.20									
				A_1^f	—	—	—	—	—	—	—									
				A_2^f	—	—	—	—	—	—	—									
Low-e Double Glazing, $e = 0.1$ on surface 2																				
21a	3	LE CLR	0.75	SHGC	0.54	0.52	0.49	0.44	0.34	0.18	0.46	0.48	0.50	0.41	0.47	0.64	0.67	0.55	0.65	
				T	0.48	0.45	0.43	0.37	0.27	0.13	0.40									
				R^f	0.24	0.24	0.26	0.29	0.38	0.58	0.28									
				R^b	0.27	0.27	0.28	0.32	0.42	0.62	0.31									
				A_1^f	0.23	0.25	0.26	0.28	0.30	0.26	0.26									
				A_2^f	0.06	0.06	0.06	0.06	0.05	0.04	0.06									
21b	6	LE CLR	0.72	SHGC	0.51	0.49	0.47	0.42	0.32	0.17	0.44	0.45	0.47	0.38	0.45	0.61	0.64	0.53	0.63	
				T	0.42	0.40	0.37	0.32	0.24	0.11	0.35									
				R^f	0.20	0.20	0.22	0.26	0.34	0.55	0.25									
				R^b	0.24	0.24	0.25	0.29	0.38	0.58	0.28									
				A_1^f	0.30	0.32	0.32	0.33	0.35	0.29	0.32									
				A_2^f	0.08	0.09	0.09	0.09	0.08	0.05	0.08									
21l	6	HI-P GRN W/LE CLR	0.57	SHGC	0.31	0.30	0.29	0.26	0.21	0.12	0.27	0.28	0.29	0.24	0.27	0.48	0.51	0.42	0.50	
				T	0.22	0.21	0.19	0.17	0.12	0.06	0.18									
				R^f	0.07	0.07	0.09	0.13	0.22	0.46	0.12									
				R^b	0.23	0.23	0.24	0.28	0.37	0.57	0.27									
				A_1^f	0.67	0.68	0.67	0.66	0.62	0.46	0.65									
				A_2^f	0.04	0.05	0.05	0.05	0.04	0.03	0.04									
Low-e Double Glazing, $e = 0.1$ on surface 3																				
21c	3	CLR LE	0.75	SHGC	0.60	0.58	0.56	0.51	0.40	0.22	0.52	0.53	0.55	0.45	0.53	0.64	0.67	0.55	0.65	
				T	0.48	0.45	0.43	0.37	0.27	0.13	0.40									
				R^f	0.26	0.27	0.28	0.32	0.42	0.62	0.31									
				R^b	0.24	0.24	0.26	0.29	0.38	0.58	0.28									
				A_1^f	0.12	0.13	0.14	0.14	0.15	0.15	0.13									
				A_2^f	0.14	0.15	0.15	0.16	0.16	0.10	0.15									
21d	6	CLR LE	0.72	SHGC	0.56	0.55	0.52	0.48	0.38	0.20	0.49	0.50	0.51	0.42	0.49	0.61	0.64	0.53	0.63	
				T	0.42	0.40	0.37	0.32	0.24	0.11	0.35									
				R^f	0.24	0.24	0.25	0.29	0.38	0.58	0.28									
				R^b	0.20	0.20	0.22	0.26	0.34	0.55	0.25									
				A_1^f	0.19	0.20	0.21	0.22	0.23	0.22	0.21									
				A_2^f	0.16	0.17	0.17	0.17	0.16	0.10	0.16									
21e	3	BRZ LE	0.57	SHGC	0.48	0.46	0.44	0.40	0.31	0.17	0.42	0.43	0.44	0.36	0.42	0.48	0.51	0.42	0.50	
				T	0.37	0.34	0.32	0.27	0.20	0.08	0.30									
				R^f	0.18	0.17	0.19	0.22	0.30	0.50	0.21									
				R^b	0.23	0.23	0.25	0.29	0.37	0.57	0.28									
				A_1^f	0.34	0.37	0.38	0.39	0.39	0.35	0.37									
				A_2^f	0.11	0.12	0.12	0.12	0.11	0.07	0.11									

Table 13 Visible Transmittance (T_v), Solar Heat Gain Coefficient (SHGC), Solar Transmittance (T_s), Reflectance (R^f), Back Reflectance (R^b), and Layer Absorptances (A_n^f) for Glazing and Window Systems

												Total Window SHGC at Normal Incidence				Total Window T_v at Normal Incidence				
												Center-of-Glazing Properties								Aluminum
Glazing System				Center Glazing T_v	Incidence Angles								Operable	Fixed	Operable	Fixed	Operable	Fixed	Operable	Fixed
ID	Glass Thick., mm				Normal 0.00	40.00	50.00	60.00	70.00	80.00	Hemis., Diffuse									
25d	6	GRN W/LE CLR	0.60	SHGC	0.31	0.30	0.28	0.26	0.21	0.12	0.27	0.28	0.29	0.23	0.27	0.51	0.53	0.44	0.52	
				T	0.22	0.21	0.20	0.17	0.13	0.06	0.18									
				R^f	0.10	0.10	0.12	0.16	0.25	0.48	0.15									
				R^b	0.35	0.34	0.35	0.37	0.44	0.60	0.37									
				A_1^f	0.64	0.64	0.64	0.63	0.59	0.43	0.62									
				A_2^f	0.05	0.05	0.05	0.05	0.04	0.03	0.05									
25e	6	GRY W/LE CLR	0.35	SHGC	0.24	0.23	0.22	0.20	0.16	0.09	0.21	0.23	0.23	0.19	0.21	0.30	0.31	0.26	0.30	
				T	0.16	0.15	0.14	0.12	0.09	0.04	0.13									
				R^f	0.12	0.13	0.15	0.18	0.26	0.49	0.17									
				R^b	0.34	0.34	0.35	0.37	0.44	0.60	0.37									
				A_1^f	0.69	0.69	0.68	0.67	0.62	0.45	0.66									
				A_2^f	0.03	0.03	0.03	0.03	0.03	0.02	0.03									
25f	6	BLUE W/LE CLR	0.45	SHGC	0.27	0.26	0.25	0.23	0.18	0.11	0.24	0.25	0.26	0.21	0.24	0.38	0.40	0.33	0.39	
				T	0.19	0.18	0.17	0.15	0.11	0.05	0.16									
				R^f	0.12	0.12	0.14	0.17	0.26	0.49	0.16									
				R^b	0.34	0.34	0.35	0.37	0.44	0.60	0.37									
				A_1^f	0.66	0.66	0.65	0.64	0.60	0.44	0.63									
				A_2^f	0.04	0.04	0.04	0.04	0.04	0.03	0.04									
25g	6	HI-P GRN W/LE CLR	0.53	SHGC	0.27	0.26	0.25	0.23	0.18	0.11	0.23	0.25	0.26	0.21	0.24	0.45	0.47	0.39	0.46	
				T	0.18	0.17	0.16	0.14	0.10	0.05	0.15									
				R^f	0.07	0.07	0.09	0.13	0.22	0.46	0.12									
				R^b	0.35	0.34	0.35	0.38	0.44	0.60	0.37									
				A_1^f	0.71	0.72	0.71	0.69	0.64	0.47	0.68									
				A_2^f	0.04	0.04	0.04	0.04	0.03	0.02	0.04									
Triple Glazing																				
29a	3	CLR CLR CLR	0.74	SHGC	0.68	0.65	0.62	0.54	0.39	0.18	0.57	0.60	0.62	0.51	0.59	0.63	0.66	0.54	0.64	
				T	0.60	0.57	0.53	0.45	0.31	0.12	0.49									
				R^f	0.17	0.18	0.21	0.28	0.42	0.65	0.25									
				R^b	0.17	0.18	0.21	0.28	0.42	0.65	0.25									
				A_1^f	0.10	0.11	0.12	0.13	0.14	0.14	0.12									
				A_2^f	0.08	0.08	0.09	0.09	0.08	0.07	0.08									
				A_3^f	0.06	0.06	0.06	0.06	0.05	0.03	0.06									
29b	6	CLR CLR CLR	0.70	SHGC	0.61	0.58	0.55	0.48	0.35	0.16	0.51	0.54	0.56	0.46	0.53	0.60	0.62	0.51	0.61	
				T	0.49	0.45	0.42	0.35	0.24	0.09	0.39									
				R^f	0.14	0.15	0.18	0.24	0.37	0.59	0.22									
				R^b	0.14	0.15	0.18	0.24	0.37	0.59	0.22									
				A_1^f	0.17	0.19	0.20	0.21	0.22	0.21	0.19									
				A_2^f	0.12	0.13	0.13	0.13	0.12	0.08	0.12									
				A_3^f	0.08	0.08	0.08	0.08	0.06	0.03	0.08									
29c	6	HI-P GRN CLR CLR	0.53	SHGC	0.34	0.31	0.29	0.25	0.19	0.10	0.28	0.31	0.32	0.26	0.30	0.45	0.47	0.39	0.46	
				T	0.20	0.17	0.15	0.12	0.07	0.02	0.15									
				R^f	0.06	0.07	0.08	0.11	0.20	0.41	0.11									
				R^b	0.13	0.14	0.16	0.22	0.35	0.57	0.20									
				A_1^f	0.64	0.67	0.68	0.68	0.66	0.53	0.65									
				A_2^f	0.06	0.06	0.05	0.05	0.05	0.03	0.05									
				A_3^f	0.04	0.04	0.04	0.03	0.02	0.01	0.04									
Triple Glazing, $e = 0.2$ on surface 2																				
32a	3	LE CLR CLR	0.68	SHGC	0.60	0.58	0.55	0.48	0.35	0.17	0.51	0.53	0.55	0.45	0.53	0.58	0.61	0.50	0.59	
				T	0.50	0.47	0.44	0.38	0.26	0.10	0.41									
				R^f	0.17	0.19	0.21	0.27	0.41	0.64	0.25									
				R^b	0.19	0.20	0.22	0.29	0.42	0.63	0.26									
				A_1^f	0.20	0.20	0.20	0.21	0.21	0.17	0.20									
				A_2^f	0.08	0.08	0.08	0.09	0.08	0.07	0.08									
				A_3^f	0.06	0.06	0.06	0.06	0.05	0.03	0.06									

Table 13 Visible Transmittance (T_v), Solar Heat Gain Coefficient (SHGC), Solar Transmittance (T), Front Reflectance (R^f), Back Reflectance (R^b), and Layer Absorptances (A_n^f) for Glazing and Window Systems (Continued)

													Total Window SHGC at Normal Incidence				Total Window T_v at Normal Incidence			
													Aluminum		Other Frames		Aluminum		Other Frames	
ID	Glazing System			Center Glazing T_v		Incidence Angles							Operable	Fixed	Operable	Fixed	Operable	Fixed	Operable	Fixed
	Glass Thick., mm					Normal 0.00	40.00	50.00	60.00	70.00	80.00	Hemis., Diffuse								
32b	6	LE CLR CLR	0.64	SHGC	0.53	0.50	0.47	0.41	0.29	0.14	0.44	0.47	0.49	0.40	0.47	0.54	0.57	0.47	0.56	
				T	0.39	0.36	0.33	0.27	0.17	0.06	0.30									
				R^f	0.14	0.15	0.17	0.21	0.31	0.53	0.20									
				R^b	0.16	0.16	0.19	0.24	0.36	0.57	0.22									
				A_1^f	0.28	0.31	0.31	0.34	0.37	0.31	0.31									
				A_2^f	0.11	0.11	0.11	0.11	0.10	0.08	0.11									
				A_3^f	0.08	0.08	0.08	0.07	0.05	0.03	0.07									
Triple Glazing, $e = 0.2$ on surface 5																				
32c	3	CLR CLR LE	0.68	SHGC	0.62	0.60	0.57	0.49	0.36	0.16	0.52	0.55	0.57	0.46	0.54	0.58	0.61	0.50	0.59	
				T	0.50	0.47	0.44	0.38	0.26	0.10	0.41									
				R^f	0.19	0.20	0.22	0.29	0.42	0.63	0.26									
				R^b	0.18	0.19	0.21	0.27	0.41	0.64	0.25									
				A_1^f	0.11	0.12	0.13	0.14	0.15	0.15	0.13									
				A_2^f	0.09	0.10	0.10	0.10	0.10	0.08	0.10									
				A_3^f	0.11	0.11	0.11	0.10	0.08	0.04	0.10									
32d	6	CLR CLR LE	0.64	SHGC	0.56	0.53	0.50	0.44	0.32	0.15	0.47	0.50	0.51	0.42	0.49	0.54	0.57	0.47	0.56	
				T	0.39	0.36	0.33	0.27	0.17	0.06	0.30									
				R^f	0.16	0.16	0.19	0.24	0.36	0.57	0.22									
				R^b	0.14	0.15	0.17	0.21	0.31	0.53	0.20									
				A_1^f	0.17	0.19	0.20	0.21	0.22	0.22	0.19									
				A_2^f	0.13	0.14	0.14	0.14	0.13	0.10	0.13									
				A_3^f	0.15	0.16	0.15	0.14	0.12	0.05	0.14									
Triple Glazing, $e = 0.1$ on surface 2 and 5																				
40a	3	LE CLR LE	0.62	SHGC	0.41	0.39	0.37	0.32	0.24	0.12	0.34	0.37	0.38	0.31	0.36	0.53	0.55	0.45	0.54	
				T	0.29	0.26	0.24	0.20	0.13	0.05	0.23									
				R^f	0.30	0.30	0.31	0.34	0.41	0.59	0.33									
				R^b	0.30	0.30	0.31	0.34	0.41	0.59	0.33									
				A_1^f	0.25	0.27	0.28	0.30	0.32	0.27	0.28									
				A_2^f	0.07	0.08	0.08	0.08	0.07	0.06	0.07									
				A_3^f	0.08	0.09	0.09	0.09	0.07	0.04	0.08									
40b	6	LE CLR LE	0.59	SHGC	0.36	0.34	0.32	0.28	0.21	0.10	0.30	0.33	0.34	0.27	0.32	0.50	0.53	0.43	0.51	
				T	0.24	0.21	0.19	0.16	0.10	0.03	0.18									
				R^f	0.34	0.34	0.35	0.38	0.44	0.61	0.37									
				R^b	0.23	0.23	0.25	0.28	0.36	0.56	0.27									
				A_1^f	0.24	0.25	0.26	0.28	0.30	0.25	0.26									
				A_2^f	0.10	0.11	0.11	0.11	0.10	0.07	0.10									
				A_3^f	0.09	0.09	0.09	0.08	0.07	0.03	0.08									
Triple Glazing, $e = 0.05$ on surface 2 and 4																				
40c	3	LE LE CLR	0.58	SHGC	0.27	0.25	0.24	0.21	0.16	0.08	0.23	0.25	0.25	0.21	0.24	0.49	0.52	0.42	0.50	
				T	0.18	0.17	0.16	0.13	0.08	0.03	0.14									
				R^f	0.41	0.41	0.42	0.44	0.50	0.65	0.44									
				R^b	0.46	0.45	0.46	0.48	0.53	0.68	0.47									
				A_1^f	0.27	0.28	0.28	0.29	0.30	0.24	0.28									
				A_2^f	0.12	0.12	0.12	0.12	0.11	0.07	0.12									
				A_3^f	0.02	0.02	0.02	0.02	0.01	0.01	0.02									
40d	6	LE LE CLR	0.55	SHGC	0.26	0.25	0.23	0.21	0.16	0.08	0.22	0.24	0.25	0.20	0.23	0.47	0.49	0.40	0.48	
				T	0.15	0.14	0.12	0.10	0.07	0.02	0.12									
				R^f	0.33	0.33	0.34	0.37	0.43	0.60	0.36									
				R^b	0.39	0.38	0.38	0.40	0.46	0.61	0.40									
				A_1^f	0.34	0.36	0.36	0.37	0.36	0.28	0.35									
				A_2^f	0.15	0.15	0.15	0.14	0.12	0.08	0.14									
				A_3^f	0.03	0.03	0.03	0.03	0.02	0.01	0.03									

KEY:

CLR = clear, BRZ = bronze, GRN = green, GRY = gray, BLUGRN = bluegreen, SS = stainless steel reflective coating, TI = titanium reflective coating

Reflective coating descriptors include percent visible transmittance as x%.

HI-P GRN = high performance green tinted glass, LE = low-emissivity coating

 T_v = visible transmittance, T = solar transmittance, SHGC = solar heat gain coefficient, and

H. = hemispherical SHGC

ID #'s refer to U-Factors in [Table 4](#).

independent of direction). In addition, the spectral dependence is assumed to be the same as for beam solar radiation. These simplifications are implicit in the use of the quantities E_d and E_r in Equation (12). To calculate these quantities from one of the detailed sky or ground models mentioned in that section (or from detailed data), rather than from the simpler equations given elsewhere in this chapter, one would use the following equations:

$$E_d = \int \int_{\lambda, sky} E_{sky}(\theta, \phi, \lambda)(\cos \theta) d\omega d\lambda \quad (68)$$

$$E_r = \int \int_{\lambda, ground} E_{ground}(\theta, \phi, \lambda)(\cos \theta) d\omega d\lambda \quad (69)$$

Since these are assumed to be direction-independent quantities, and since for vertical glazings the sky and ground subtend equal solid angles, in most cases the fact that these quantities originate from distinct solid angle regions is ignored. More careful consideration must be given to these quantities for tilted glazings or for direction-dependent shading (such as overhangs and venetian blinds) when high accuracy in the results is desired.

The optical properties to be used with these quantities are then the **hemispherical averages** of the corresponding angle-dependent properties. For example, for an L -layer unshaded glazing, the average transmittance, front reflectance, and layer-specific overall front absorptance would be

$$\begin{aligned} \langle T_{1,L} \rangle_D &= \frac{\int \int_{hem} T_{1,L}(\theta)(\cos \theta) d\omega}{\int \int_{hem} (\cos \theta) d\omega} \\ &= 2 \int_0^{\pi/2} T_{1,L}(\theta)(\cos \theta)(\sin \theta) d\theta \quad (70) \end{aligned}$$

$$\begin{aligned} \langle R_{1,L}^f \rangle_D &= \frac{\int \int_{hem} R_{1,L}^f(\theta)(\cos \theta) d\omega}{\int \int_{hem} (\cos \theta) d\omega} \\ &= 2 \int_0^{\pi/2} R_{1,L}^f(\theta)(\cos \theta)(\sin \theta) d\theta \quad (71) \end{aligned}$$

$$\begin{aligned} \langle A_{n:(1,L)}^f \rangle_D &= \frac{\int \int_{hem} A_{n:(1,L)}^f(\theta)(\cos \theta) d\omega}{\int \int_{hem} (\cos \theta) d\omega} \\ &= 2 \int_0^{\pi/2} A_{n:(1,L)}^f(\theta)(\cos \theta)(\sin \theta) d\theta \quad (72) \end{aligned}$$

Table 14 Angular Weighting Function and Double Glazing System (Example 10) Transmittance Calculated for the Angular Mesh Used to Calculate Hemispherical Average Transmittance

θ°	Angular Weight	$T_{1,2}(\theta)$
0	0.000	0.331
10	0.060	0.329
20	0.113	0.325
30	0.153	0.318
40	0.174	0.309
50	0.174	0.294
60	0.153	0.260
70	0.113	0.194
80	0.060	0.094
90	0.000	0.000

and similarly for the back reflectance and layer-specific absorptances. The simplified expression at the end of each equation follows from the fact that the quantities being averaged are independent of the angle ϕ .

Example 12. Calculate the hemispherical average properties for the two glazings and the glazing system in Examples 8, 9, and 10, and compare the results with Table 13.

Solution: Equations (70) through (72) are used, and the integration is done numerically, using an angular grid of 10° intervals extending from 0° to 90° . To carry out this calculation, all of the properties in the three examples must be recalculated at each angle. A single-band model rather than a 2-band is used to reduce the calculational labor. Values of $T_{1,2}(\theta)$ used in calculating $\langle T_{1,2} \rangle_D$ are shown in Table 14, together with the angular weighting functions used in the numerical integration. The angular weighting functions are the values, at each angle, of $2(\cos \theta)(\sin \theta)\Delta\theta$ at that angle, where $\Delta\theta$ is the grid interval (10°) expressed in radians.

The resulting values are $\langle T_1 \rangle_D = 0.335$, $\langle R_1^f \rangle_D = 0.401$, $\langle R_1^b \rangle_D = 0.496$, $\langle a_1^f \rangle_D = 0.264$, and $\langle a_1^b \rangle_D = 0.169$ for the selective glazing of Example 9; $\langle T_2 \rangle_D = 0.761$, $\langle R_2^f \rangle_D = \langle R_2^b \rangle_D = 0.137$, and $\langle a_2^f \rangle_D = \langle a_2^b \rangle_D = 0.101$ for the clear glazing of Example 8; $\langle T_{1,2} \rangle_D = 0.277$, $\langle R_{1,2}^f \rangle_D = 0.405$, $\langle R_{1,2}^b \rangle_D = 0.442$, and $\langle A_{1:(1,2)}^f \rangle_D = 0.271$, $\langle A_{1:(1,2)}^b \rangle_D = 0.138$, $\langle A_{2:(1,2)}^f \rangle_D = 0.036$, and $\langle A_{2:(1,2)}^b \rangle_D = 0.141$ for the double-glazing system of Example 10.

The corresponding values listed for system 25a in Table 13 are $[\langle T_{1,2} \rangle_D]_{25a} = 0.31$, $[\langle R_{1,2}^f \rangle_D]_{25a} = 0.39$, and $[\langle R_{1,2}^b \rangle_D]_{25a} = 0.42$. When we correct them as in Example 11 for the differences between the glazing system of interest and ID 25a at normal incidence, we obtain $[\langle T_{1,2} \rangle_D]_{table} = 0.31 \times 0.331/0.37 = 0.28$, $[\langle R_{1,2}^f \rangle_D]_{table} = 0.39 \times 0.388/0.35 = 0.43$, and $[\langle R_{1,2}^b \rangle_D]_{table} = 0.42 \times 0.396/0.39 = 0.43$. These are reasonably close to the values we obtained from the calculation using the more detailed equations.

Spectrally Selective Glazing

The spectral range from 350 nm to over 50 μm contains radiation from both the sun and sky incident upon fenestration systems as well as the longer wavelength **thermal radiation**. Thermal radiation is emitted by warm bodies both outside and inside the building. Figure 23 shows the human eye spectral response, the solar spectrum for an air mass $m = 1.5$, and a room temperature blackbody radiation spectrum. The blackbody radiation is scaled to compare with the solar spectrum. Spectral selectivity was defined previously as strong changes in the optical properties of a glazing system over the spectrum. Figure 23 illustrates the basic concept in terms of the spectral reflectance and Figure 24, the spectral transmittance of ideal low solar gain glazings. One can see in this figure the human eye spectral response (called the human photopic visibility function), an air mass 1.5 solar spectrum, and a room temperature (24°C) blackbody radiation spectrum. The latter has been scaled up to better compare it with the shape of the solar spectrum. What is clear

from this diagram is the separation of the solar spectrum from the emission spectrum characteristic of an interior room of a multiple-pane glazing system.

Almost all architectural glass is opaque to the long-wave radiation emitted by surfaces at temperatures below about 1200°C. This characteristic produces the **greenhouse effect**, by which solar radiation passing through a window is partially retained inside by the following mechanism. Radiation absorbed by surfaces within the room is emitted as long-wavelength radiation, and it cannot escape directly through the glass since it is opaque to all radiation beyond 4.5 μm . Instead, the radiation from the room surfaces falling on the glass is absorbed and re-emitted to both sides as determined by several parameters, such as the inside and outside film heat transfer coefficients, the surface emissivities, and other glazing properties.

A good reflector in the long-wavelength infrared portion of the spectrum can be a poor reflector and a good transmitter in the solar portion. Because of the conservation of energy ($T + R + A = 1.0$), a high reflectance in the long-wavelength infrared portion of the spectrum means a low transmittance and absorptance. Because of Kirchhoff's law [Equation (29)], a low absorptance means a low emissivity as well. This is the principle of operation of the high-solar-gain (or cold-climate) **low-e coating** on window glass. Such a coating has high transmittance over the entire solar spectrum, producing high solar heat gain while being highly reflective to the long-wavelength infrared radiation emitted by the interior surfaces, reflecting this radiation back inward. The *low-e* in low-e coating refers to a low emissivity over the long-wavelength portion of the spectrum.

Another characteristic of glazing is that at a given wavelength, or over a defined range of wavelengths, the transmittance is the same in both directions. A glazing with a coating or consisting of multiple glazing layers will have one solar transmittance value, but it will have two reflectance values—one for radiation approaching each side of the system.

Figure 24 shows a hypothetical glazing system with improved performance for hot climates. In this case, the sharp **reflectance edge** that the ideal cold-climate low-e coating exhibited just past the end of the solar spectrum in Figure 23 is shifted closer to the edge of the visible portion of the spectrum, thereby increasing the solar near-infrared (NIR) reflectance of the glazing. This results, as seen in Figure 24, in a drop in the hot-climate transmittance to the right of the visible portion of the spectrum. The effect is to reflect the near-infrared portion of the solar spectrum outside, reducing

solar gain, while still admitting visible light in the wavelength region below about 800 nm. This hot-climate, solar-gain-rejecting coating also exhibits low emissivity over the long-wavelength spectrum, and is therefore also properly termed a low-e coating. To distinguish the cold- from the hot-climate version, a glazing with this type of spectral response is often termed **selective low-e**. This is somewhat of a misnomer, because both hot- and cold-climate glazings are spectrally selective. Another terminology is **high-solar-gain low-e** glazing system for cold climates, contrasted with **low-solar-gain low-e** glazing system for hot climates.

The reduced infrared transmittance for the hot-climate glazing in Figure 24 is ideally achieved by high reflectance and low absorptance (meaning also low emissivity). It can also be accomplished with high infrared absorptance, if the flow of the absorbed solar radiation to the interior of the building can be reduced, introducing a second approach to the construction of a hot-climate, low-solar-gain glazing system. In this case, the outer pane of a multiple-pane glazing system is made to have good visible transmittance but high absorptance over the solar infrared spectrum. To protect the interior of the building from the heat of this absorbed radiation, additional glazings, gas spaces, and cold-climate type, low-e coatings are added.

By this means, radiation, conduction, and convection of heat from the hot outer pane to the interior ones and to the interior of the building are reduced because of the coating, the insulating gas space, and the additional panes. Such a glazing system for hot climates is insulated primarily *not* to protect the building from conductive heat losses in winter but to protect the interior from the solar radiant heat absorbed by the hot outer pane in summer. Several manufacturers offer this kind of nonreflecting spectrally selective glazing system for commercial buildings having large cooling loads. (If this glazing system is placed in a flip window, one that rotates open for cleaning and can be closed with either side facing outward, then flipping it over in winter can make it an effective trap for passive solar heating of the interior (McCluney and Jindra 2000). Such a system will have two different SHGC values, depending upon which way the window is flipped.

Figure 24 shows that glazings intended for hot climates should have (1) high transmittance over the visible portion of the spectrum to let daylight in for both illumination and view and (2) low transmittance over all other portions of the spectrum to reduce solar heat gain. In contrast, glazings intended for very cold climates should have high transmittance over the whole solar spectrum, from 380 nm

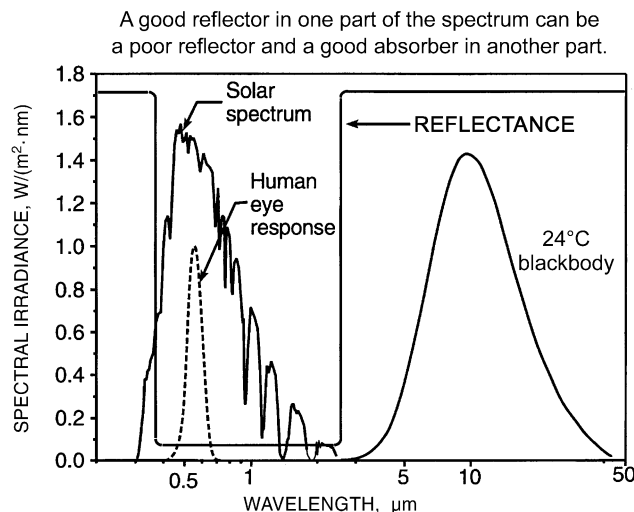


Fig. 23 Solar Spectrum, Human Eye Response Spectrum, Scaled Blackbody Radiation Spectrum, and Idealized Glazing Reflectance Spectrum

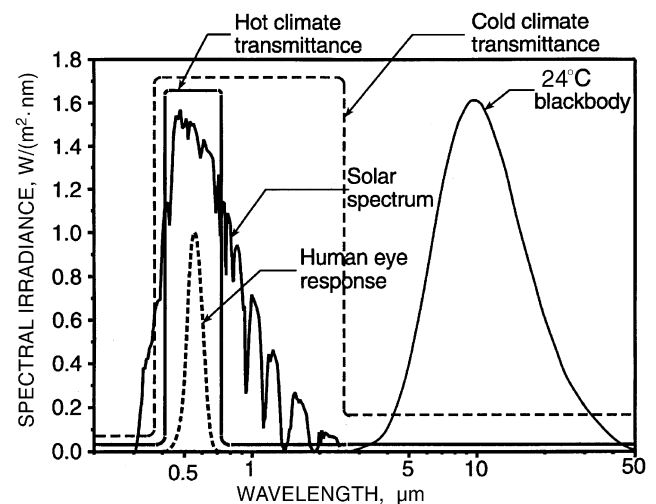


Fig. 24 Demonstration of Two Spectrally Selective Glazing Concepts, Showing Ideal Spectral Transmittances for Glazings Intended for Hot and Cold Climates

to over 3500 nm, for maximum admission of solar radiant heat gain and light. In addition, glazings for cold climates should have low transmittance over the long-wavelength portion of the spectrum in order to block the radiant heat emitted by the relatively warm interior surfaces of buildings, preventing its escape to the outside.

Extreme spectral selectivity in glazing systems in the visible portion of the spectrum can produce an unwanted color shift in the transmitted light. The color of the transmitted light and its color-rendering properties should be considered in the design.

SOLAR HEAT GAIN COEFFICIENT

Fenestration solar heat gain has two components. First is the directly transmitted solar radiation. The quantity of radiation entering the fenestration directly is governed by the solar transmittance of the glazing system. Multiplying the incident irradiance by the glazing area and its solar transmittance yields the solar heat entering the fenestration directly. The second component is the inward-flowing portion of the absorbed solar radiation, radiation that is absorbed in the glazing and framing materials of the window and is subsequently conducted, convected, and radiated to the interior of the building.

The solar heat gain coefficient values presented in this chapter are based on a standard spectral irradiance distribution for air mass 1.5. This spectrum is recommended by the National Fenestration Rating Council (NFRC) for the purpose of rating fenestrations for instantaneous energy performance using defined environmental and incident irradiance conditions. The NFRC standard spectrum can be found in ASTM *Standard E 891*. For real solar gain calculation situations, and with glazing systems exhibiting spectral selectivity over the solar spectrum, the incident solar spectrum used should be altered from the representative one contained in this standard in order to be more realistic for the atmospheric conditions at the location and time of the calculation. Gueymard (1987a, 1987b, 1993a, 1993b, and 1995) has developed an algorithm to guide a computerized methodology for calculating realistic solar spectra that are sensitive to changes in the atmospheric constituents.

The ASTM standard spectrum is different from Parry Moon's (Moon 1940) air mass 2 spectrum used by the glazing industry in the past. Both are different from solar spectral distributions incident upon fenestrations with different atmospheric conditions and for different sun angles. These differences will have little impact on the SHGC of glazing systems containing only glazings with relatively flat spectral transmittances, that is, glazings that are not strongly spectrally selective. Glazings that do exhibit strong spectral selectivity (such as those shown in [Figures 15](#) and [16](#)), however, can have different SHGC values. The visible transmittances are less sensitive to solar spectral changes. However, for glazings with very strong spectral selectivity in the visible portion of the spectrum, such as those exhibiting strong color, the visible transmittance also can be sensitive to the shape of the incident spectrum.

Absorbed solar radiation, including ultraviolet, visible, and infrared radiation from the sun and sky, is turned into heat inside the absorbing material. In a window, the glazing system temperature rises as a result to some approximately equilibrium value at which the energy gains from absorbed radiation are balanced by equal losses. The absorbed solar radiation is dissipated through the mechanisms of conduction, convection, and radiation. Some heat goes outside the building, and the remainder goes inside, adding to the directly transmitted solar radiation. The magnitude of what is called the **inward-flowing fraction** N of the absorbed radiation depends on the nature of the air boundary layers adjacent to both sides of the glazing, including any gas between the panes of a multiple-pane glazing system (N_i is often used to distinguish the inward-flowing fraction from the outward-flowing fraction, N_o). However, since only the inward-flowing fraction is used here, the subscript i is dropped for clarity.).

The concept of the solar heat gain coefficient is best illustrated for the case of a single glass pane in direct sunlight. Let E_D be the direct solar irradiance incident upon a single pane of glass, T be its solar transmittance, A be the solar absorptance, and N be the inward-flowing fraction of the absorbed radiation. In this case, the total solar gain (heat flow per unit area) q_b that enters the space due to the incident solar radiation is

$$q_b = E_D(T + NA) \quad (73)$$

in units of energy flux per unit area, W/m^2 . Multiple glazings are discussed in the section on Calculation of Solar Heat Gain Coefficient.

The quantity in parenthesis in Equation (73) is called the **solar heat gain coefficient** or **SHGC**. It is the fraction of incident irradiance that enters through the glazing and becomes heat gain. It includes both the directly transmitted portion and the absorbed and re-emitted portion:

$$SHGC = T + NA \quad (74)$$

The SHGC is needed to determine the solar radiant heat gain through a window's glazing system. The SHGC for certain defined conditions of spectrum and incident angle θ should be included along with U-factor and other instantaneous performance properties in any manufacturer's description of a window's energy performance. Since the optical properties A and T vary with the angle of incidence [defined as the angle between the rays incident on the glazing and the normal (perpendicular) to the glazing], according to Equation (74), the solar heat gain coefficient is also a function of angle of incidence. Once the incident irradiance and SHGC are known for a given angle of incidence, the solar gain (from direct beam radiation) can be computed with the following equation:

$$q_b = E_D SHGC \quad (75)$$

Optical properties also vary with wavelength. The quantities A and T are spectral averages, as described by Equation (30).

Calculation of Solar Heat Gain Coefficient

In the most general way, the solar heat gain q and the solar heat gain coefficient SHGC are defined as angle-dependent and spectrally dependent properties:

$$\begin{aligned} q(\theta) &= \int_{\lambda} E_D(\lambda) [T(\theta, \lambda) + NA(\theta, \lambda)] d\lambda \\ &= \int_{\lambda} E_D(\lambda) SHGC(\theta, \lambda) d\lambda \end{aligned} \quad (76)$$

where the definition of Equation (74) implies an angle- and wavelength-dependent solar heat gain coefficient:

$$SHGC(\theta, \lambda) = T(\theta, \lambda) + NA(\theta, \lambda) \quad (77)$$

This can in turn be used to define a wavelength-averaged solar heat gain coefficient:

$$SHGC(\theta) = \frac{\int_{\lambda} E_D(\lambda) [T(\theta, \lambda) + NA(\theta, \lambda)] d\lambda}{\int_{\lambda} E_D(\lambda) d\lambda} \quad (78)$$

where

$E_D(\lambda)$ = incident solar spectral irradiance

$T(\theta, \lambda)$ = spectral transmittance of the glazing system

$A(\theta, \lambda)$ = total spectral absorptance of the glazing system

Starting with this edition of the Handbook, Equations (76) through (78) indicate the preferred way of determining the solar gain of glazing systems and calculating the solar heat gain coefficient. At least two computer programs are available to assist in the calculation (Arasteh et al. 1994, AGSL 1992). This approach has been adopted by the National Fenestration Rating Council in NFRC 200 for the rating, certification, and labeling of windows for energy performance and by the Canadian Standards Association (CSA *Standard* A440.2). The method is valid for strongly spectrally selective glazing systems as well as for nonselective ones. In these programs, the overall system optical properties at a given incident angle are calculated for each wavelength and the results averaged following Equation (31). The ASTM *Standard* E 891 spectrum is used in the averaging. The wavelength-averaged properties (at a given incident angle) can then be used in Equation (76).

When a glazing system is not strongly spectrally selective, the solar-weighted spectral broadband values of the optical properties can be used, and the integral over wavelength shown in Equations (76) and (78) is not needed. In this case, and for a general unshaded glazing system, which may consist of several glazing layers, each glazing layer will have its own individual inward-flowing fraction of the absorbed radiation for that layer. Let the glazings be numbered from the outside inward, and k be the glazing index. Then, the SHGC is given by

$$\text{SHGC}(\theta) = T_{1,L}^f(\theta) + \sum_{k=1}^L N_k A_{k:(1,L)}^f(\theta) \quad (79)$$

where

$T_{1,L}^f(\theta)$ = front transmittance of the glazing system

L = number of glazing layers

$A_{k:(1,L)}^f$ = absorptance of layer k

N_k = inward-flowing fraction for layer k

The wavelength-independent quantities in this equation are obtained by the averaging procedure of Equation (66). Conversely, the wavelength-dependent form of Equation (79) is obtained by adding the wavelength dependence to the indicated angle dependence; the N_k and the layer decomposition are independent of wavelength.

The solar heat gain coefficient is a combination of the solar-optical properties discussed in the section on Solar Optical Properties of Glazings and a new set of quantities N_k , which account for the fact that of the energy absorbed in a given layer, the fraction that reaches the interior space will depend on the location of the layer. The N_k are thermal in origin; they depend on the heat transfer properties of the assembly rather than on its optical properties.

The inward-flowing fractions can be calculated from simplified heat transfer models, using the following equation:

$$N_k = \frac{U}{h_{o,k}} \quad (80)$$

where

U = U-factor of the glazing

$h_{o,k}$ = effective heat transfer coefficient between the exterior environment and the k th glazing layer

The effective heat transfer coefficient can be calculated in a one-dimensional model as the reciprocal of the sum of the thermal resistances of all elements between layer k and the exterior (see [Chapter 3](#)). For example, for single glazing,

$$N = \frac{U}{h_o} \quad (81)$$

where U is the U-factor of the glazing and h_o is the exterior heat transfer coefficient (see [Chapter 3](#)). For double glazing, the two inward-flowing fractions are

$$N_1 = \frac{U}{h_o}, \quad N_2 = \frac{h_o + U}{h_o} \quad (82)$$

where the numeric subscripts obey the usual layer numbering convention (1 is the exterior glazing).

In more complicated multilayer glazing systems, it is advisable to perform a detailed heat transfer analysis of the system to determine the values of N_k , since the effective heat transfer coefficients and U depend (weakly) on the glazing layer temperatures and other environmental conditions (e.g., Finlayson and Arasteh 1993, LBL 1994, and Wright 1995c).

Diffuse Radiation

For incident radiation that is diffuse, the hemispherical average solar heat gain coefficient must be used. This may be calculated either by a direct hemispherical averaging of Equation (79) using the analog of Equation (70) as follows:

$$\begin{aligned} \langle \text{SHGC}(\theta) \rangle_D &= \frac{\int_{hem} \int \text{SHGC}(\theta) (\cos \theta) d\omega}{\int_{hem} \int (\cos \theta) d\omega} \\ &= 2 \int_0^{\pi/2} \text{SHGC}(\theta) (\cos \theta) d\theta \end{aligned} \quad (83)$$

or equivalently by simply using the hemispherically averaged solar-optical properties in Equation (79):

$$\langle \text{SHGC} \rangle_D = \langle T_{1,L}^f \rangle_D + \sum_{k=1}^L N_k \langle A_{k:(1,L)}^f \rangle_D \quad (84)$$

In any case, N_k is unaffected in the averaging process, since it does not depend on the incident angle or the wavelength. Considerations of the solar spectrum discussed previously in the sections on Spectral Averaging of Glazing Properties and Angular Averaging of Glazing Properties also apply to the solar heat gain coefficient.

Solar Gain Through Frame and Other Opaque Elements

[Figure 25](#) illustrates the mechanisms by which a window provides solar gain. It is assumed that all of the directly transmitted solar radiation is absorbed at indoor surfaces, where it is converted to heat. Solar gain also enters a building through opaque elements such as the frame and any mullion or dividers that are part of the fenestration system because a portion of the solar energy absorbed at the surfaces of these elements is redirected to the indoor side by heat transfer.

The solar heat gain coefficient of the fenestration system can be calculated while accounting for solar gain through the opaque elements by area-weighting the solar heat gain coefficients of the glazing, frame, and M divider elements. Thus,

$$\text{SHGC} = \frac{\text{SHGC}_g A_g + \text{SHGC}_f A_f + \sum_{i=1}^M A_i \text{SHGC}_i}{A_g + A_f + \sum_{i=1}^M A_i} \quad (85)$$

where $SHGC_g$, $SHGC_f$, and $SHGC_i$ are the solar heat gain coefficients of the glazed area, frame, and i th divider, respectively. A_g , A_f , and A_i are the corresponding projected areas.

In some cases, it is useful to have an overall SHGC for the opaque elements only, which is defined by

$$SHGC_{op} = \frac{SHGC_f A_f + \sum_{i=1}^M A_i SHGC_i}{A_{op}} \quad (86)$$

where

$$A_{op} = A_f + \sum_{i=1}^M A_i$$

$SHGC_f$ can be estimated (Wright 1995a) using

$$SHGC_f = \alpha_f^s \left(\frac{U_f}{h_f} \right) \left(\frac{A_f}{A_{surf}} \right) \quad (87)$$

where α_f^s is the solar absorptivity of the outdoor surface of the frame, U_f is the frame U-factor, and h_f is the heat transfer coefficient (radiative plus convective) between the frame and the outdoor environment. The projected-to-surface area ratio (A_f/A_{surf}) corrects for the fact that U_f is based on projected area A_f and h_f is based on the exposed outdoor frame surface area A_{surf} . $SHGC_i$ can be calculated in the same way:

$$SHGC_i = \alpha_i^s \left(\frac{U_i}{h_i} \right) \left(\frac{A_i}{A_{surf,i}} \right) \quad (88)$$

The outdoor side heat transfer coefficients h_f and h_i can be estimated using ASHRAE (1996):

$$h_f \text{ or } h_i = h_{co} + 4\sigma e_f T_{out}^3 \quad (89)$$

where h_{co} is the convective heat transfer coefficient between the frame (or divider) surface and the outdoor environment, e_f is the emissivity (long-wave) of the outdoor frame (or divider) surface, T_{out} is the outdoor absolute temperature, and σ is the Stefan-Boltzmann constant.

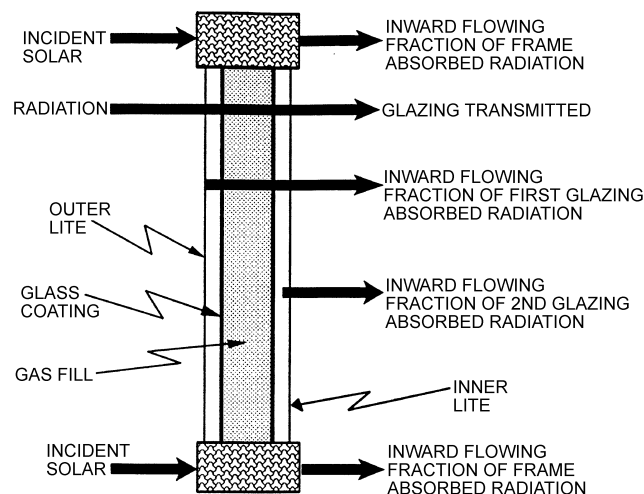


Fig. 25 Components of Solar Radiant Heat Gain with Double-Pane Window, Including Both Frame and Glazing Contributions

Shading Coefficient—A Historical Perspective

Before modern complex windows were marketed in quantity, the determination of fenestration solar gain was substantially simpler. Frame and edge effects were largely ignored, and attention focused on the glazing, which was typically made up of single-pane clear or tinted glass. ASHRAE provided a method for calculating the incident solar beam irradiance for any direction of incidence and tabulated the resulting solar gains through single-pane clear glass in units of flux per unit area in tables of what were called **solar heat gain factors** (SHGFs). These factors, having units of W/m^2 , are to be distinguished from the solar heat gain coefficient, which is dimensionless. Solar heat gain factors provide the total solar radiant heat gain through a standard single-glazing system, including both the directly transmitted radiant component and the inward flowing fraction of the radiation absorbed in the glazing system.

The engineer's job is relatively easy with this method. One first figures out the angle of direct beam incidence on the glass for a typical peak solar gain date and time. This is done by (1) using equations provided in the section on Determining Solar Angle under Determining Incident Solar Flux or (2) by looking up the data for a latitude close to that of the building being designed for a chosen glazing orientation and for a given time of day expected to produce peak solar gain, in Tables 15 through 22 in Chapter 29 of the 1997 *ASHRAE Handbook—Fundamentals*. These tables provide the solar heat gain factor for clear single-pane glass (the so-called **standard reference glazing**, having $T=0.86$, $R=0.08$, and $a=0.06$ at normal incidence) under these conditions.

The next step is simply a matter of multiplying the solar heat gain factor by the area of the glazing, producing the solar gain expected, in W. This provides directly the solar gain for single-pane clear glass.

In order to deal with windows having shades or tinted glass, the concept of a **shading coefficient** was introduced. The idea behind the shading coefficient was to find a multiplicative factor for the shaded glass that allowed the engineer to correct the previously determined solar gain number through clear glass to the proper value for the window with a shade or tint. This could be done because the commonly used shading systems (interior shades and drapes) were assumed not to have strongly varying angular properties, leaving the single glazing as the only determinant of angular dependence. Spectral variation was not considered. This concept was later extended to tinted glazings, which often do not violate the basic underlying assumptions, and to glass blocks and single-glazed windows with interior venetian blinds, for which the application is more dubious.

The shading coefficient was defined to be the ratio of the solar heat gain coefficient of a glazing system at a particular angle of incidence and incident solar spectrum to that for standard reference glazing at the same angle of incidence and spectral distribution:

$$SC = \frac{SHGC(\theta)_{test}}{SHGC(\theta)_{ref}} \quad (90)$$

For single-pane clear and many single-pane tinted glazings, this ratio remains constant as the solar spectral shape varies and as the angle of incidence varies. Thus, a single number can be used to convert from the reference SHGC to the SHGC for the tinted glazing at the angle of incidence selected. Due to its lack of sensitivity to angle of incidence, the same SC value works for beam radiation at any angle of incidence, as well as for diffuse radiation. This meant that the complicated calculation of solar heat gain transmission through glass could be done once and tabulated, a quantity appearing in previous editions of this Handbook as the SHGF. For other systems, the SHGF obtained from the table could simply be multiplied by the SC, a great simplification. The value of the SC for standard reference glass is 1.0, but the SHGC for this glass is 0.87 at normal inci-

dence, using ASHRAE standard summer conditions, and for the standard ASTM solar spectrum. This was useful for dealing with glazings of different thicknesses (and was later extended to tinted glazings). Because the principal property causing angular dependence in single glazing is reflectance, angular properties do not depend strongly on thickness, so that the SC defined by Equation (90) remains approximately constant. While tinted glazings, having different spectral transmission from the reference glazing, have a very different SHGC, this difference does not depend strongly on angle, so again SC is approximately constant. Since it is easiest to determine the transmittance of a glazing at normal incidence, it became standard practice to calculate the SC for clear and tinted single glazing from the following relation:

$$SC = \frac{SHGC}{0.87} \quad (91)$$

This equation applies only to the glazing portion of single-pane tinted or clear windows. It does not include frame effects. It may still be used to determine the SC of commercially available, single, uncoated glazing products from the solar heat gain coefficient (or vice versa) published by the manufacturer.

Solar Heat Gain Coefficient, Visible Transmittance, and Spectrally Averaged Solar-Optical Property Values

Table 13 lists the visible transmittance, solar transmittance, front and back reflectance, and solar heat gain coefficients for common glazing and window systems. The window systems include windows with aluminum or metal frames and windows with other frames that have a lower conductivity (e.g., thermally broken aluminum, wood, vinyl, and fiberglass). As can be seen in Table 13, the total window solar heat gain coefficient varies with the type of operator, size of the fenestration product, and type of frame.

The glazing T_v , T_{sol} , R_f^f , R_b^b , and SHGC values have been calculated using manufacturers' spectral data following methods described in the section on Solar-Optical Properties of Glazing (Finlayson et al. 1994, Wright 1995a). The glazing values are given for 3 mm and 6 mm glass and will vary with glass thickness and glass manufacturer. The values shown are average values and may vary by ± 0.05 . It is recommended that actual values be determined using the methods described in this chapter with detailed spectral data from NFRC (1994). The front reflectance is the reflectance of the unit to the outside, and the back reflectance is the reflectance to the room side.

The visible transmittances are center-glazing values at normal incidence. A rule of thumb is to select a glazing unit whose visible transmittance is greater than its solar heat gain coefficient, especially if daylighting strategies will be used in the building. For maximum light with minimum solar gain, there are fenestration products available having visible transmittance that is 1.4 times their SHGC.

The solar heat gain coefficients are center-glazing values and total window values. The center-glazing solar heat gain coefficients are given at normal incidence (0°) and at 40° , 50° , 60° , 70° , and 80° incidence angles. For angles other than those listed, straight-line interpolation can be used between the two closest angles for which values are shown.

The solar transmittances and front and back reflectances are also center-glazing values and are given at normal incidence (0°) and at 40° , 50° , 60° , 70° , and 80° incidence angles. The solar absorptances can be calculated from these values using Equation (26). The effective inward-flowing fraction of absorbed radiation for the entire system (not layer-specific values) can be determined from Equation (74) by inserting the solar transmittance and corresponding SHGC.

The total window solar heat gain coefficients in Table 13 assume normal incidence. The operable and fixed window sizes in Table 4 were used. To calculate the frame area, the frame heights shown in

Figure 4 for aluminum and aluminum-clad wood/wood/vinyl were used. The frame area for the aluminum windows is 15% for the operable size and 11% for the fixed size. The frame area for other frames is 27% for the operable size and 13% for the fixed size. The ratio of projected frame area to frame surface area is assumed to be 1.0, based on Wright (1995a).

The frame solar heat gain coefficients used to determine the total window solar heat gain coefficients are calculated according to the section on solar heat gain coefficients for frames and other nonglazing elements in this chapter. The frame U-factors are taken from Table 1. The frame absorptance is assumed to be 0.5. The outside film coefficient is $22.2 \text{ W}/(\text{m}^2 \cdot \text{K})$, corresponding to a wind speed of 3.4 m/s. For the aluminum window, the frame solar heat gain coefficient is 0.14 for the operable window and 0.11 for the fixed window. For the other frames, the frame solar heat gain coefficient was found to vary between 0.02 and 0.07 for the various lower conductivity frame types. A frame solar heat gain coefficient of 0.04 is used for the operable window, and 0.03 is used for the fixed window. These values correspond directly to the aluminum-clad wood/reinforced vinyl frames.

For energy calculations on a daylit building, the visible transmittance for the entire window should be used. The visible transmittance of a window can be calculated by multiplying the fraction of glazing area by the center-glazing visible transmittance (see Example 13).

The U-factor of a window listed in Table 13 can be found in Table 4. The ID number for each entry in Table 13 refers to an ID number in Table 4. For a particular glazing system in Table 13, the corresponding glazing system should be the glazing system with that ID number or following that ID number in Table 4. Remember that while the gap width and gas fill have a negligible impact on the solar heat gain coefficient and other optical properties, they are important factors when determining U-factors.

Example 13. Estimate the overall visible light transmittance for an operable wood casement window with clear, uncoated 6 mm double glazing.

Solution: From Table 13, ID 5b, the center-glazing visible light transmittance is 0.78. The operable window has 27% frame area with a wood frame. The overall visible light transmittance is

$$T_v = 0.27(0) + 0.73(0.78) = 0.57$$

Passive Solar Gain

Energy analysis of a fenestration product should include the value of passive solar gain through the product in winter. As described in Chapter 33 of the *ASHRAE Handbook—Applications*, the magnitude of this energy gain depends on such variables as latitude and orientation. In some cases, properly designed and operated fenestration allows more energy into the building over a heating season than it loses, thus making it energy-contributing rather than energy-consuming. Excessive solar gain during the cooling season must be controlled, however.

Direct beam admission to occupied spaces can often produce severe localized glare and overheating conditions. Judicious use of shades and other fenestration control strategies, as well as placement and orientation of workstations and furniture, can alleviate these problems in most cases.

Solar Gain Rejection and Internal Load Dominated Buildings

For some buildings in certain climates, preventing solar gain is more important from an energy perspective than improving thermal insulation using multiple panes of glazing. For example, internal load dominated buildings in cool, clear climates can have substantial daytime solar and internal heat gains. These gains can be rejected by conduction through the building envelope and/or forced ventilation through the HVAC system. Preventing excessive solar gain through the fenestration systems of such buildings is very important.

Airflow Windows

If properly managed, airflow between panes of a double-glazed window can improve fenestration performance. In normal use, a venetian blind is located between the glazing layers. Ventilation air from the room enters the double-glazed cavity, flows over the blind, and is, in some designs, exhausted from the building or returned through the ducts to the central HVAC system. In cold weather, the window acts as a heat exchanger when sunlit so that the inner glass temperature nearly equals the room air temperature and improves thermal comfort.

The apparent conductance across the inner glazing is very low, but this is misleading since additional heat is lost to the outdoors from the moving airstream in the window cavity. During sunny winter days, the blind acts as a solar air collector; heat removed by the moving air can be used elsewhere in the building. In the summer, the window can have a very low shading coefficient if the blinds are appropriately placed since the majority of solar gains are removed from the window. These systems can control window heat transfer under many different operating conditions. Sodergren and Bostrom (1971) and Brandle and Boehm (1982) give details on airflow or exhaust windows.

Skylights

Skylight solar heat gain strongly depends on the configuration of the space below or adjacent to (i.e., in sloped applications) the skylight formed by the skylight curb and any associated light well.

Five aspects must be considered (1) the transmittance and absorptance of the skylight unit, (2) the transmitted solar flux that reaches the aperture of the light well, (3) whether that aperture is covered by a diffuser, (4) the transmitted solar flux that strikes the walls of the light well, and (5) the reflectance of the walls of the light well. Data for flat skylights, which may be considered as sloped glazings, are found in [Tables 4 and 13](#).

Domed Skylights. Solar and total heat gains for domed skylights can be determined by the same procedure used for windows. [Table 15](#) gives SHGCs for plastic domed skylights at normal incidence. Manufacturers' literature has further details. Given the poorly defined incident angle conditions for domed skylights, it is best to use these values without correction for incident angle, together with the correct (angle-dependent) value of incident solar irradiance.

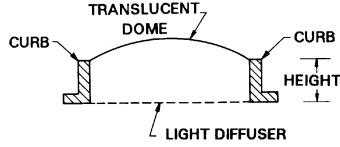
Results should be considered approximate. In the absence of other data, these values may also be used to make estimates for skylights on slanted roofs.

Glass Block Walls

Glass block can be used for light transmission through exterior walls when optical clarity for view is not needed or wanted. [Table 16](#) describes a variety of glass block patterns and gives solar heat gain coefficients to be applied to the solar irradiances so that approximate instantaneous solar heat gains can be calculated.

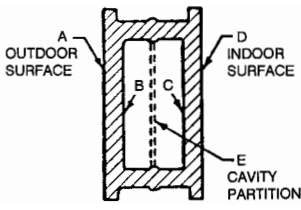
Convection and low-temperature radiative heat gain for all hollow glass block panels fall within a narrow range. Differences in SHGCs are largely the result of differences in the transmittance of the glass blocks for solar radiation. Solar heat gain coefficients for any particular glass block pattern vary depending on orientation and time of day. The SHGC for western exposures in the morning (in the

Table 15 Solar Heat Gain Coefficients for Domed Horizontal Skylights



Dome	Light Diffuser (Translucent)	Curb		Solar Heat Gain Coefficient
		Height, in.	Width-to- Height Ratio	
Clear $\tau = 0.86$	Yes $\tau = 0.58$	0	∞	0.53
		9	5	0.50
		18	2.5	0.44
Clear $\tau = 0.86$	None	0	∞	0.86
		9	5	0.77
		18	2.5	0.70
Translucent $\tau = 0.52$	None	0	∞	0.50
		18	2.5	0.40
Translucent $\tau = 0.27$	None	0	∞	0.30
		9	5	0.26
		18	2.5	0.24

Table 16 Shading Coefficients and U-Factors for Standard Hollow Glass Block Wall Panels



Type of Glass Block ^a	Description of Glass Block	Solar Heat Gain Coefficient		U-Factor, ^c W/(m ² ·K)
		in Sun	in Shade ^b	
Type I	Glass colorless or aqua A, D: Smooth B, C: Smooth or wide ribs, or flutes horizontal or vertical, or shallow configuration E: None	0.65	0.40	2.9
Type IA	Same as Type I except ceramic enamel on A	0.27	0.20	2.9
Type II	Same as Type I except glass fiber screen partition E	0.44	0.34	2.7
Type III	Glass colorless or aqua A, D: Narrow vertical ribs or flutes. B, C: Horizontal light-diffusing prisms, or horizontal light-directing prisms E: Glass fiber screen	0.33	0.27	2.7
Type IIIA	Same as Type III except E: Glass fiber screen with green ceramic spray coating or glass fiber screen and gray glass or glass fiber screen with light-selecting prisms	0.25	0.18	2.7
Type IV	Same as Type I except reflective oxide coating on A	0.16	0.12	2.9

^aAll values are for 200 by 200 by 100 mm block, set in light-colored mortar. For 300 by 300 by 100 mm block, increase coefficients by 15%, and for 150 by 150 by 100 mm block reduce coefficients by 15%.

^bFor NE, E, and SE panels in shade, add 50% to the values listed for panels in the shade.

^cValues shown are the same for all size block.

shade) is depressed because of the heat storage within the block, whereas the SHGC for eastern exposures in the afternoon (in the shade) is elevated as the stored heat is dissipated. Time lag effects from heat storage are estimated by using solar gains and air-to-air temperature differences for one hour earlier than the time for which the load calculation is made.

Calorimeter tests of Type 1A glass block showed little difference in solar heat gains between glass block with either black or white ceramic enamel on the exterior of the block. Because white and black ceramic enamel surfaces represent the two extremes for reflecting or absorbing solar energy, glass block with enamel surfaces of other colors should have solar heat gain coefficients between these values. Since glass blocks are good examples of strongly angularly selective fenestrations, all cautions in the section on Angular Dependence of Glazing Optical Properties apply here.

Plastic Materials for Glazing

Generally, the factors outlined for glass apply also to glazing materials such as acrylic, polycarbonate, polystyrene, or other plastic panels. If the solar transmittance, absorptance, and reflectance are known, an SHGC and a shading coefficient can be calculated in the same way as for glass. These properties can be obtained from the manufacturer or be determined by simple laboratory tests. The National Fenestration Rating Council has developed standards for testing the optical properties of glazing (NFRC 301, NFRC 300).

In selecting plastic panels for glazing, possible deterioration from the sun, expansion and contraction because of temperature extremes, and possible damage from abrasion are concerns.

CALCULATION OF SOLAR HEAT GAIN

As indicated in the section on Determining Fenestration Energy Flow, the solar energy flow through a fenestration may be divided into two parts, opaque and glazing portions, q_{op} and q_s , respectively, as given in Equation (5).

The glazing solar energy flux can be split into that due to incident beam radiation (b) and that due to incident diffuse radiation (d), which includes both diffuse sky radiation and radiation scattered (reflected) from the ground:

$$q_s = q_b + q_d \quad (92)$$

The net heat balance that would occur for a sunlit glazing if there were no diffuse radiation is shown in [Figure 26](#). This net heat balance does not include any of the heat flows contained in Q_{th} in Equation (1) (i.e., those resulting from inside-outside temperature differences). The heat balance due to sunlight is pictured as an effect superimposed on the thermal effect, with, for example, glazing temperatures somewhat elevated over their value without the sunlight. This superposition picture cannot be carried too far, however, because the heat flows indicated in [Figure 26](#) as resulting from convection and radiation depend in part on processes that are nonlinear with respect to temperature [e.g., Equation (25)], so that in reality the two effects cannot be separated. To calculate them, one would need the actual glazing (and other) temperatures, not simply the incremental temperature rise due to the sunlight.

One can see from [Figure 26](#) that the glazing solar energy flow consists of two parts:

$$q_b = q_{bt} + q_{ba} \quad (93)$$

where

q_{bt} = glazing solar energy flux due to transmitted incident beam radiation

q_{ba} = glazing solar energy flux due to inward heat flow of absorbed beam radiation by convection and radiation

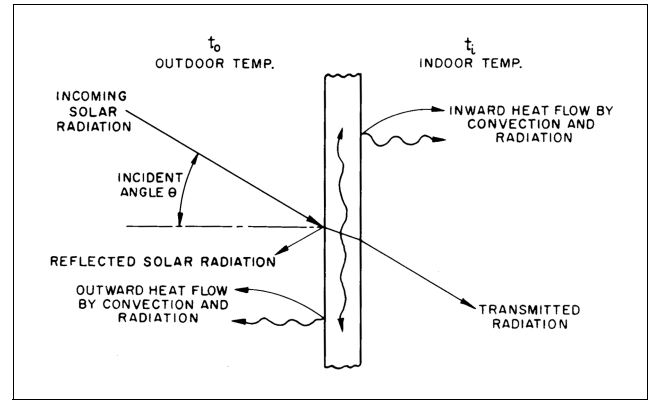


Fig. 26 Instantaneous Heat Balance for Sunlit Glazing Material

However, there is always also diffuse incident radiation, so that the glazing heat flux is in reality given by

$$q_s = q_t + q_a \quad (94)$$

where

q_t = glazing solar energy flux due to all transmitted incident solar radiation

q_a = glazing solar energy flux due to inward flow of absorbed incident solar radiation (by heat transfer processes)

It is convenient to separate the solar energy fluxes due to the two types of incident radiation for purposes of calculation. We can do this by making a definition analogous to Equation (93) for the diffuse solar heat flux:

$$q_d = q_{dt} + q_{da} \quad (95)$$

In order to calculate solar energy fluxes, one must first calculate the incident angle θ from the local standard time and the longitude using Equations (10) and (13) through (17). The direct normal solar irradiance E_{DN} is then calculated from Equation (20), the diffuse sky irradiance E_d from Equation (22) or (23), and the ground-reflected radiation E_r from Equation (24). Note that the latter two are assumed to be ideally diffuse radiation. The total incident irradiance E_t may be calculated from Equation (12).

Because of the distinctions between beam and diffuse incident radiation, one must determine the overall solar heat gain coefficient $SHGC_o$, if desired, by first calculating Q_{sol} and then solving Equations (2) and (1).

Opaque Fenestration Elements

The opaque portion solar energy flux is calculated from

$$q_{op} = (E_{DN}\cos\theta + E_d + E_r)SHGC_{op} \quad (96)$$

where $SHGC_{op}$ is obtained from Equation (86).

Glazing Systems

The following discussion of glazing system solar energy fluxes applies to unshaded glazings. For shaded glazings, see the section on Shading Devices and Fenestration Attachments.

The glazing solar energy flux due to incident beam radiation is calculated from

$$q_b = E_{DN}\cos\theta SHGC(\theta) \quad (97)$$

where the beam solar heat gain coefficient is given by Equation (79). If instead one desires the solar radiant and heat fluxes separately, one can calculate the glazing transmitted solar flux (which is solar radiation traveling in the incident direction) from

$$q_{bt} = E_{DN} \cos \theta T_{1,L}^f(\theta) \quad (98)$$

and the inward-flowing absorbed solar flux (which is heat) from

$$q_{ba} = E_{DN} \cos \theta \sum_{k=1}^L N_k A_{k:(1,L)}^f(\theta) \quad (99)$$

Calculation of $T_{1,L}^f(\theta)$ and $A_{k:(1,L)}^f(\theta)$ in these equations is described in the section on Optical Properties of Multiple-Layer Glazing Systems, and determination of N_k is discussed in the section on Calculation of Solar Heat Gain Coefficient.

The glazing solar energy flux due to diffuse incident radiation is calculated from

$$q_d = (E_d + E_r) \langle \text{SHGC} \rangle_D \quad (100)$$

where the hemispherically averaged solar heat gain coefficient is calculated from Equation (83). The solar radiant and heat fluxes can be separately calculated from

$$q_{dt} = (E_d + E_r) \langle T_{1,L}(\theta) \rangle_D \quad (101)$$

which is diffusely distributed solar radiation (note that effects of finite glazing size and thickness are neglected), and

$$q_{da} = (E_d + E_r) \sum_{n=1}^L N_n \langle A_{n:1,L}^f \rangle_D \quad (102)$$

The hemispherically averaged optical properties are calculated using Equations (70) and (72).

Example 14. Calculate the solar energy flux through the glazing system of Example 10 under the conditions of Example 5 using (a) Table 13 and (b) the equations for optical properties.

Solution:

(a) The exact glazing system used in this example is not listed in Table 13 (as will frequently be the case in practice), so we must locate the glazing system that is closest in properties. The emissivity of the selective coating on surface 2 of the outer glazing is 0.05, and the transmission and reflectances for the insulating glass unit at normal incidence are $T(0^\circ) = 0.331$, $R^f(0^\circ) = 0.388$, and $R^b(0^\circ) = 0.396$. The most similar unit is ID 25a, which has $T(0^\circ) = 0.37$, $R^f(0^\circ) = 0.35$, and $R^b(0^\circ) = 0.39$ (i.e., slightly lower front reflectance and therefore higher transmittance). Near the required angle of incidence, the table values listed for the solar heat gain coefficient are $[\text{SHGC}(60^\circ)]_{25a} = 0.34$ and $[\text{SHGC}(70^\circ)]_{25a} = 0.27$, and from the diffuse column of the table we obtain $[\langle \text{SHGC} \rangle_D]_{25a} = 0.36$. Linear interpolation in angle yields the value $[\text{SHGC}(63.2^\circ)]_{25a} = 0.34 + (0.27 - 0.34)/(70^\circ - 60^\circ) \times (63.2^\circ - 60^\circ) = 0.32$. This value can then be approximately corrected for the (small) difference between the glazing of interest and ID 25a in Table 13 as follows. We first note that entry 25a has a transmittance that is 0.04 higher than the glazing in question and a front reflectance that is 0.04 lower. This means that the absorptance of the two glazings is the same to within the accuracy of Table 13. Referring to Equation (79), we see that with the absorptance held constant, a change in the transmittance of the glazing produces an additive correction to the SHGC that is equal to the difference in transmittance. Referring to Examples 11 and 12 where the transmittances for this case are calculated, we make the correction:

$$\text{SHGC}(63.2^\circ) = [\text{SHGC}(63.2^\circ)]_{25a}$$

$$+ \{T_{1,2}(0^\circ) - [T_{1,2}(0^\circ)]_{25a}\} \times \frac{T_{1,2}(63.2^\circ)}{T_{1,2}(0^\circ)}$$

$$= 0.32 + (0.33 - 0.37) \times \frac{0.24}{0.33} = 0.32 - 0.3 = 0.29$$

and

$$\langle \text{SHGC} \rangle_D = [\langle \text{SHGC} \rangle_D]_{25a}$$

$$+ \{T_{1,2}(0^\circ) - [T_{1,2}(0^\circ)]_{25a}\} \times \frac{\langle T_{1,2} \rangle_D}{T_{1,2}(0^\circ)}$$

$$= 0.36 + (0.33 - 0.37) \times \frac{0.25}{0.33} = 0.36 - 0.3 = 0.33$$

Note that these values are very close to those calculated below in part (b) of the solution. The solar energy flux is then calculated from Equations (92), (97), and (100), using the incident solar fluxes calculated in Example 7:

$$q_s = q_t + q_a = E_{DN} \cos(63.2^\circ) \text{SHGC}(63.2^\circ) + (E_d + E_r) \langle \text{SHGC} \rangle_D$$

$$= (388.0)(0.29) + (93.5 + 86.6)(0.33) = 172 \text{ W/(m}^2 \cdot \text{K)}$$

(b) We use the previously calculated optical properties of the glazing to determine the SHGC. To do this we need the inward-flowing fractions N_1 and N_2 for the two glazing layers. The simplest way to obtain these is to do a heat transfer analysis of the glazing and determine the glazing temperatures under the appropriate conditions. We assume an exterior temperature t_o of 31.7°C , a wind speed of 3.4 m/s , and an indoor temperature t_i of 23.9°C . Using methods presented in the section on Determining Fenestration U-Factors, the heat transfer analysis yields a central glazing U of $1.22 \text{ W/(m}^2 \cdot \text{K)}$ and glazing layer temperatures of $t_1 = 31.2^\circ\text{C}$ and $t_2 = 25.3^\circ\text{C}$. Since the temperature differences will be proportional to the thermal resistances (which are inversely proportional to the effective heat transfer coefficients), $N_1 = (t_1 - t_o)/(t_i - t_o) = 0.064$ and $N_2 = (t_2 - t_o)/(t_i - t_o) = 0.821$. We can then calculate the solar heat gain coefficient for beam radiation incident at 63.2° from Examples 5 and 6, using the results from Example 11, from Equation (79):

$$\text{SHGC}(63.2^\circ) = T_{1,2}(63.2^\circ) + N_1 A_{1:(1,2)}^f(63.2^\circ) + N_2 A_{2:(1,2)}^f(63.2^\circ)$$

$$= 0.244 + (0.064)(0.289) + (0.821)(0.022) = 0.281$$

and for diffuse radiation, using the results from Example 12, from Equation (84):

$$\langle \text{SHGC} \rangle_D = \langle T_{1,2} \rangle_D + N_1 \langle A_{1:(1,2)}^f \rangle_D + N_2 \langle A_{2:(1,2)}^f \rangle_D$$

$$= 0.277 + (0.064)(0.271) + (0.821)(0.036) = 0.324$$

The solar energy flux is then calculated from Equations (92), (97), and (100), using the incident solar fluxes calculated in Example 7:

$$q_s = q_t + q_a = E_{DN} \cos(63.2^\circ) \text{SHGC}(63.2^\circ) + (E_d + E_r) \langle \text{SHGC} \rangle_D$$

$$= (388.0)(0.281) + (93.5 + 86.6)(0.324) = 167.4 \text{ W/(m}^2 \cdot \text{K)}$$

SHADING DEVICES AND FENESTRATION ATTACHMENTS

Fenestrations with shading devices and attachments have a degree of optical and geometric complexity far greater than that of fenestrations with unshaded glazings. ASHRAE has sponsored the development of a method for determining the SHGC of glazing systems of arbitrary complexity. However, there are as yet insufficient data to make this method easy to use as a design tool. For the large number of shading systems for which there are no adequate data, it is still necessary to use the simplified solar heat gain coefficient data to estimate solar gain. In the following section, a detailed calculation method is described, and it should be used for those cases where the necessary data are available.

Table 17 Measured Layer Inward-Flowing Fractions N_k for Typical Fenestration

System	Bind Angle Below Horizontal	Inner Shading Layer	Inner Glass	Between-Pane Shading	Outer Glass	Exterior Shading Layer
Single glazing with interior shade		0.80 ± 0.08			0.08 ± 0.06	
Single glazing with interior venetian blind and/or a single reflected direction. Examples of nonspecular elements are shades, drapes, blinds, honeycombs, figured glass, ground glass, and other diffusers, lenses, prisms, and holographic glazings.	−45°	0.69 ± 0.05			0.24 ± 0.09	
	30°	0.83 ± 0.08			0.21 ± 0.07	
	Closed	0.72 ± 0.07			0.14 ± 0.05	
Single glazing with exterior venetian blind	45°				0.46 ± 0.12	0.04 ± 0.01
Double glazing with interior shade		0.85 ± 0.10	0.52 ± 0.12		0.28 ± 0.06	
Double glazing with interior venetian blind	45°	0.86 ± 0.06	0.69 ± 0.14		0.21 ± 0.09	
Double glazing with between-pane blind	45°		0.69 ± 0.14	0.45 ± 0.06	0.34 ± 0.10	
	−45°		0.76 ± 0.10	0.40 ± 0.07	0.27 ± 0.14	
Low-e double glazing with between-pane blind	35°		0.46 ± 0.12	0.38 ± 0.05	0.32 ± 0.11	
Double glazing with exterior venetian blind	45°		0.73 ± 0.13		0.28 ± 0.12	0.03 ± 0.02

Generalized Calculation Procedure for Shading Devices and Fenestration Attachments

A complex fenestration system is one that contains one or more nonspecular optical elements in the glazed area of the window. A **nonspecular optical element** is one for which light (or short-wave infrared radiation) incident on the element from a single spatial direction does not emerge traveling in a single transmitted direction and/or a single reflected direction. Examples of nonspecular elements are shades, drapes, blinds, honeycombs, figured glass, ground glass, and other diffusers, lenses, prisms, and holographic glazings.

These systems may have a more complicated angle dependence than do the specular glazings discussed previously. The optical properties and solar heat gain coefficient may now depend on both angles defining the incident direction rather than simply on the angle θ between the incident direction and the surface normal. In addition, radiation incident from a given direction is not necessarily reflected or transmitted in a unique direction but may be distributed over a variety of directions. One must therefore introduce the concept of the **directional-hemispherical** transmittance (reflectance) [i.e., the fraction of radiation incident from a given direction that is transmitted (reflected) into the complete outgoing hemisphere].

With these extensions, the equation for the solar heat gain coefficient of a system with L layers becomes

$$\text{SHGC}(\theta, \phi) = T_{1,L}^{fH}(\theta, \phi) + \sum_{k=1}^L N_k A_{k:(1,L)}^f(\theta, \phi) \quad (103)$$

where

- θ = incident angle relative to normal layer
- ϕ = azimuthal angle (in plane of layer, about normal)
- $T_{1,L}^{fH}(\theta, \phi)$ = directional-hemispherical front transmittance of system
- $A_{i:(1,L)}^f(\theta, \phi)$ = directional absorptance of i th layer in system
- N_k = inward-flowing fraction of absorbed energy for i th layer in system

The usual approach to complex fenestration solar heat gain has been either direct measurement or calculation of $\text{SHGC}(\theta, \phi)$ at some specified incident direction, usually either normal incidence or $\theta = 30^\circ$, $\phi = 0^\circ$. Such values, with SHGC re-expressed as shading coefficient, are given for a variety of systems in Tables 18 through 20 and 22. Although in the past it has been assumed that the result would be the same for all incident directions, this is not generally a true assumption, and users of these tables should be aware that they apply only to incident directions of 30° or less and may not include important azimuthal angle dependence. While the values in these tables may give an approximate “first guess” in the absence of better information, for accurate and reliable data, one should rely on a measurement or calculation for the incident directions of interest

unless there is independent reason for believing that incident angle or azimuthal dependencies are unimportant.

Solar-Thermal Separation

It is possible to use Equation (103) to calculate the solar heat gain coefficient for a system from separate determinations of the system transmittance $T_{1,L}^{fH}(\theta, \phi)$, the layer absorptances $A_{k:(1,L)}^f(\theta, \phi)$, and the inward-flowing fractions N_k . This has been termed **solar-thermal separation**, since the processes determining the N_k are thermal in nature, while those determining $T_{1,L}^{fH}(\theta, \phi)$ and $A_{k:(1,L)}^f(\theta, \phi)$ are solar-optical. Table 17 gives calorimetrically determined values of N_k for a number of generic glazing/shading systems (Klems and Kelley 1996). These are independent of the solar-optical properties of the particular system.

The transmittances and layer absorptances in Equation (103) may be determined by a variety of different methods, ranging from calculation to overall system measurement. The computation procedure has advantages, for example, when one wishes to compare the performance of differing glazings or shading system colors in the same general configuration. Optical data are sometimes more readily available or more economically obtained than overall calorimetric measurements of SHGC. For example, $T_{1,L}^{fH}(\theta, \phi)$ is rather simply measurable by an optical technique using an integrating sphere. The layer absorptances $A_{k:(1,L)}^f(\theta, \phi)$ present a more difficult problem of determination, since the data easily available are likely to be the directional absorptance of an **isolated** layer, $a_k^f(\theta, \phi)$, whereas $A_{k:(1,L)}^f(\theta, \phi)$ is the **in-system** layer absorptance (i.e., it includes the contributions of absorbed radiation multiply reflected back to the i th layer from all the other layers in the system). Isolated layer absorptances $a_k^f(\theta, \phi)$ must be corrected for this effect.

Calculating System Transmittance and Absorptances from Layer Properties

The key feature of nonspecular elements is that they produce distributions of outgoing radiation (in the solar-optical spectral region) in the transmitted and/or reflected hemisphere, even for incident radiation from a single direction. This means that they are characterized by bidirectional transmittance (BTDF) and reflectance (BRDF) distribution functions that give the outgoing radiance (energy flux per unit area per unit solid angle) as a fraction of the incident irradiance (energy flux per unit area):

$$\begin{aligned} I(\theta_o, \phi_o; \theta_i, \phi_i) &= \tau(\theta_o, \phi_o; \theta_i, \phi_i)E \\ J(\theta_o, \phi_o; \theta_i, \phi_i) &= \rho(\theta_o, \phi_o; \theta_i, \phi_i)E \end{aligned} \quad (104)$$

where

- θ_o, ϕ_o = angles specifying outgoing direction
- θ_i, ϕ_i = angles specifying incident direction

E = incident irradiance
 I, J = transmitted, reflected radiance

In a real nonspecular element, these quantities are also functions of the location in space at which the radiation is incident on the fenestration, as can be seen by visualizing a venetian blind. However, this level of detail is only useful if one wishes to find the detailed spatial images of the outgoing radiation patterns. For determining the solar heat gain, it is sufficient to consider the process as spatially averaged over the nonspecular device so that it can be considered as a thin uniform layer with only angular dependence (Klems 1994a). By dividing the (transmission or reflection) hemisphere into a grid of solid angle sections, the bidirectional property functions can be approximated as matrices (Klems 1994b).

There are many standard commercial computer programs executable on personal computers that can perform the matrix calculations, including many popular spreadsheet programs. Use of this biangular grid to characterize a nonspecular layer with azimuthal dependence requires handling matrices that are 145×145 elements, and for this level of complexity a special-purpose computer program for handling the large amount of data involved is probably desirable.

Figure 27 shows the results of such a calculation for an interior buff-colored blind (slat reflectance 62%) in combination with sealed double glazing (3 mm glass panes). The calculation used bidirectional transmittance and reflectance measurements averaged over a 200 mm square section of the blind, with 25 mm slats. These measurements were used to construct layer property matrices with the clear glazing properties taken from published literature (Rubin 1985). The SHGC was calculated using Equation (103), solar-optical transmittances and absorptances calculated by the matrix method of Klems (1994b), and inward-flowing fractions from Table 17 (Klems and Kelley 1996, Klems and Warner 1995).

Simplified Calculation Procedure

The detailed methodology has been shown to agree with measurement (Klems et al. 1996) and should be used whenever accurate calculations are necessary and the data needed are available. Once the necessary data are available for a shading layer, Klems and Warner (1997) have shown how to calculate the performance for any

combination of that shading layer and unshaded glazings. However, the data necessary to use this exact calculation method are not readily available for many shading systems and are difficult to obtain by measurement for some (e.g., venetian blinds). It will therefore be necessary to use a simpler and less accurate method for most design purposes.

Two simplified approaches are described below. For some simple glazing systems (single glazing and clear double glazing) at solar incident angles below 30° , measurements of the solar heat gain coefficient exist for a number of shading configurations. These are presented in tables, and the first approach, described in the sections on Exterior Shading and Indoor and Between Glass Shading Devices on Simple Fenestrations, may be used. For situations not covered by these tables, the second approach, consisting of the following simplifying approximation together with the section on Completely Shaded Glazings, should be used.

First, one must determine the fraction (if any) of the incident radiation that passes through the fenestration essentially without encountering the shading element. This is termed the **unshaded fraction** F_u . For example, an overhang might shadow only part of a fenestration, a venetian blind or louver might under some conditions permit radiation to pass through it without encountering any of the slats, and for a drapery of open weave, some radiation passes through the gaps between threads and is effectively specularly transmitted (as opposed to radiation that is diffusely scattered by the threads). For this fraction of the incident radiation, the fenestration is essentially an unshaded one. The unshaded fraction is determined from geometric considerations, either those described below for exterior shading or those described for draperies. Once the unshaded fraction has been determined, the glazed area A_G is divided into two equivalent glazings, an unshaded one of area $F_u A_G$ and a completely shaded one of area $(1 - F_u) A_G$. Heat gain through the unshaded equivalent glazing is calculated using the methods given in the section on Calculation of Solar Heat Gain, in the subsection on Glazing Systems, for unshaded glazings. Heat gain through the completely shaded equivalent glazing is calculated by the methods given in the section on Completely Shaded Glazings, which assume that the shading layer is a uniform diffuse reflector or transmitter. A **uniform diffuse reflector or transmitter** is one for which a given incident irradiance produces an outgoing reflected or transmitted radiance that is the same in all directions and is independent of the incident direction.

EXTERIOR SHADING

The most effective way to reduce the solar load on fenestration is to intercept direct radiation from the sun before it reaches the glass. Fenestration products fully shaded from the outside reduce solar heat gain as much as 80%. In one way or another, fenestration can be shaded by roof overhangs, vertical and horizontal architectural projections, awnings, heavily proportioned exterior louvers, insect or shading screens, patterned screens having a weave designed for sunlight interception, sun screens of narrow fixed louvers, or a variety of vegetative shades including trees, hedges, and trellis vines. In all exterior shading structures, the air must move freely to carry away heat absorbed by the shading and glazing materials. See manufacturers' instructions regarding proper installation for achieving the expected performance by providing suitable free convection ventilation between the shading and glazing. Also, consider the geometry of the structures relative to changing sun position to determine the times and quantities of direct sunlight penetration. Detailed discussions of the effectiveness of various outside shading devices are given in Pennington (1968), Yellott (1972), and Ewing and Yellott (1976).

The general effect of exterior shading is to attenuate the solar radiation. Some of the beam radiation may pass through or around the shading, and this is accounted for by the unshaded fraction F_u

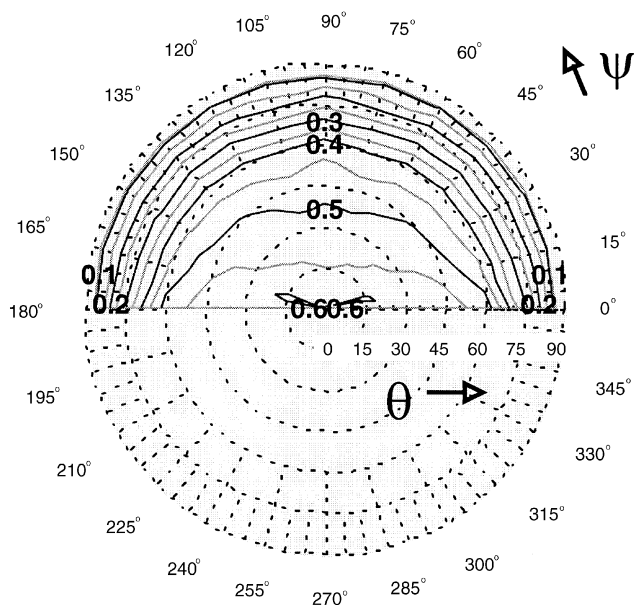
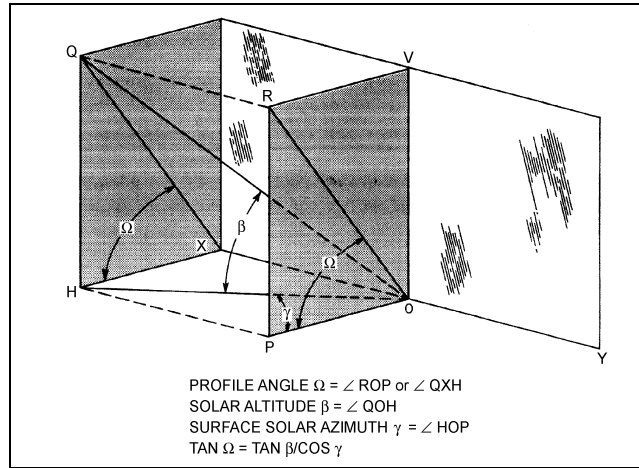


Fig. 27 Contour Plot of Beam SHGC for Double Glazed Window with Interior Venetian Blind with Slats Tilted at 45°

Table 18 Unshaded Fractions (F_u) and Exterior Solar Attenuation Coefficients (EAC) for Louvered Sun Screens

Profile Angle	Group 1			Group 2			Group 3			Group 4		
	Transmittance	F_u	EAC	Transmittance	F_u	EAC	Transmittance	F_u	EAC	Transmittance	F_u	EAC
10°	0.23	0.20	0.15	0.25	0.13	0.02	0.4	0.33	0.18	0.48	0.29	0.3
20°	0.06	0.02	0.15	0.14	0.03	0.02	0.32	0.24	0.18	0.39	0.2	0.3
30°	0.04	0.00	0.15	0.12	0.01	0.02	0.21	0.13	0.18	0.28	0.08	0.3
≥ 40°	0.04	0.00	0.15	0.11	0.00	0.02	0.07	0.00	0.18	0.2	0.00	0.3

Group 1: Black, width over spacing ratio 1.15/1; 1.1 mm between louvers. Group 2: Light color; high reflectance, otherwise same as Group 1. Group 3: Black or dark color; w/s ratio 0.85/1; 1.5 mm between louvers. Group 4: Light color or unpainted aluminum; high reflectance; otherwise same as Group 3. U-factor = 4.83 W/(m²·K) for all groups when used with single glazing.

**Fig. 28 Profile Angle for South-Facing Slat-Type Sunshades**

defined above. Some fraction of the remainder of the solar radiation will be transmitted by the shading system and will be incident on the glazing, but in the form of diffuse radiation. The actual angular distribution of this radiation may be quite complex, but for simplicity it is treated here as uniformly diffuse radiation, and it is considered to compose a fraction EAC, the exterior solar attenuation coefficient, of the total incident radiation interacting with the exterior shading system. The solar energy flux through the glazing with exterior shading is then given by

$$q = F_u E_{DN} \cos \theta \text{SHGC}(\theta) + [(1 - F_u) E_{DN} \cos \theta + E_d + E_r] \text{EAC} \langle \text{SHGC} \rangle_D \quad (105)$$

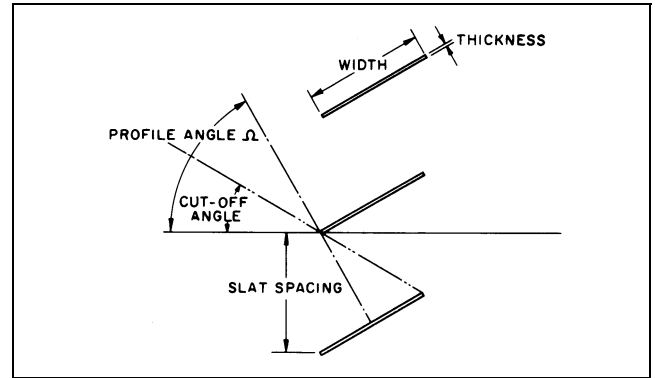
The quantities SHGC(θ) and $\langle \text{SHGC} \rangle_D$ in Equation (105) are the beam and diffuse solar heat gain coefficients of the unshaded glazing system. The second of the two terms on the right-hand side of the equation is the flux through the *completely shaded* glazing and is discussed in more detail in Equation (114) and the associated text, which makes clear the physical basis of the EAC.

Louvers and Sunshades

The ability of horizontal panels or louvers to intercept the direct component of solar radiation depends on their geometry and the profile or shadow-line angle Ω (Figure 28), defined as the angular difference between a horizontal plane and a plane tilted about a horizontal axis in the plane of the fenestration until it includes the sun. The profile angle can be calculated by

$$\tan \Omega = \tan \beta / \cos \gamma \quad (106)$$

For slat-type sunshades, the transmitted solar radiation consists of straight-through and transmitted-through components. When the profile angle Ω is above the cutoff angle (see Figure 29), straight-through transmission of direct radiation is completely eliminated,

**Fig. 29 Geometry of Slat-Type Sunshades**

but the transmitted diffuse and the reflected-through components remain. Their magnitude depends largely on the reflectance of the sunshade surfaces and of exterior objects.

Narrow horizontal louvers, fabricated in conventional width-to-spacing ratios and framed as window screens, retain their shading characteristics, while gaining in effective transparency (view) by eliminating the coarse striation pattern of wide louvers. Table 18 gives values of F_u and EAC for several types of louvered sun screens. Commercially available sun screens completely exclude direct solar radiation when the profile angle exceeds approximately 26° (Groups 1 and 2) or 40° (Groups 3 and 4). Group designations are defined in the footnote to Table 18.

Roof Overhangs: Horizontal and Vertical Projections

In the northern hemisphere, horizontal projections can considerably reduce solar heat gain on south, southeast, and southwest exposures during late spring, summer, and early fall. On east and west exposures during the entire year, and on south exposures in winter, the solar altitude is generally so low that to be effective, horizontal projections must be excessively long.

The shadow width S_W and shadow height S_H (Figure 30) produced by the vertical and horizontal projections (P_V and P_H), respectively, can be calculated using the surface solar azimuth γ and the horizontal profile angle Ω determined by Equation (106).

$$S_W = P_V |\tan \gamma| \quad (107)$$

$$S_H = P_H \tan \Omega \quad (108)$$

Note: When the surface solar azimuth γ is greater than 90° and less than 270°, the fenestration product is completely in the shade; thus, $S_W = W + R_w$ and $A_{SL} = 0$.

The sunlit A_{SL} and shaded A_{SH} areas of the fenestration product are variable during the day and can be calculated for each moment using the following relations (see Figure 30):

$$A_{SL} = [W - (S_W - R_w)][H - (S_H - R_H)] \quad (109)$$

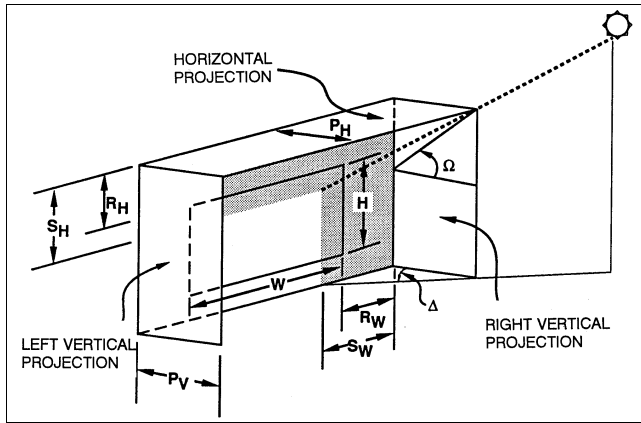


Fig. 30 Vertical and Horizontal Projections and Related Profile Angles for Vertical Surface Containing Fenestration

$$A_{SH} = A - A_{SL} \quad (110)$$

where A is total fenestration product area. McCluney (1990) described an algorithm for computer use to calculate the unshaded fraction of a window equipped with overhangs, awnings, or side fins.

Example 15. A window in the southwest wall of a building at 40°N latitude is 870 mm wide and 1480 mm high. The depth of the horizontal and vertical projections is 150 mm, and they are located 75 mm beyond the edges of the window.

(a) Find the sunlit and shaded area of the window at 3:00 P.M. on July 21.

(b) Find the depth of the projections necessary to fully shade the window just described.

Solution:

(a) The wall azimuth ψ for a southwest wall is +45° (Table 9). The solar azimuth ϕ can be calculated using Equation (15). At 3:00 P.M., $H = 0.25 \times 180 = 45^\circ$; from Table 7, for July 21, $\delta = 20.6^\circ$.

Find the solar altitude β using Equation (14):

$$\sin \beta = \cos(40)\cos(20.6)\cos(45) + \sin(40)\sin(20.6)$$

$$\beta = 47.2^\circ$$

Find the solar azimuth ϕ using Equation (15):

$$\cos \phi = [\sin(47.2)\sin(40) - \sin(20.6)]/[\cos(47.2)\cos(40)]$$

$$\phi = 76.7^\circ$$

Thus, from Equation (16), $\gamma = 76.7 - 45 = 31.7^\circ$.

Using Equation (107), the width of the vertical projection shadow is

$$S_W = 150 \tan(31.7) = 93 \text{ mm}$$

Using Equation (106), the profile angle for the horizontal projection is

$$\tan \Omega = \tan(47.2)/\cos(31.7)$$

$$\Omega = 51.8^\circ$$

Using Equation (108), the height of the horizontal projection shadow is

$$S_H = 150 \tan(51.8) = 191 \text{ mm}$$

Using Equations (109) and (110), the sunlit and shaded area of the window are now

$$A_{SL} = [870 - (93 - 75)][1480 - (191 - 75)]/10^6 = 1.162 \text{ m}^2$$

$$A_{SH} = (870 \times 1480)/10^6 - 1.162 = 0.128 \text{ m}^2$$

(b) The shadow length necessary to fully shade the given window $S_{H(fs)}$ and $S_{W(fs)}$ from the horizontal and vertical projection are given by (see Figure 30)

$$S_{H(fs)} = 1480 + 75 = 1555 \text{ mm}$$

$$S_{W(fs)} = 850 + 75 = 945 \text{ mm}$$

Thus, using Equations (107) and (108),

$$P_{V(fs)} = 1555 \phi \cot(31.7) = 1224 \text{ mm}$$

$$P_{H(fs)} = 945 [\cot(51.8)] = 1530 \text{ mm}$$

For this example, because both horizontal and vertical projections do not need to fully shade the window, a horizontal projection of 1224 mm is satisfactory. Also, to accurately analyze the influence of external projections, an hour-by-hour calculation must be performed over the periods of the year for which shadowing is desired.

Example 16. Suppose that the glazing of Examples 10 and 14 has a black exterior louver shade with a width-to-spacing ratio of 1.15/1. Find the solar energy flux through the system if it is on a west-facing orientation under the conditions of Example 5.

Solution: In Example 5, the solar altitude was found to be $\beta = 60.76^\circ$ and the solar azimuth was found to be $\phi = 67.4^\circ$. The incident angle was found in Example 6 to be $\theta = 63.2^\circ$. Referring to Table 9, we see that $\psi = 90^\circ$ for a west-facing window, and so $\gamma = \phi - \psi = 67.4^\circ - 90^\circ = -22.6^\circ$. We can discard the sign of γ as irrelevant to the calculation of profile angle, since it merely determines whether the sun lies to the south or the north of the normal to the glazing. From Equation (106), we find that the profile angle is $\Omega = \arctan(\tan \beta / \tan \gamma) = \arctan[\tan(60.76^\circ) / \tan(22.6^\circ)] = 76.9^\circ$.

From the footnote to Table 18, we see that the louver system corresponds to Group 1, and from the table, we see that for profile angles greater than or equal to 40° we should use $F_u = 0$ and $EAC = 0.15$. In Example 14, the (unshaded) glazing system was determined to have $SHGC(63.2^\circ) = 0.29$ and $\langle SHGC \rangle_D = 0.33$, respectively, using Table 13. In Example 7, the incident solar fluxes for these conditions were calculated to be $E_{DN} \cos(\theta) = 388 \text{ W/m}^2$, $E_d = 93.5 \text{ W/m}^2$, and $E_r = 86.6 \text{ W/m}^2$. Using Equation (105), we calculate

$$q = (0)(388)(0.29) + [(1 - 0)(388) + 93.5 + 86.6](0.15)(0.33) = 28 \text{ W/m}^2$$

Equations for Computer Calculations of External Shadowing of Inclined Surfaces

$$\text{Incident angle: } \theta = \cos^{-1}(\cos \beta \cos \gamma \sin \Sigma + \sin \beta \cos \Sigma)$$

$$\text{Vertical surface: } \theta_V = \cos^{-1}(\cos \beta \cos \gamma)$$

$$\text{Horizontal surface: } \theta_H = \cos^{-1}(\sin \beta)$$

Vertical projection profile angle:

$$\Delta = \tan^{-1}\left(\frac{\sin \gamma \cos \beta}{\cos \theta}\right); |\theta| < 90^\circ$$

For $\theta > 90^\circ$ $A_{SL} = 0$ and $A_{SH} = A$

$$\text{Vertical surface: } \Delta_V = \tan^{-1}(\gamma) \text{ for } 90^\circ > |\gamma| > 270^\circ$$

$$\text{Horizontal surface: } \Delta_H = \tan^{-1}\left(\frac{\sin \gamma}{\tan \beta}\right) \text{ for all } \gamma$$

Horizontal projection profile:

$$\text{Angle: } \Omega = \tan^{-1} \left(\frac{\sin \beta \sin \Sigma - \cos \beta \cos \gamma \cos \Sigma}{\cos \theta} \right) \text{ for } |\theta| < 90^\circ$$

$$\text{Vertical surface: } \Omega_V = \tan^{-1} \left(\frac{\tan \beta}{\cos \gamma} \right) \text{ for } 90^\circ > |\gamma| > 270^\circ$$

$$\text{Horizontal surface: } \Omega_H = \tan^{-1} \left(\frac{\cos \gamma}{\tan \beta} \right) \text{ for } 90^\circ < |\gamma| < 270^\circ$$

$$\text{Length of shadow from vertical projection: } S_W = P_V |\tan \Delta|$$

$$\text{Length of shadow from horizontal projection: } S_H = P_H |\tan \Omega|$$

Sunlit and shaded areas of the fenestration product are determined using Equations (109) and (110).

where

ϕ = solar azimuth

β = solar altitude

γ = surface solar azimuth

Σ = surface tilt angle

P_V = vertical projection depth

P_H = horizontal projection depth

W = fenestration product width

H = fenestration product height

R_W = width of opaque surface between fenestration product and vertical projection

R_H = height of opaque surface between fenestration product and horizontal projection

A = total projected area of the fenestration product

θ = angle of incidence

Ω = horizontal projection profile angle

Δ = vertical projection profile angle

INDOOR AND BETWEEN-GLASS SHADING DEVICES ON SIMPLE FENESTRATIONS

Venetian Blinds and Roller Shades

Most fenestration has some type of internal shading to provide privacy and aesthetic effects, as well as to give varying degrees of sunshine control (Ozisik and Schutrum 1960). This section provides a method of calculating the approximate SHGC for such fenestrations for a selection of simple and somewhat common shading elements and glazing systems. The information presented here is based on measurements that predate many modern developments in fenestration systems. For this reason, desired systems may not be represented in the tables, or it may be difficult to determine whether the desired conditions match those of the table. If information is not available in this section or greater accuracy or detail is desired, the reader should refer to the subsequent section on Completely Shaded Glazings, where calculation formulas are presented. However, the present state of data availability on shading devices does not permit great accuracy in the calculation of heat flow through shaded fenestrations. The user should proceed with caution.

As discussed in the text and equations associated with Equation (129), the details of solar transmission through a glazing with interior shading are quite complex. However, if one is interested only in the approximate total heat flux through the fenestration, rather than in the detailed separation into transmitted and absorbed (and thermally retransmitted) fluxes and the distribution of the absorbed energy among the fenestration layers, it will frequently be the case that measurements made on a fenestration under one set of conditions can be extrapolated to other fenestrations and conditions to give an adequate answer. In this case, the heat flux is represented by

$$q = [E_{DN} \cos \theta \text{SHGC}(\theta) + (E_d + E_r) \langle \text{SHGC} \rangle_D] \text{IAC} \quad (111)$$

where the quantity in the brackets represents the heat flow through the unshaded glazing system [compare Equations (97) and (100)] and the constant interior solar attenuation coefficient IAC represents the fraction of that heat flow that enters the room, some energy having been excluded by the shading. The solar heat gain coefficients in Equation (111) may be obtained from [Table 13](#) or calculated by Equations (79) and (84) for unshaded glazing. [Table 19](#) gives values of IAC (derived from measurements) for a variety of glazing and shading combinations.

It will be noticed that the IAC bears a certain similarity to the shading coefficient. There is, however, an important difference: we must calculate the solar heat flux through the unshaded glazing at the appropriate angle before applying the IAC. With the shading coefficient, only the angular dependence of single glazing was included (through the now-discarded SHGF). The effectiveness of any internal shading device depends on its ability to reflect incoming solar radiation back through the fenestration before it can be absorbed and converted into heat within the building. [Table 21](#) lists approximate values of solar-optical properties for the typical indoor shading devices described in [Tables 19](#) and [20](#).

For shading between the panes of a double-glazing system, an equation similar to Equation (111) can be used, but in this case one defines the unshaded glazing system to be the portion of the glazing that is exterior to the shading and defines a new coefficient, the between-pane solar attenuation coefficient (BAC), to describe the effect of the shading system together with the portion of the glazing that is interior to it:

$$q = [E_{DN} \cos \theta \text{SHGC}(\theta) + (E_d + E_r) \langle \text{SHGC} \rangle_D]_{\text{ext}} \text{BAC} \quad (112)$$

Values of BAC for those systems for which measurements are available are given in [Table 20](#). For other systems, one should use the detailed equations of the section on Completely Shaded Glazings.

Example 17. Find the approximate SHGC and solar heat flux for a heat-absorbing double glazing with a light-colored interior venetian blind under the conditions of Example 5. The heat-absorbing double glazing has a visible transmittance of 0.41.

Solution: Referring to [Table 19](#), we see that an interior, light venetian blind, heat-absorbing double glazing has an IAC value of 0.66. For the conditions of Example 5, the incident angle was found in Example 6 to be $\theta = 63.2^\circ$, and in Example 7 the incident solar fluxes for these conditions were calculated to be $E_{DN} \cos \theta = 388 \text{ W/m}^2$, $E_d = 93.5 \text{ W/m}^2$, and $E_r = 86.6 \text{ W/m}^2$. Referring to [Table 13](#), we see that the closest glazing system corresponds to ID 5h, 6 mm gray glass exterior, clear interior, which has $\text{SHGC}(60^\circ) = 0.37$, $\text{SHGC}(70^\circ) = 0.29$, and $\langle \text{SHGC} \rangle_D = 0.39$. Interpolating in incident angle between the two table values gives $\text{SHGC}(63.2^\circ) = 0.34$. Using Equation (111), we find the solar heat flux $q = [388 \times 0.34 + (93.5 + 86.6) \times 0.39] 0.66 = 133 \text{ W/m}^2$.

There is some ambiguity about the meaning of the SHGC in this case. One could pick out the terms in Equation (111) corresponding to either the effective beam or diffuse SHGC for the overall system, but, given the fact that the IAC values in [Table 19](#) were measured in outdoor calorimeters so that the incident radiation consisted of both beam and diffuse radiation, it is most reasonable to calculate an effective SHGC for these conditions by dividing the estimated solar heat flux by the total incident intensity:

$$\text{SHGC}_{\text{eff}} = \frac{133}{388 + 93.5 + 86.6} = 0.23$$

Example 18. Estimate the solar heat flux for the glazing and conditions of Example 17, but assume that the venetian blind is between the glazing panes.

Solution: Referring to [Table 20](#), we see that a light venetian blind between the panes of a heat-absorbing double-glazing system has a BAC value of 0.28. We use this value in Equation (112), but in contrast to Example 17, we need the SHGC values of the exterior glazing layer rather than the full glazing system. In Example 17, we used ID 5h,

Table 19 Interior Solar Attenuation Coefficients (IAC) for Single or Double Glazings Shaded by Interior Venetian Blinds or Roller Shades

Glazing System ^a	Nominal Thickness ^b Each Pane, mm	Glazing Solar Transmittance ^b		Glazing SHGC	IAC				
		Outer Pane	Single or Inner Pane		Venetian Blinds		Roller Shades		
					Medium	Light	Opaque Dark	Opaque White	Translucent Light
Single Glazing Systems									
Clear, residential	3		0.87 to 0.80	0.86	0.75 ^d	0.68 ^d	0.82	0.40	0.40
Clear, commercial	6 to 13		0.80 to 0.71	0.82					
Clear, pattern	3 to 13		0.87 to 0.79						
Heat absorbing, pattern	3			0.59					
Tinted	5, 5.5		0.74, 0.71						
Above glazings, automated blinds ^c				0.86	0.64	0.59			
Above glazings, tightly closed vertical blinds				0.85	0.30	0.26			
Heat absorbing ^f	6		0.46	0.59	0.84	0.78	0.66	0.44	0.47
Heat absorbing, pattern	6								
Tinted	3, 6		0.59, 0.45						
Heat absorbing or pattern			0.44 to 0.30	0.59	0.79	0.76	0.59	0.41	0.47
Heat absorbing	10		0.34						
Heat absorbing or pattern			0.29 to 0.15						
			0.24	0.37	0.99	0.94	0.85	0.66	0.73
Reflective coated glass			0.26 to 0.52	0.83	0.75				
Double Glazing Systems^g									
Clear double, residential	3	0.87	0.87	0.76	0.71 ^d	0.66 ^d	0.81	0.40	0.46
Clear double, commercial	6	0.80	0.80	0.70					
Heat absorbing double ^f	6	0.46	0.8	0.47	0.72	0.66	0.74	0.41	0.55
Reflective double				0.17 to 0.35	0.90	0.86			
Other Glazings (Approximate)					0.83	0.77	0.74	0.45	0.52
± Range of Variation^h					0.15	0.17	0.16	0.21	0.21

^a Systems listed in the same table block have the same IAC.^b Values or ranges given for identification of appropriate IAC value; where paired, solar transmittances and thicknesses correspond. SHGC is for unshaded glazing at normal incidence.^c Typical thickness for residential glass.^d From measurements by Van Dyke and Konen (1982) for 45° open venetian blinds, 35° solar incidence, and 35° profile angle.^e Use these values only when operation is automated for exclusion of beam solar (as opposed to daylight maximization). Also applies to tightly closed horizontal blinds.^f Refers to gray, bronze and green tinted heat-absorbing glass (on exterior pane in double glazing)^g Applies either to factory-fabricated insulating glazing units or to prime windows plus storm windows.^h The listed approximate IAC value may be higher or lower by this amount, due to glazing/shading interactions and variations in the shading properties (e.g., manufacturing tolerances).**Table 20 Between-Glass Solar Attenuation Coefficients (BAC) for Double Glazing with Between-Glass Shading**

Type of Glass	Nominal Thickness, Each Pane	Solar Transmittance ^a		Description of Air Space	Type of Shading		
		Outer Pane	Inner Pane		Venetian Blinds		Louvered Sun Screen
					Light	Medium	
Clear out, Clear in	2.4, 3 mm	0.87	0.87	Shade in contact with glass or shade separated from glass by air space.	0.33	0.36	0.43
Clear out, Clear in	6 mm	0.80	0.80	Shade in contact with glass-voids filled with plastic.	—	—	0.49
Heat-absorbing ^b out, Clear in				Shade in contact with glass or shade separated from glass by air space.	0.28	0.30	0.37
	6 mm	0.46	0.80	Shade in contact with glass-voids filled with plastic.	—	—	0.41

^a Refer to manufacturers' literature for exact values.^b Refers to gray, bronze and green tinted heat-absorbing glass.**Table 21 Properties of Representative Indoor Shading Devices Shown in [Tables 19](#) and [20](#)**

Indoor Shade	Solar-Optical Properties (Normal Incidence)		
	Transmittance	Reflectance	Absorptance
Venetian blinds ^a (ratio of slat width to slat spacing 1.2, slat angle 45°)			
Light colored slat	0.05	0.55	0.40
Medium colored slat	0.05	0.35	0.60
Vertical blinds			
White louvers	0.00	0.77	0.23
Roller shades			
Light shades (translucent)	0.25	0.60	0.15
White shade (opaque)	0.00	0.65	0.35
Dark colored shade (opaque)	0.00	0.20	0.80

^a Values in this table and [Tables 19](#) and [20](#) are based on horizontal venetian blinds. However, tests show that these values can be used for vertical blinds with good accuracy.

which Table 13 shows had an exterior glazing that is 6 mm gray glass. We find that ID 1h is the entry for clear 6 mm gray glass, for which $\text{SHGC}(60^\circ) = 0.51$, $\text{SHGC}(70^\circ) = 0.44$, and $\langle \text{SHGC} \rangle_D = 0.52$. Interpolating the beam SHGC values in incident angle gives $\text{SHGC}(63.2^\circ) = 0.49$. We then use Equation (112) to calculate

$$q = [388 \times 0.49 + (93.5 + 86.6) \times 0.52]0.41 = 116 \text{ W/m}^2$$

This indicates that having the blind between the glazings yields slightly better solar heat gain rejection than an interior placement.

Draperies

Draperies reduce heating and cooling loads, depending on the type and the use by the occupant. Rudoy and Duran (1975) found annual reductions between 5 and 20%. An approximate model for determining the SHGC of free-standing vertical interior shades was developed by McCluney and Mills (1993). Solar heat gain may be estimated by using Equation (111) and the IAC values listed in Table 22.

The solar optical properties of drapery fabrics can be determined accurately by laboratory tests (Yellott 1963), and manufacturers can usually supply solar transmittance and reflectance values for their products. In addition to these properties, the **openness factor** (ratio of the open area between the fibers to the total area of the fabric) is a useful property that can be measured exactly (Keyes 1967, Pennington and Moore 1967). It can also be estimated by inspection, since the human eye can readily distinguish between tightly woven fabrics that permit little direct radiation to pass between the fibers and loosely woven fabrics that allow the sun's rays to pass freely.

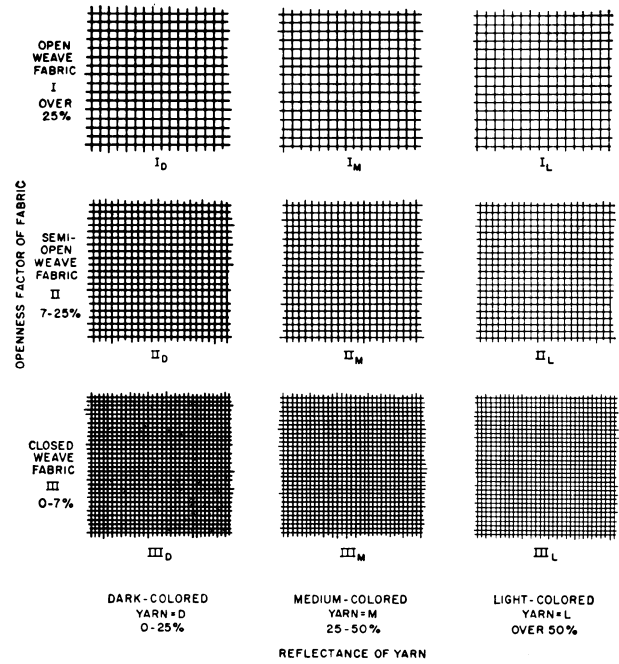
Drapery fabrics can be classified in terms of their solar-optical properties as having specific values of fabric transmittance and reflectance. Fabric reflectance is the major factor in determining the ability of a fabric to reduce solar heat gain. Based on their appearance, draperies can also be classified by yarn color as dark, medium, and light and by weave as closed, semiopen, and open. The apparent color of a fabric is determined by the reflectance of the yarn itself. The figure in Table 22 shows yarn reflectance. Figure 31 classifies drapery fabrics into nine types, rated by openness and yarn reflectances.

Figure 31 guides in the use of Table 22 for a fabric-glass combination when the solar-optical properties are unknown. Whenever possible, fabric reflectance and transmittance values should be obtained from the manufacturer, which permits more accurate solar heat flux estimates to be made. Visual estimations of openness and yarn reflectance, interpreted through Table 22, are valuable in judging the effectiveness of drapes for (1) protection from excessive radiant energy from either sunlight or sun-heated glass, (2) brightness control, (3) providing either outward view or privacy, and (4) sound control.

Table 22 applies to glass and a single drape hung with 100% fullness (drapery width is twice the width of the draped area). If the drapery is hung flat, like a fenestration product shade, a different IAC applies; with a low transmittance and high reflectance, the IAC is appreciably lower. As an extreme example, a flat opaque drapery having an aluminized or similar coating with reflectance of 0.80, in combination with 6 mm clear glass, has an SHGC of 0.18, compared with 0.32 for this material in draped form. Pennington and Moore (1967) explain the effect of folding drapery materials to provide 100% fullness and describe a method for calculating SHGC when materials are used flat.

Example 19. A drape with 100% fullness, having a fabric transmittance of 0.20 and a fabric reflectance of 0.40, is used with 6 mm glass. What IAC should be used?

Solution: Locating the point on the ideogram in Table 22 corresponding to fabric reflectance 0.40 and transmittance 0.20, we find that it is close to the diagonal line labeled "F". In column F of the table, we find



Note: Classes may be approximated by eye. With closed fabrics, no objects are visible through the material, but large light or dark areas may show. Semiopen fabrics do not permit details to be seen, and large objects are clearly defined. Open fabrics allow details to be seen, and the general view is relatively clear with no confusion of vision. The yarn color or shade of light or dark may be observed to determine whether the fabric is light, medium, or dark.

Fig. 31 Designation of Drapery Fabrics

a value of 0.58 on the line corresponding to 6 mm clear glass. This is the desired IAC value.

Example 20. Determine the fabric designator for a fabric having an openness factor of 0.10 and a yarn reflectance of 0.60.

Solution: On the figure in Table 22, these lines intersect in the area of Designator II_L . Refer also to Figure 30. Fabric is semiopen and light in color. Additional information: probable fabric reflectance is 0.50, and fabric transmittance is 0.35.

COMPLETELY SHADED GLAZINGS

This section presents approximate models (Klems 2001) for calculating the heat flow through glazing systems with shading for all cases not covered by the sections on Exterior Shading and Indoor and Between-Glass Shading Devices on Simple Fenestrations (i.e., glazing or shading systems not covered by the tables or with incident angles above 30°). With the exception of exterior fins and overhangs, all shading is modeled as a **planar, ideally diffuse layer** parallel to the glass layers, and the models do not apply if there is more than one shading layer. The effects of specular transmission or partial shading are assumed to have been separated out using the method described above under Simplified Calculation Procedure.

The shading layer is denoted by the subscript S . To apply these models, one or more of the following quantities must be known for the shading (the number depends on the position of the shading in the glazing system):

$$\begin{aligned} T_S^{FH} &= \text{front directional-hemispherical transmittance of the shading layer} \\ T_S^{bH} &= \text{back directional-hemispherical transmittance of the shading layer} \\ R_S^{FH} &= \text{front directional-hemispherical reflectance of the shading layer} \\ R_S^{bH} &= \text{back directional-hemispherical reflectance of the shading layer} \end{aligned}$$

Table 22 Interior Solar Attenuation Coefficients for Single and Insulating Glass with Draperies

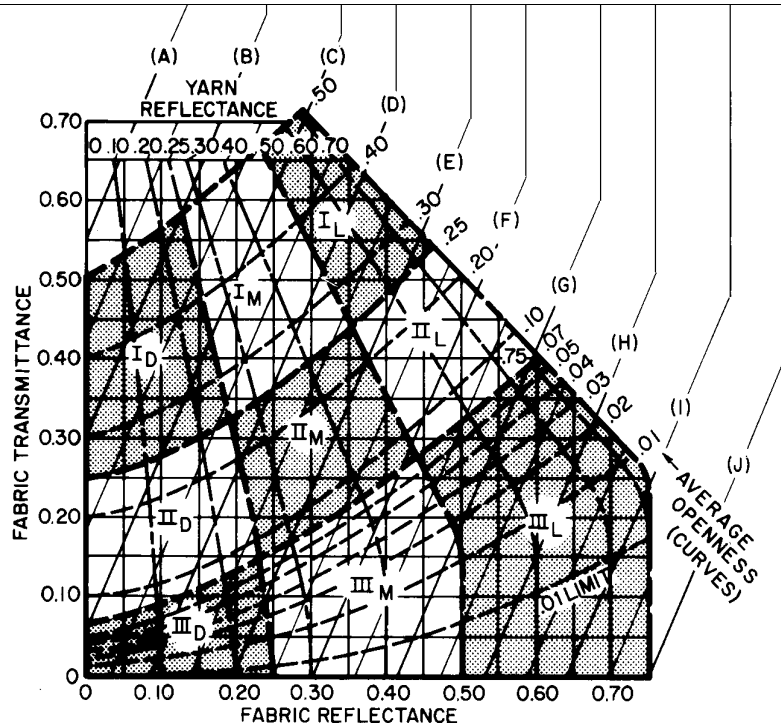
Glazing	Glass Trans- mission	Glazing SHGC (No Drapes)	IAC									
			A	B	C	D	E	F	G	H	I	J
Single glass												
3 mm clear	0.86	0.87	0.87	0.82	0.74	0.69	0.64	0.59	0.53	0.48	0.42	0.37
6 mm clear	0.80	0.83	0.84	0.79	0.74	0.68	0.63	0.58	0.53	0.47	0.42	0.37
13 mm clear	0.71	0.77	0.84	0.80	0.75	0.69	0.64	0.59	0.55	0.49	0.44	0.40
6 mm heat absorbing	0.46	0.58	0.85	0.81	0.78	0.73	0.69	0.66	0.61	0.57	0.54	0.49
13 mm heat absorbing	0.24	0.44	0.86	0.84	0.80	0.78	0.76	0.72	0.68	0.66	0.64	0.60
Reflective coated	—	0.52	0.95	0.90	0.85	0.82	0.77	0.72	0.68	0.63	0.60	0.55
	—	0.44	0.92	0.88	0.84	0.82	0.78	0.76	0.72	0.68	0.66	0.62
	—	0.35	0.90	0.88	0.85	0.83	0.80	0.75	0.73	0.70	0.68	0.65
	—	0.26	0.83	0.80	0.80	0.77	0.77	0.77	0.73	0.70	0.70	0.67
Insulating glass, 6 mm air space												
(3 mm out and 3 mm in)	0.76	0.77	0.84	0.80	0.73	0.71	0.64	0.60	0.54	0.51	0.43	0.40
Insulating glass 13 mm air space												
Clear out and clear in	0.64	0.72	0.80	0.75	0.70	0.67	0.63	0.58	0.54	0.51	0.45	0.42
Heat absorbing out and clear in	0.37	0.48	0.89	0.85	0.82	0.78	0.75	0.71	0.67	0.64	0.60	0.58
Reflective coated	—	0.35	0.95	0.93	0.93	0.90	0.85	0.80	0.78	0.73	0.70	0.70
	—	0.26	0.97	0.93	0.90	0.90	0.87	0.87	0.83	0.83	0.80	0.80
	—	0.17	0.95	0.95	0.90	0.90	0.85	0.85	0.80	0.80	0.75	0.75

Interior Solar Attenuation (IAC)**Notes:**

1. Interior attenuation coefficients are for draped fabrics.
2. Other properties are for fabrics in flat orientation.
3. Use fabric reflectance and transmittance to obtain accurate IAC values.
4. Use openness and yarn reflectance or openness and fabric reflectance to obtain the various environmental characteristics, or to obtain approximate IAC values.

Classification of Fabrics

- I = Open weave
 II = Semiopen weave
 III = Closed weave
- D = Dark color
 M = Medium color
 L = Light color



To obtain fabric designer (III_L, I_M, etc.). Using either (1) fabric transmittance and fabric reflectance coordinates, or (2) openness and yarn reflectance coordinates, find a point on the chart and note the designer for that area. If properties are not known, the classification may be approximated by eye as described in the note in [Figure 31](#).

To obtain interior attenuation (IAC). (1) Locate drapery fabric as a point using its known properties, or approximate using its fabric classification designer. For accuracy, use fabric transmittance and fabric reflectance; (2) follow diagonal IAC lines to lettered columns in the table. Find IAC value in selected column on line corresponding to glazing used. For example, IAC is 0.4 for 6 mm clear single glass with III_L drapery (Column H).

Note: Unlike specular transmittance, front and back directional-hemispherical transmittances are not necessarily equal.

To match the assumptions of the model, the specular component should be *excluded* from the transmittance but *included* in the reflectances. Since the shading layer is assumed to be an ideal diffuser, the above quantities are the same for all incident directions. In addition, the notation $\langle \rangle_D$ will be applied to various optical properties of specular glazings. This notation means the hemispherical average of the quantity over all incident directions and is the quantity labeled “diffuse” in Table 13. For example, for a particular glass layer j , $\langle T_j \rangle_D$ would be the hemispherical average transmittance of the glass layer, which is also the transmittance for ideally diffuse incident radiation.

Another addition to the notation is needed for discussing absorption in this section. In the treatment of unshaded multiple glazings, the notation $A_n^f(\theta)$ was used to denote the actual front absorption of the n th layer of an L -layer system. Since only one system was under consideration, no ambiguity could arise from the fact that the notation does not specifically reference the number of layers in the system. Here it will be necessary to discuss multi-layer systems that are subdivided into one or more subsystems. Since the actual absorption depends on the other layers in the system because of reflections from those layers and because it is referenced to the incident intensity on the front (or back) surface of the system, rather than on the specific layer, it is necessary to include the particular subsystem in the notation. The following notation will be used. We assume that the overall system has L layers that are numbered sequentially from outside to inside, as before. Now $A_{n:(M,N)}^f(\theta)$ is the actual front absorption of layer n in subsystem of layers M through N , and similarly for back absorption. In this notation, the front absorptance of layer n in the overall system, which previously was called $A_n^f(\theta)$, would now be denoted $A_{n:(1,L)}^f(\theta)$. Note that for the subsystem (M,N) the front absorptance $A_{n:(M,N)}^f$ is the fraction of the radiation incident on the front of layer M that is absorbed in layer n , while the back absorptance $A_{n:(M,N)}^b$ is the fraction of the radiation incident on the back side of layer N that is absorbed in layer n .

In all cases, we assume that there is a specular glazing of L layers, labeled as described in the section on Optical Properties of Multiple-Layer Glazing Systems in the discussion of unshaded glazing optical properties. The shading layer, denoted S , is not counted in this labeling. Differing locations of the shading layer are discussed in the following sections.

Exterior Shading by Overhangs, Fins, etc.

In this case, we neglect (1) reduction of the sky view by the shading and (2) reflection of diffuse radiation by the face of the shading seen by the glazing. It will usually be the case that this results in an overestimate of the heat flow, but exceptions are possible (e.g., highly reflective ground and light-colored overhang). Here the effect of the shading is simply to eliminate the direct beam radiation, and one is left with an unshaded glazing with diffuse radiation incident; the relevant optical properties are the hemispherical averages of those of the unshaded glazing system.

$$q = (E_d + E_r) \langle \text{SHGC} \rangle_D \quad (113)$$

The designer should be aware that because the diffuse solar radiation is small compared to that of the direct beam, reflection of direct beam radiation from other surfaces visible to the glazing can result in significant additional heat flow (e.g., beam radiation falling on the “wrong” side of a fin or overhang intended to shade an adjacent window).

Exterior Shading Layer

Examples of planar exterior shading layers include exterior louvers or venetian blinds. It is assumed that air has free flow between

the exterior shading system and the glazing system. Under these conditions, as Table 17 shows, the fraction of the energy absorbed in the shading that flows inward is small. If this energy flow is neglected, then the whole effect of the shading layer is to modify the intensity of the (diffuse) radiation incident on the unshaded glazing, and the heat flow is

$$q = [(1 - F_u)E_{DN} \cos \theta + E_d + E_r] \frac{T_S^{fH}}{1 - R_S^{bH} \langle R_{1,L}^f \rangle_D} \langle \text{SHGC} \rangle_D \quad (114)$$

where $\langle \text{SHGC} \rangle_D$ is for the unshaded glazing system. To compute the amount of energy absorbed in the shading layer, one must estimate the isolated-layer absorptances of the shading layer from

$$\begin{aligned} a_S^f &= 1 - T_S^{fH} - R_S^{fH} \\ a_S^b &= 1 - T_S^{bH} - R_S^{bH} \end{aligned} \quad (115)$$

When attached to the glazing, and using $S = 0$ to fit into the labeling scheme, the shading layer front absorptance is then

$$A_{S:(S,L)}^f = a_S^f + \frac{a_S^b T_S^{fH} \langle R_{1,L}^f \rangle_D}{1 - R_S^{bH} \langle R_{1,L}^f \rangle_D} \quad (116)$$

where $R_{1,L}^f$ refers to the unshaded glazing system. $R_{1,L}^f$ may either be obtained from Table 13 or calculated as described previously in the section on Solar-Optical Properties of Glazings. The addition to the heat flow in Equation (114) is then

$$\Delta q = [(1 - F_u)E_{DN} \cos \theta + E_d + E_r] A_{S:(S,L)}^f N_S \quad (117)$$

where the inward-flowing fraction N_S for the shading layer is taken from the appropriate line of Table 17.

Between-Glass Shading Layer

One must first identify the position of the shading layer within the L -layer glazing system, remembering that the labeling of glazing layers did not count the shading layer S . We count the layers, beginning with the one in contact with the exterior air, until we reach the layer next to the shading layer. Let the number of that layer be K . We now relabel the shading layer by setting $S = K + 1$ and relabel all subsequent glazing layers, making the one to the interior of S layer $K + 2$ (or $S + 1$), and continuing until we reach glazing layer L , which becomes $L + 1$ in the new labeling scheme. We now have an $L + 1$ layer system that consists of three parts: (1) an exterior glazing subsystem of $S - 1$ layers, (2) the shading layer S , and (3) an interior glazing subsystem, consisting of layers $S + 1$ to $L + 1$, a total of $(L + 1) - S$ or $L - K$ layers in all. Both the exterior glazing and interior glazing subsystems are assemblies of unshaded, specular glazing layers, and their optical properties are calculated by the methods described in the section on Optical Properties of Multiple-Layer Glazing Systems for unshaded glazings. The exterior and interior glazing subsystems will often be either a single or double glazing, and, if they are sufficiently common, their properties may then be found in Table 13.

For calculational purposes, it is convenient to consider two other subsystems, one consisting of the shading layer together with the exterior glazing, an S -layer subsystem consisting of layers 1 through S , and the other consisting of the shading layer together with the interior glazing, consisting of layers S through $L + 1$, a total of $L - S + 2$ or $L - K + 1$ layers. For the former subsystem, we will need the directional-hemispherical transmittance:

$$T_{1,S}^{fH}(\theta) = \frac{T_{1,S-1}(\theta)T_S^{fH}}{1 - R_S^{fH}\langle R_{1,S-1}^b \rangle_D} \quad (118)$$

and the hemispherical back reflectance (which is the same for all incident directions):

$$R_{1,S}^{bH} = R_S^{bH} + \frac{\langle R_{1,S-1}^b \rangle_D T_S^{bH} T_S^{fH}}{1 - R_S^{fH}\langle R_{1,S-1}^b \rangle_D} \quad (119)$$

For the latter subsystem, we need the hemispherical front reflectance:

$$R_{S,L+1}^{fH} = R_S^{fH} + \frac{\langle R_{S+1,L+1}^f \rangle_D T_S^{bH} T_S^{fH}}{1 - R_S^{bH}\langle R_{S+1,L+1}^f \rangle_D} \quad (120)$$

The directional-hemispherical transmittance of the total system is then

$$\begin{aligned} T_{1,L+1}^{fH}(\theta) &= \frac{T_{1,S}^{fH}(\theta)T_{S+1,L+1}^{fH}}{1 - R_{1,S}^{bH}\langle R_{S+1,L+1}^f \rangle_D} \\ &= \frac{T_{1,S-1}(\theta)T_S^{fH}T_{S+1,L+1}^{fH}}{[1 - R_S^{fH}\langle R_{1,S-1}^b \rangle_D][1 - R_{S,L+1}^{bH}\langle R_{S+1,L+1}^f \rangle_D]} \quad (121) \end{aligned}$$

The absorptances for the k th layer are for $k < S$

$$\begin{aligned} A_{k:(1,L+1)}^f(\theta) &= A_{k:(1,S-1)}^f(\theta) \\ &+ \langle A_{k:(1,S-1)}^b \rangle_D \frac{T_{1,S}^{fH}(\theta)}{1 - R_{S,L+1}^{fH}\langle R_{1,S-1}^b \rangle_D} \quad (122) \end{aligned}$$

for $k = S$

$$\begin{aligned} A_{k:(1,L+1)}^f(\theta) &= \frac{a_S^f T_{1,S-1}(\theta)}{1 - R_{S,L+1}^{fH}\langle R_{1,S-1}^b \rangle_D} \\ &+ \frac{a_S^b T_{1,S}^{fH}(\theta)\langle R_{S+1,L+1}^f \rangle_D}{1 - R_{1,S}^{bH}\langle R_{S+1,L+1}^f \rangle_D} \quad (123) \end{aligned}$$

for $k > S$

$$A_{k:(1,L+1)}^f(\theta) = \langle A_{k:(S+1,L+1)}^f \rangle_D \frac{T_{1,S}^{fH}(\theta)}{1 - R_{1,S}^{bH}\langle R_{S+1,L+1}^f \rangle_D} \quad (124)$$

The hemispherical average of the appropriate above equation then gives $\langle A_{k:(1,L+1)}^f \rangle_D$.

For convenience, we split the heat flow up into three parts: that due to transmitted direct beam radiation (subscript B), that due to transmitted diffuse beam and ground-reflected radiation (subscript d), and that due to energy absorbed in the various layers and flowing inward by the normal mechanisms of heat transfer (subscript a):

$$q = q_B + q_d + q_a \quad (125)$$

We note that q_B and q_d consist of diffusely distributed radiation in the solar wavelength range, while q_a is a heat flux. The quantities in Equation (125) are given by

$$q_B = E_{DN} \cos(\theta) T_{1,L+1}^{fH}(\theta) \quad (126)$$

$$q_d = (E_d + E_r) \langle T_{1,L+1}^{fH} \rangle_D \quad (127)$$

$$\begin{aligned} q_a &= E_{DN} \cos(\theta) \sum_{k=1}^{L+1} A_{k:(1,L+1)}^f(\theta) N_k \\ &+ (E_d + E_r) \sum_{k=1}^{L+1} \langle A_{k:(1,L+1)}^f \rangle_D N_k \quad (128) \end{aligned}$$

The values of the layer-specific inward-flowing fractions N_k are chosen from the appropriate lines of [Table 17](#). All types of shading should be considered equivalent when using [Table 17](#) with this simplified method; accordingly, corresponding entries in the lines for differing blind tilts should be averaged in the case of double glazing.

For systems with more than two glazing layers, for which no information exists in [Table 17](#), the following estimate should be used. If the glazing system contains no low-e coating, then information for double glazing with between-pane shading should be averaged; if the system contains one or more low-e coatings, then the line corresponding to low-e double glazing should be chosen. For $k < S$, use for N_k the value in [Table 17](#) corresponding to the outer glass; for $k = S$, use the value for the shading layer; and for $k > S$, use the value corresponding to the inner glass.

Interior Shading Layer

For interior shading, we can consider the shading layer S to form the $(L+1)$ th layer of an $(L+1)$ layer system. The total directional-hemispherical transmittance of this system is given by

$$T_{1,L+1}^{fH}(\theta) = \frac{T_{1,L}(\theta)T_S^{fH}}{1 - R_S^{fH}\langle R_{1,L}^b \rangle_D} \quad (129)$$

and the total diffuse transmittance of the system is the hemispherical average of this quantity is given by

$$\langle T_{1,L+1}^{fH} \rangle_D = \frac{\langle T_{1,L}(\theta) \rangle_D T_S^{fH}}{1 - R_S^{fH}\langle R_{1,L}^b \rangle_D} \quad (130)$$

In discussing layer absorptance, we need to consider a layer both in its role in the L -layer unshaded system and in the $(L+1)$ -layer system formed by adding the shading layer. The L -layer system is an unshaded one, so all quantities pertaining to that system can be calculated from Equations (60) through (65), (79), and (84) for the optical properties of multilayer, unshaded glazings above. If it is a sufficiently common system, its properties may be found in [Table 13](#), and the table values may be linearly interpolated to the desired incident angle; see also the previous section on Spectral Averaging of Glazing Properties and Examples 11, 12, and 13. The addition of the shading layer causes an additional contribution to the absorptance in each layer of the L -layer system due to the backward incidence of diffuse radiation reflected by the shade:

$$A_{k:(1,L+1)}^f(\theta) = A_{k:(1,L)}^f(\theta) + \langle A_{k:(1,L)}^b \rangle_D \frac{T_{1,L}(\theta) R_S^{fH}}{1 - R_S^{fH} \langle R_{1,L}^b \rangle_D} \quad (131)$$

and the hemispherical average of this quantity over incident direction is given by

$$\langle A_{k:(1,L+1)}^f \rangle_D = \langle A_{k:(1,L)}^f \rangle_D + \langle A_{k:(1,L)}^b \rangle_D \frac{\langle T_{1,L} \rangle_D R_S^{fH}}{1 - R_S^{fH} \langle R_{1,L}^b \rangle_D} \quad (132)$$

The absorptance in the shade layer is

$$A_{S:(1,L+1)}^f(\theta) \equiv A_{L+1:(1,L+1)}^f(\theta) = \frac{T_{1,L}(\theta) d_S^f}{1 - R_S^{fH} \langle R_{1,L}^b \rangle_D} \quad (133)$$

with, again, a hemispherical average given by

$$\langle A_{L+1:(1,L+1)}^f \rangle_D = \frac{\langle T_{1,L} \rangle_D d_S^f}{1 - R_S^{fH} \langle R_{1,L}^b \rangle_D} \quad (134)$$

The heat flow is calculated from Equations (125) through (128).

The inward-flowing fractions N_k in Equation (128) are chosen from Table 17 when possible. The most thermally resistive glazing system with interior shading in this table is double glazing. For higher resistance systems (low-e double glazing, triple glazing, or higher, etc.), there are three possible procedures:

1. Calculate the N_k ($k < S$) for the unshaded glazing, and for the shading layer ($k = S$), take the value from the Inner Shading Layer column of Table 17 for the system that is closest to the desired one.
2. Treat the shading layer as an additional (uncoated, unless the shading layer has low emissivity on the exterior side) glazing and calculate the N_k for the resulting $(L+1)$ -layer glazing.
3. Take N_1 , N_2 , and the value for the interior shading layer from the table entries for double glazing with interior shade, and take $N_k = N_2$ for all subsequent glazing layers. Using as an alternative assumption $N_L = N_2$ and $N_k = N_1$ for all $k < L$ will give an estimate of the range of error to be expected.

Method (1) will produce values of N_k for $k \leq L$ that tend to be too high, and a value of N_S ($S = L+1$) that may be too low. Method (2) will produce values of N_k for $k \leq L$ that tend to be too low and a value of N_S that also tends to be too low (since some heat that transfers outward by convection from layer S would be carried to the interior with an unsealed air space). By comparing the resulting solar energy fluxes using each of the three methods, one can obtain an estimate of the sensitivity of the results to uncertainty in calculating N_k .

Example 21. Calculate the solar energy flux through the glazing system of Example 10 with a closed interior translucent light shade, under the conditions of Example 5.

Solution: From Table 21, we take the properties of a translucent light shade to be $T_S^{fH} = 0.25$, $R_S^{fH} = 0.60$, and $\alpha_S^f = 0.15$. We assume that the reflectance is diffuse and that the transmittance is independent of incident angle. By using method (1) above for determining the inward-flowing fractions, we can take the values of $N_1 = 0.064$ and $N_2 = 0.821$ calculated in Example 14, and we take $N_S = 0.85$ from the entry in Table 17 for double glazing with interior shade. We use the property values for an incident angle θ of 63.2° (from Example 6) that were calculated for the unshaded glazing in Example 11: $T_{1,2}(63.2^\circ) = 0.244$,

$R_{1,2}^f(63.2^\circ) = 0.446$, $R_{1,2}^b(63.2^\circ) = 0.444$, $A_{1:(1,2)}^f(63.2^\circ) = 0.289$, $A_{1:(1,2)}^b(63.2^\circ) = 0.144$, $A_{2:(1,2)}^f(63.2^\circ) = 0.022$, $A_{2:(1,2)}^b(63.2^\circ) = 0.167$. We use the hemispherical average properties calculated in Example 12: $\langle T_{1,2} \rangle_D = 0.277$, $\langle R_{1,2}^f \rangle_D = 0.405$, $\langle R_{1,2}^b \rangle_D = 0.442$, $\langle A_{1:(1,2)}^f \rangle_D = 0.271$, $\langle A_{1:(1,2)}^b \rangle_D = 0.138$, $\langle A_{2:(1,2)}^f \rangle_D = 0.036$, and $\langle A_{2:(1,2)}^b \rangle_D = 0.141$. In the shaded fenestration, the shade comprises layer 3 (i.e., $S = 3$); the total transmittance at an incident angle of 63.2° is calculated from Equation (129).

$$T_{1,S}^{fH}(63.2^\circ) = \frac{T_{1,2}(63.2^\circ) T_S^{fH}}{1 - R_S^{fH} \langle R_{1,2}^b \rangle_D} = \frac{(0.244)(0.25)}{1 - (0.60)(0.442)} = 0.083$$

The layer absorptances are calculated from Equation (131):

$$\begin{aligned} A_{1:(1,S)}^f(63.2^\circ) &= A_{1:(1,2)}^f(63.2^\circ) + \langle A_{1:(1,2)}^b \rangle_D \frac{T_{1,2}(63.2^\circ) R_S^{fH}}{1 - R_S^{fH} \langle R_{1,2}^b \rangle_D} \\ &= 0.289 + (0.138) \frac{(0.244)(0.60)}{1 - (0.60)(0.442)} = 0.316 \end{aligned}$$

$$\begin{aligned} A_{2:(1,S)}^f(63.2^\circ) &= A_{2:(1,2)}^f(63.2^\circ) + \langle A_{2:(1,2)}^b \rangle_D \frac{T_{1,2}(63.2^\circ) R_S^{fH}}{1 - R_S^{fH} \langle R_{1,2}^b \rangle_D} \\ &= 0.022 + (0.141) \frac{(0.244)(0.60)}{1 - (0.60)(0.442)} = 0.050 \end{aligned}$$

and Equation (133):

$$A_{S:(1,S)}^f(63.2^\circ) = \frac{T_{1,2}(63.2^\circ) \alpha_S^f}{1 - R_S^{fH} \langle R_{1,2}^b \rangle_D} = \frac{(0.244)(0.15)}{1 - (0.60)(0.442)} = 0.050$$

From this we calculate the solar heat gain coefficient, using Equation (79),

$$\begin{aligned} \text{SHGC}(63.2^\circ) &= T_{1,S}^f(63.2^\circ) + \sum_{k=1}^{S(=3)} N_k A_{k:(1,2)}^f(63.2^\circ) \\ &= T_{1,S}^f(63.2^\circ) + N_1 A_{1:(1,S)}^f(63.2^\circ) \\ &\quad + N_2 A_{2:(1,S)}^f(63.2^\circ) + N_S A_{S:(1,S)}^f(63.2^\circ) = (0.083) \\ &\quad + (0.064)(0.316) + (0.821)(0.050) + (0.85)(0.050) = 0.187 \end{aligned}$$

The corresponding hemispherical average properties are calculated from Equations (130), (131), and (134):

$$\langle T_{1,S}^{fH} \rangle_D = \frac{\langle T_{1,2} \rangle_D T_S^{fH}}{1 - R_S^{fH} \langle R_{1,2}^b \rangle_D} = \frac{(0.277)(0.25)}{1 - (0.60)(0.442)} = 0.094$$

$$\begin{aligned} \langle A_{1:(1,S)}^f \rangle_D &= \langle A_{1:(1,2)}^f \rangle_D + \langle A_{1:(1,2)}^b \rangle_D \frac{\langle T_{1,2} \rangle_D R_S^{fH}}{1 - R_S^{fH} \langle R_{1,2}^b \rangle_D} \\ &= 0.271 + (0.138) \frac{(0.277)(0.25)}{1 - (0.60)(0.442)} = 0.302 \end{aligned}$$

$$\begin{aligned} \langle A_{2:(1,S)}^f \rangle_D &= \langle A_{2:(1,2)}^f \rangle_D + \langle A_{2:(1,2)}^b \rangle_D \frac{\langle T_{1,2} \rangle_D R_S^{fH}}{1 - R_S^{fH} \langle R_{1,2}^b \rangle_D} \\ &= 0.036 + (0.141) \frac{(0.277)(0.60)}{1 - (0.60)(0.442)} = 0.068 \end{aligned}$$

$$\langle A_{S:(1,S)}^f \rangle_D = \frac{\langle T_{1,2} \rangle_D \alpha_S^f}{1 - R_S^{fH} \langle R_{1,2}^b \rangle_D} = \frac{(0.277)(0.15)}{1 - (0.60)(0.442)} = 0.057$$

Using these values, one calculates the diffuse solar heat gain coefficient from Equation (84):

$$\begin{aligned}
\langle \text{SHGC} \rangle_D &= \langle T_{1,s}^f \rangle_D + \sum_{k=1}^{S(=3)} N_k \langle A_{k:(1,2)}^f \rangle_D \\
&= \langle T_{1,s}^f \rangle_D + N_1 \langle A_{1:(1,s)}^f \rangle_D + N_2 \langle A_{2:(1,s)}^f \rangle_D + N_3 \langle A_{3:(1,s)}^f \rangle_D \\
&= 0.094 + (0.064)(0.302) + (0.821)(0.068) + (0.85)(0.057) \\
&= 0.218
\end{aligned}$$

In Example 7, the incident solar irradiances are calculated: $E_{DN}\cos(63.2^\circ) = 388 \text{ W/m}^2$, $E_d\cos(63.2^\circ) = 93.5 \text{ W/m}^2$, and $E_r\cos(63.2^\circ) = 86.6 \text{ W/m}^2$. From these values, the solar energy flux is calculated from Equations (92), (97), and (100):

$$\begin{aligned}
q_s &= q_b + q_d = [E_{DN}\cos(63.2^\circ)]\text{SHGC}(63.2^\circ) + (E_d + E_r)\langle \text{SHGC} \rangle_D \\
&= [388](0.243) + (93.5 + 86.6)(0.218) = 133 \text{ W/m}^2
\end{aligned}$$

VISUAL AND THERMAL CONTROLS

The ideal fenestration system permits optimum light, heat, ventilation, and visibility; minimizes moisture and sound transfer between the exterior and the interior; and produces a satisfactory physiological and psychological environment. The controls of an optimum system will react to varying climatological and occupant demands. Fixed controls may have operations or cost advantages or both but do not react to physical and psychological variations. Variable controls are, therefore, more effective in energy conservation and environmental satisfaction.

Operational Effectiveness of Shading Devices

Shading devices vary in their operational effectiveness. Some devices such as overhangs, light shelves, and tinted glazings do not require operation, have long life expectancies, and do not degrade significantly over their effective life. Other types of shading devices, especially operable interior shades, may have reduced effectiveness due to less than optimal operation and degradation of effectiveness over time. It is important to evaluate operational effectiveness when considering the actual heat rejection potential of shading devices.

The performance of shading devices for the reduction of peak cooling loads and annual energy use should account for operational effectiveness or reliability in actual operation. Passive devices, such as architectural elements and glazing tinting, are considered 100% effective in operation. Glazing coatings and adherent films may degrade over time. Shade screens are removable and may be assumed to be operated seasonally, but in any given population of users, some will remain in place all year long and some will not be installed or removed at optimum times. Automated shading devices controlled for optimum thermal operation are considered more effective than manual devices, but controls require ongoing maintenance,

and some occupants may object to the lack of personal control with totally automated devices. Automated shading devices may also be operated for nonthermal purposes such as glare and daylighting optimization, and this may reduce thermal effectiveness. Manually operated devices will be subject to wide variation in use effectiveness, and this diversity in effective use should be considered when evaluating performance.

Indoor Shading Devices

While the thermal comfort of occupants within the glazed space may be paramount to the HVAC designer, other factors (see Table 22 and Figure 31) that should be considered, some of which may be more important to the user, include the following:

Radiant Energy Protection. Unshaded fenestration products become sources of radiant heat by transmitting short-wave solar radiation and by emitting long-wave radiation to dissipate some of the absorbed solar energy. In winter, glass temperatures usually fall below room air temperature, which may produce thermal discomfort to occupants near the fenestration. In summer, individuals seated near the unshaded fenestration product may experience discomfort from both direct solar rays and long-wave radiation emitted by sun-heated glass. In winter, loss of heat by radiation to cold glass can also cause discomfort. Tightly woven, highly reflective drapes minimize such discomfort; drapes with high openness factors are less effective because they permit short-wave and long-wave radiation to pass more freely. Light-colored shading devices with maximum total surface usually provide the best protection since they absorb less heat and tend to lose heat readily by convection to the conditioned air.

Outward Vision. Outward vision is normally desirable in both business and living spaces. Open-weave, dark-colored fabrics of uniform pattern permit maximum outward vision, while uneven pattern weaves reduce the ability to see out. A semiopen weave modifies the view without completely obscuring the outdoors. Tightly woven fabrics block off outward vision completely.

Privacy. Venetian blinds, either vertical or horizontal, can be adjusted and, when completely closed, afford full privacy. When draperies are closed, the degree of privacy is determined by their color and tightness of weave and the source of the principal illumination. To obscure the view so completely that not even shadows or silhouettes can be detected, fully opaque materials are used. Generally, the more brightly lit side of a partially shaded glazing is the most visible from the opposite side, making the interior fairly private in daytime, but not at night.

Brightness Control. Visual comfort is essential in many occupied areas, and freedom from glare is an important factor in performing tasks. *Discomfort glare* is produced by uneven brightnesses in occupied spaces, with areas or spots that are much brighter than

Table 23 Summary of Environmental Control Capabilities of Draperies

Item	Designator (Table 22 and Figure 31)								
	I _D	I _M	I _L	II _D	II _M	II _L	III _D	III _M	III _L
1. Protection from direct solar radiation and long-wave radiation to or from window areas	Fair	Fair	Fair	Fair	Good	Good	Fair	Good	Good
2. Effectiveness in allowing outward vision through fenestration	Good	Good	Fair	Fair	Fair	Some	None	None	None
3. Effectiveness in attaining privacy (limiting inward vision from outside)	None	None	Poor ^a Good ^a	Poor	Fair	Fair ^a Good ^a	Good ^b	Good ^b	Good ^b
4. Protection against excessive brightness and glare from sunshine and external objects	Mild	Mild	Mild ^c Poor ^c	Good	Good	Good ^c Poor ^c	Good	Good	Good ^c Poor ^c
5. Effectiveness in modifying unattractive or distracting view out of window	Little	Little	Some	Some	Good	Good	Blocks	Blocks	Blocks

^aGood when bright illumination is on the viewing side.

^bTo obscure view completely, material must be completely opaque.

^cPoor rating applies to white fabric in direct sunlight. Use off-white color to avoid excessive transmitted light.

surrounding surfaces. Windows themselves, when they look out onto bright skies or brightly reflecting surfaces, can be glare sources if care is not taken to keep surround brightnesses comparable. A maximum brightness ratio of about 3 to 1 is sometimes quoted. Moderation of this ratio can be achieved through the use of interior furnishings and wall coverings, which on average have moderately high diffuse reflectances and access to admitted daylight. Conversely, dark interior surfaces, and those shaded from daylight illumination, will accentuate the brightness difference between the window and its surroundings. Interior surface brightness can also be elevated by ample use of interior electric lighting, but this can have adverse consequences for the building's energy use. In general, larger window apertures admit more sunlight, increasing interior brightnesses without affecting the perceived brightness of the window, all other things being equal.

An important guideline is the dictum that direct sunlight must not strike the eye, and reflected sunlight from bright or shiny surfaces is equally disturbing and even disabling. A tightly woven white fabric with high solar transmittance attains such brilliance when illuminated by direct sunshine that, by contrast with its surroundings, it creates excessive glare. Off-white colors should be used so their surface brightness is not too great. Venetian blinds permit considerable light to enter by interreflection between slats. When two shading devices are used, the one on the inside (away from the fenestration product) should be darker and more open. With this arrangement, the inside device can be used to control brightness for the other shading devices and, when used alone, to reduce brightness while still permitting some view of the outside.

View Modification. When the view is unattractive or distracting, draperies modify the view to some degree, depending on the fabric weave and color (summarized in Table 23), but the fenestration product remains as an effective connection to the outside.

Sound Control. Indoor shading devices, particularly draperies, can absorb some of the sounds originating within the room but have little or no effect in preventing outdoor sounds from entering. For excessive internally generated sound, the usual remedy is to apply acoustical treatment to the ceiling and other room surfaces. While these materials can be effective in controlling sound, they are often located on the two horizontal surfaces (ceiling and floor) and leave the opposing vertical surfaces of glass and bare wall to reflect sound. The noise reduction coefficient (NRC = average absorbance coefficient at four frequencies) for venetian blinds is about 0.10, compared to 0.02 for glass and 0.03 for plaster. For drapery fabrics at 100% fullness, NRC ranges from 0.10 to 0.65, depending on the tightness of weave. Class III (tightly woven) fabrics have NRC values of 0.35 to 0.65. Figure 32 shows the relationship between NRC and openness factor for fabrics of normal weight.

Example 22. To select a drapery fabric, consider the five environmental factors listed in Table 23. Choose a fabric designator that has suitable performance for all the factors important to the case being considered. If this is not possible, make compromises resulting in an acceptable designator. Determine from Table 23 if the IAC for the chosen designator is satisfactory. Specific cases follow:

1. Where modification of a distracting view is necessary but a degree of outward vision is needed and an IAC of 0.50 with 6 mm gray glass is satisfactory (see Table 23, Item 5), select II_M or II_L ; from Item 2, select II_M . The IAC for II_M on Table 23 is approximately 0.46, therefore satisfactory.
2. Where protection from radiation is paramount and minimum IAC is necessary (see Table 23, Item 1), select a closed weave, III_M or III_L . Since the IAC for III_L is lowest (see Table 23), choose III_L .
3. When good outward vision is desired, together with some reduction in brightness, choose I_M or I_D (Table 23).

Double Drapery

Double draperies (two sets of drapery covering the same area) have a light, open weave on the fenestration product side for out-

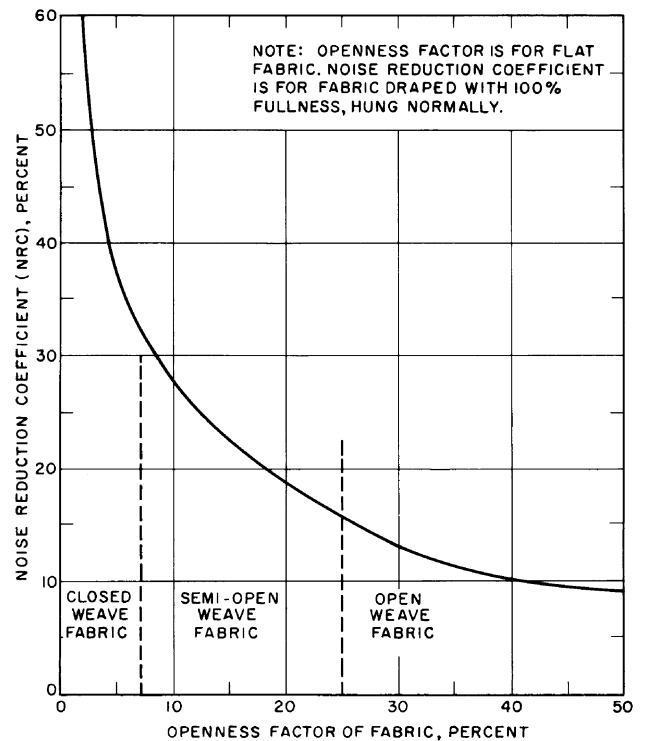


Fig. 32 Noise Reduction Coefficient Versus Openness Factor for Draperies

ward vision and daylight when desired and a heavy, closed weave or opaque drapery on the room side to block out sunlight and provide privacy when desired. When properly selected and used, double draperies can provide a reduced U-factor and a lowered IAC.

The reduced U-factor results principally from adding a semi-closed air space to the barrier. A U-factor of about $1.80 \text{ W}/(\text{m}^2 \cdot \text{K})$ is achieved using double draperies with single glass, and about $1.17 \text{ W}/(\text{m}^2 \cdot \text{K})$ with insulating glass.

To most effectively reduce solar heat gain, the drapery exposed to sunlight should have high reflectance and low transmittance. The light, open-weave drapery should be opened when the heavy drapery is closed to prevent entry of sunlight.

Properly used double draperies give (1) extreme flexibility of vision and light intensity, (2) a lowered U-factor and IAC, and (3) an improved comfort condition, since the room-side drapery is more nearly at room temperature. Table 23 gives characteristics of individual draperies. For large areas, the IAC should be calculated in detail to determine the cooling load.

AIR LEAKAGE

Infiltration Through Fenestration

Air infiltration through fenestration products affects occupant comfort and energy consumption. Infiltration should not be confused with ventilation. Infiltration is the uncontrolled inward leakage of air caused by pressure effects of wind or differences in air density, such as the stack effect. While fenestration products can be operated to intentionally provide natural ventilation and increase comfort, infiltration should be reasonably minimized to avoid unpleasant accompanying problems. If additional air is required, controlled ventilation is preferable to infiltration. Mechanical ventilation provides air in a comfortable manner and when desired. For infiltration, however, the peak supply is more likely to occur as an

uncomfortable draft and when least desired, such as during a storm or the coldest weather.

ASHRAE/IESNA *Standard* 90.1, ASHRAE's energy standard for all buildings other than low-rise residential buildings, establishes an air leakage maximum of XX per square metre of gross fenestration product area (XX/m² for swinging entrance doors and revolving doors). This air leakage is as determined in accordance with NFRC 400 and ASTM *Standard* E 283 and allows direct comparison of all fenestration products: operable and fixed, windows and doors.

Most manufactured fenestration products achieve these reasonable standards of maximum air infiltration. However, products that do not completely seal, such as jalousie windows or doors, are not likely to do so and are most appropriate for installation in unconditioned spaces.

For products achieving this infiltration standard, the energy consumption due to infiltration is likely to be significantly less than the energy associated with U-factor and solar heat gain coefficient. Also, while overall air infiltration is a significant component in determining a building's heating and cooling loads, the infiltration through fenestration products meeting the above standard is generally likely to be a small portion of that total. [Chapter 26](#) presents calculation procedures for air infiltration.

Indoor Air Movement

Because supply air grilles are frequently located directly below fenestration products, air sweeps the interior glass surface. Heated supply air should be directed away from the glass to prevent large temperature differences between the center and edges of the glass. These thermal effects must be considered, particularly when annealed glass is used and air is forced over the glass surface during the heating season. Direct flow of heated air over the glass surface can increase the heat transfer coefficient and the temperature difference, causing a substantial increase in heat loss; it may also lead to thermally induced stress and risk of glass breakage.

Systems designed predominantly for cooling lower the glass temperature and rapidly pick up the cooling load. Both tend to improve the comfort condition of the space. However, the air-conditioned space has an increased net heat gain caused by (1) increase in the solar heat gain coefficient (SHGC) due to delivery of a larger portion of the absorbed heat to the indoor space, (2) increase in the fenestration U-factor because of the greater convection effect at the indoor surface, and (3) increase in the air-to-air temperature difference since supply air rather than room air is in contact with the indoor glass surface. The principal increase in heat gain with clear glass is the result of the higher U-factor and the greater air-to-air temperature difference.

DAYLIGHTING

DAYLIGHT PREDICTION

Daylighting is the illumination of building interiors with sunlight and sky light and is known to affect visual performance, lighting quality, health, human performance, and energy efficiency. In many European countries with predominantly cloudy skies, there are codes regulating minimum window size, minimum daylight factor, and window position in order to provide views to all occupants and to create a minimum interior brightness level. For practical reasons, daylighting provides backup interior illumination in the event of power outages. Daylighting may have some positive or negative health effects on the skin, eyes, hormone secretion, and mood. Its temporal variation, intensity, spectral content, and diurnal and temporal variation may be used to combat jet lag, sick building syndrome, and other health problems.

In terms of energy efficiency, daylighting can provide substantial whole-building energy reductions in nonresidential buildings

through the use of electric lighting controls. Daylight admission can displace the need for electric lighting at the perimeter zone with vertical windows and at the core zone with skylights. Lighting and its associated cooling energy use constitute 30 to 40% of a nonresidential building's energy use. Energy use reductions can be achieved, perhaps less reliably, in residential buildings with manual or automated switching of electric lights on and off to match space occupancy. For internal load-dominated buildings, daylight admission must be balanced against solar heat admission to achieve optimum energy efficiency. Since the heat gains from solar radiation typically define peak load conditions, daylighting is also a very effective method of decreasing peak demand. The use of daylighting can not only decrease annual operating costs through energy efficiency but may also reduce capital cost due to mechanical downsizing.

For conventional sidelit nonresidential buildings, three fundamental relationships for daylight optimization are given as a function of (1) glazing properties and (2) window area or the **window-to-wall area ratio** (WWR), which is defined as the ratio of the transparent glazing area to the exterior floor-to-floor wall area:

1. Annual cooling energy use (including fan energy use) increases linearly with solar radiation admission, as indicated by the product of SHGC and WWR, but is affected by decreases in electric lighting heat gains.
2. Annual lighting energy use decreases exponentially/asymptotically with daylight admission, as indicated by the product of T_v and WWR.
3. Annual heating energy use (including fan energy use) increases linearly with decreased lighting heat gains.

[Figure 33](#) illustrates the first two relationships for a prototypical nonresidential building. A similar relationship can be demonstrated with skylights.

To determine the fenestration design that achieves an optimum balance between daylight admission and solar rejection requires iterative calculations where the glazing area and/or glazing solar-optical properties are varied parametrically. For each case, the following general steps should be taken for each hour over a year:

1. **Interior Daylight Illuminance.** Determine the building characteristics, configuration, outdoor design conditions, and operating schedules as described in the section on Initial Design Considerations in [Chapter 29](#). These include building orientation, exterior obstructions, ground reflectance, etc. Determine the depth from the window wall for each electric lighting zone. Typical sidelighting windows can effectively daylight the perimeter zone to a depth of 1.5 times the head height of the window. In private offices, one dimming zone is typically cost-effective, while in open plan offices, two zones are cost-effective.

Select a typical task location within each of the lighting zones. Determine interior daylight illuminance due to all window and skylight sources at these locations. Interior illuminance may be determined using computer simulation tools or physical scale models. Comprehensive explanations of simple and computer-based tools are available (IEA 1999). The majority of these tools can model simple box geometry with noncomplex fenestration systems. Some advanced simulation tools, such as Radiance (Ward 1990) and Adeline (Erhorn and Dirksmöller 2000), are capable of modeling complex geometry and fenestration systems with adequate bidirectional solar-optical data, but this capability is not routine.

2. **Lighting Energy Use.** Determine the type of lamps, ballasts, and control system to be used in the perimeter zones. Determine whether the lamp is capable of being dimmed or switched. For example, fluorescent lamps can be dimmed, while metal halides cannot be switched or dimmed. Cold, outdoor applications of some lamps may prevent switching. For electronic dimming bal-

lasts, obtain dimming power and light output characteristics. Obtain control specifications to determine how the system will respond to available light; dead-band ranges, response times, and commissioning will affect the sensitivity and accuracy of the system. The type of switching (on-off, bilevel, multilevel, and continuous dimming controls) will be dictated by both the type of lamp and space use.

Determine the task illuminance design set point for each zone. Determine the percentage electric lighting power reduction F_{daylight} [see Equation (135)] that will result with automatic daylight controls, and apply to the installed wattage. Simplified methods for calculating lighting power reductions based on task illuminance levels are given in Robbins (1986). More sophisticated programs (Choi and Mistrick 1999) model commercially available photosensor dimming control systems (typically located in the ceiling above the work plane task) more rigorously; the spectral and bidirectional response of the photosensor to incident flux is used to determine voltage output, which is then used by the ballast controller algorithm to determine the lighting power reduction. Response delays and commissioning set points will further affect this predicted output. Lights may also be switched manually, but there are no modeling prediction tools for manual switching. Field tests (Jennings et al. 1999) indicate that with bilevel switching, 45% of the lighting zone-hours were at less than full power lighting, with 28% at only one-third of full lighting output levels. Manual switching occurred less in public spaces. Occupancy and other types of switching may occur as well and should be accounted for as a confounding effect with any daylighting controls.

3. **Mechanical Energy Use.** Determine mechanical energy use due to the fenestration loads and reduced electric lighting heat gains.

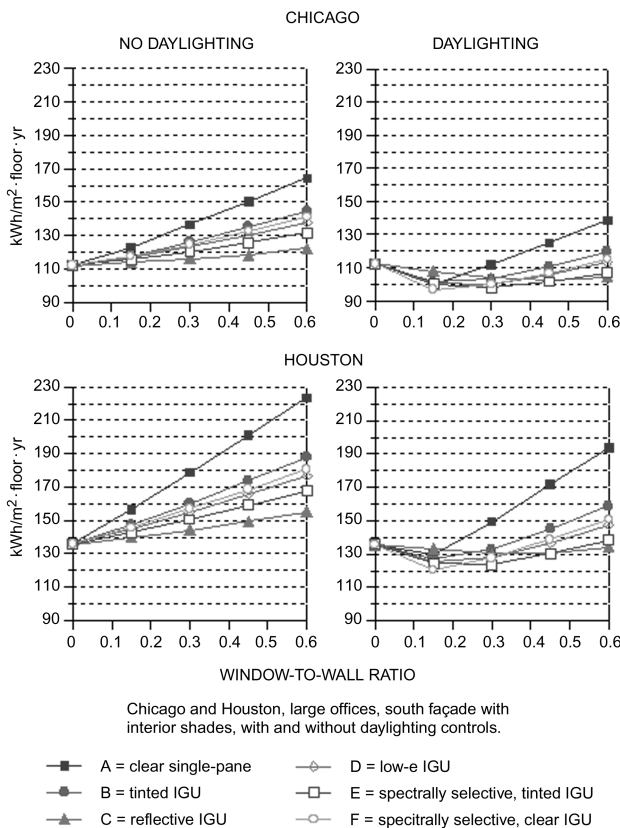


Fig. 33 Window-to-Wall Ratio Versus Annual Electricity Use ($\text{kWh}/\text{m}^2 \cdot \text{floor} \cdot \text{year}$)

Fenestration heat gains and losses may be computed using the section on Determining Fenestration Energy Flow. Instantaneous lighting heat gains q_{el} , described by Equation (1) in Chapter 29, must be multiplied by the power reduction factor F_{daylight} .

Mechanical loads and energy use may then be determined as described in Chapter 29. There have been many studies investigating the magnitude of change in heating and cooling energy use associated with reductions of lighting energy use in nonresidential buildings, as will be realized with daylighting controls. In a DOE-2.1E simulation study (Sezgen and Koomey 2000), the greatest savings were generated in hospitals, large offices, and large hotels; for every \$1.00 saved through lighting energy efficiency, additional savings as a result of reduced HVAC were \$0.26, \$0.16, and \$0.14, respectively. These results emphasize the need to include HVAC effects when assessing the impact of daylighting. Simplified design tools are available that enable one to conduct such parametric runs for preliminary analysis. For vertical windows, the BEEM program can be used to determine the relative impacts of daylighting on energy use, peak demand, and costs for a given window and lighting control system (Rundquist 1991). Skylighting tools based on regressions using DOE-2 data or simplified DOE-2 procedures are also available (AAMA 1988, Heschong et al. 1998). More comprehensive building energy prediction tools combined with daylighting algorithms, such as DOE-2.1E (Winkelmann 1983), implement hour-by-hour calculations using existing weather data and enable one to evaluate glare, visual comfort, and quality of light as well.

In the United States, a general rule has been that the fenestration area should be at least 20% of the floor area. In Europe, a similar rule was based on a minimum illumination value on the normal work plane from a standard overcast sky condition. In general, it is more energy-efficient to use larger window areas to elevate interior surface brightnesses as a glare reduction strategy than to increase interior electric lighting levels. As window area increases, interior brightness increases while window brightness remains the same. Of course there are mitigating considerations, such as the higher cost of larger windows and increased heat transfers through larger windows. The latter problem can be mitigated through the use of insulating multiple-pane windows and special coatings to reduce solar gain without serious loss of light transmission, as discussed in the section on Selecting Fenestration.

The secondary visual benefit of fenestration is the amount and quality of light it produces in the work environment. One general rule determined the need for auxiliary electric light by assuming that daylight was adequate for a depth of two-and-one-half times the height of the fenestration product into the room based on a normal sill height. To prevent excessive glare, all fenestration should have sun controls. Variable and removable controls are often more effective in daylight than fixed controls.

For more accurate evaluation of daylight distribution within a space, several prediction tools, such as the *Recommended Practice of Daylighting* (IESNA 1999), are available. This practice shows a simple way of calculating the daylight distribution on the work plane from windows and skylights with and without controls. Many other daylight prediction tools calculate illuminance from radiant flux transfer or ray tracing.

Any or all of the various daylight prediction tools can be used to compare the relative value of daylight distribution from alternative fenestration systems, but ultimately the designer must evaluate costs and benefits to choose between alternative designs. This may be based on energy use or, more properly, on overall costs and benefits to the client. Also, the negative possibility of total loss of productivity from an electric brown-out in a space with no natural ventilation or daylight may be as important as the benefits of many energy-saving schemes.

LIGHT TRANSMITTANCE AND DAYLIGHT USE

When daylight is to be the primary lighting system, the minimum expected daylight in the building must be calculated for the building performance cycle and integrated into the lighting calculations. IESNA (1999) gives daylight design and calculation procedures. In some glazing applications, such as artists' studios and showrooms, maximum transmittance may be required for adequate daylighting of the interior. Regular clear glass, produced by float, plate, or sheet process, may be the logical choice.

When daylight is a supplementary light source, the electric lighting can be designed independently of the daylight system. However, adequate switching must be included in the electric distribution to substitute available daylight for electric lighting by automatic or prescribed manual control whenever possible and practical. Photosensitive controls automatically adjust shading devices to provide uniform illumination and reduce energy consumption. Manual control is less effective.

Buildings with large areas of glass usually have insulating glass units with clear, tinted, or reflective coatings. The tinted and reflecting units reduce the brightness contrast between fenestration products and other room surfaces and provide a relatively glare-free environment for most daylight conditions.

Tables 13 and 24 list typical solar energy transmittances and daylight transmittances for various glass types. Manufacturers' literature has more appropriate values.

The color of glass chosen for a building depends largely on where and how it is used. For commercial building lobbies, showroom fenestration products, and other areas where maximum visibility from exterior to interior is required, regular clear glass is generally best. Clear glass with a low-e coating is also suitable for these locations, including for retail storefronts, as it only decreases the light transmittance by 10% or so. For other glass areas, a tinted glass may best complement the interior colors. Bronze, gray, and reflective-film glasses also give some privacy to building occupants during daylight hours. Patterned, etched, or sandblasted glass that diffuses lighting is available. In warm climates, a tinted outer glass in an insulated double-pane system can have solar heat gain rejection benefits, while providing good color rendering illumination of the interior without apparent color.

The primary purpose of a fenestration product is not just to save energy but to provide a view of the exterior. One sees out of a fenestration product by virtue of the light from the outside that comes through that fenestration product into the occupant's eyes. The light from outside is valuable not only for views of the outdoors but for providing daylight illumination of the interior.

Some buildings are designed especially to use the daylight coming through fenestration systems in displacing electric lighting and

its attendant energy costs. Using daylighting to displace electric lighting benefits the energy bill directly through reduced direct consumption by the lighting systems involved and indirectly through reduced electrically produced heat gain that may have to be removed by the air-conditioning system.

The light-transmitting properties of fenestration systems are therefore of great importance, not only for permitting views of the outdoors but also for admitting daylight to reduce electric lighting. It is conceivable that one could design a fenestration product with excellent solar heat gain performance for hot climates (meaning a very low solar heat gain coefficient) but very poor view and daylight illumination performance. If this problem is bad enough, it can cause occupants to turn on electric lights indoors during the day-time, which adds to the electric bill and possibly causes problems of thermal discomfort as well.

The light-transmitting property of a fenestration product is called the visible **transmittance** T_v . It is similar to the solar-weighted solar transmittance, except that an additional weighting function is needed, in this case to account for the spectral response of the human eye.

In most applications, it is important to have a high visible transmittance. In northern climates, a good solar heat gain is also important for offsetting wintertime heating costs. In southern climates, a low solar heat gain is good for offsetting summertime cooling costs. In the latter situation, it is difficult to have both a high visible transmittance and a low solar heat gain coefficient. Figures 34 and 35 show a plot of visible transmittance versus SHGC for a number of glazing systems covering a range of spectral selectivities. The data are for normal incidence and a single, ASTM standard solar spectral distribution.

A rule of thumb is to select a glazing unit having a visible transmittance greater than its shading solar heat gain coefficient, especially if daylighting strategies will be used in the building. For maximum light with minimum solar gain, there are fenestration products available having a visible transmittance 1.4 times the SHGC.

Three different zones are delineated on Figure 35. In the **neutral zone**, it is possible to have colorless glazing systems, meaning glazings with approximately uniform transmittance over the visible spectrum. Of course, one can have glazings in this zone with color, but this is not necessary. In the **color zone**, the only way to achieve higher visible transmittance for a given level of solar heat gain coefficient is by stripping off some of the red and blue wavelengths at the edges of the V- λ function with a spectrally selective glazing transmittance, imparting color to the transmitted radiation (or by other-

Table 24 Daylight Transmittance for Various Types of Glass

Type of Glass	Visible Transmittance T_v
3 mm regular sheet or float glass	0.86 to 0.91
3 mm gray sheet	0.31 to 0.71
5 mm gray sheet	0.61
5.5 mm gray sheet	0.14 to 0.56
6 mm gray sheet	0.52
6 mm green/float glass	0.75
6 mm gray plate glass	0.44
6 mm bronze plate glass	0.49
13 mm gray plate glass	0.21
13 mm bronze plate glass	0.25
Coated glasses (single, laminated, insulating)	0.07 to 0.50

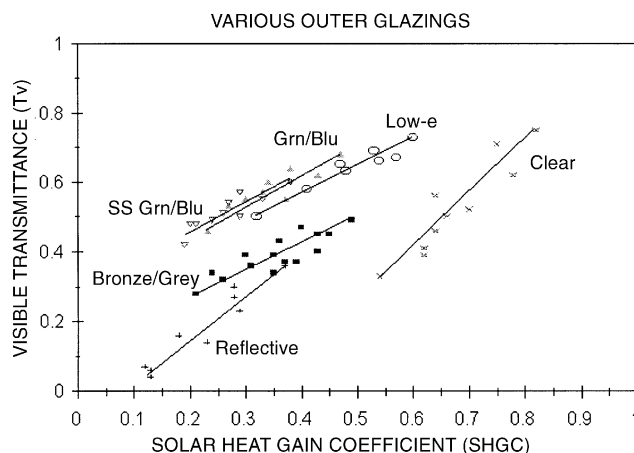


Fig. 34 Visible Transmittance Versus SHGC for Several Glazings with Different Spectral Selectivities

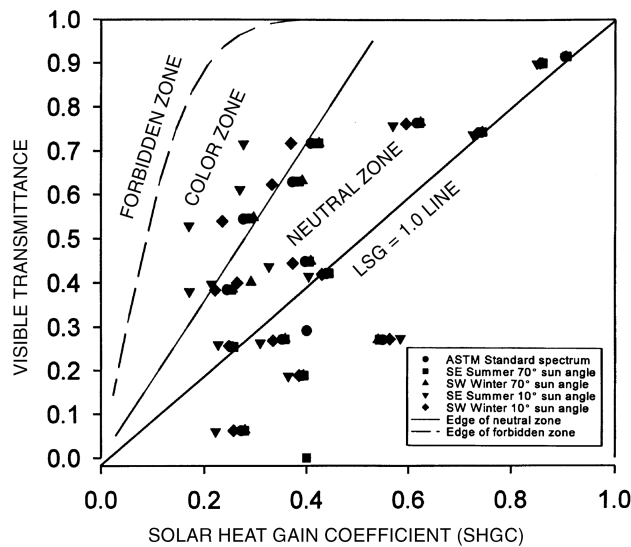


Fig. 35 Visible Transmittance Versus SHGC at Various Spectral Selectivities (McCluney 1996)

wise altering the spectral transmittance and hence the color over the visible portion of the spectrum). In the **forbidden zone**, no combination of visible transmittance and solar heat gain coefficient is possible for normal incidence and for the solar spectral distribution used. (Changing the solar spectral distribution used to calculate T_v and SHGC will shift the transition curves somewhat. A low solar altitude angle, direct-beam spectrum will move the curves to the left on the plot in Figure 35.) It can be seen that the glazings that transmit more solar radiant heat than light cluster on the lower portion of the plot.

The T_v versus SHGC chart can be a useful tool for illustrating the degree of spectral selectivity attained by a glazing system. These concepts lead to an index of spectral selectivity that can be useful. It is called the **light-to-solar-gain ratio**, or LSG, defined as

$$LSG = \frac{T_v}{SHGC} \quad (135)$$

Some characteristic values for T_v , SHGC, and LSG are given in Table 25 for several different glazings, using the ASTM standard spectral distribution at normal incidence to calculate the values.

The LSG can be useful in spotting errors in the calculation of the SHGC. Values of SHGC that lie outside reasonable ranges can be spotted fairly quickly and used to identify possible problems in calculations or measurements. In general, it is very difficult and therefore unlikely to have a useful glazing system for buildings with an LSG value greater than 2.0. Values near 0 should be particularly suspect, since they indicate a glazing that transmits considerably more heat than light and would be unlikely candidates for general use. Generally, a high value of LSG is desired for residential buildings in hot climates, to maximize daylight admission with minimal solar heat gain. This is also true for internal load-dominated nonresidential buildings in many climates, since solar gain rejection is often desired for such buildings, even in cool or cold climates. An LSG value somewhat below 1.0 would be appropriate in cold climates for residential buildings and nonresidential buildings without strong internal cooling loads.

Table 25 Spectral Selectivity of Several Glazings

Glazing	T_v	SHGC	LSG
Reflective blue-green	0.33	0.38	0.87
Film on clear glass	0.19	0.22	0.86
Green tinted, medium	0.75	0.69	1.09
Green low-e	0.71	0.49	1.45
Sun-control low-e + green	0.36	0.23	1.56
Super low-e + clear	0.71	0.40	1.77
Super low-e + green	0.60	0.30	2.00

SELECTING FENESTRATION

Since fenestration systems provide so many functions and because environmental conditions and user needs vary widely, it is difficult to make a completely optimal selection of a fenestration system. Aesthetic and cost considerations are perhaps the most important to residential users, with visual and comfort performance also being of interest. Considering annual energy costs, peak load consequences, and acoustic characteristics, the choice is seldom optimal. The HVAC system designer, fortunately, has a more restricted range of interests, mainly dealing with the energy consequences of a particular fenestration selection. This section therefore focuses on fenestration energy performance determination.

ANNUAL ENERGY PERFORMANCE

Instantaneous energy performance indices (U-factor, solar heat gain coefficient, air leakage, etc.) are typically used to compare fenestration systems under a fixed set of conditions. However, the absolute and relative effect of these indices on a building's heating and cooling load can fluctuate as environmental conditions change. As a result, these indices alone are not good indicators of the annual energy performance (energy savings/costs) attributable to the fenestration. Furthermore, fenestration annual energy performance is difficult to quantify in and of itself because of the many dynamic responses that occur between the fenestration system and the total environment in which it is installed. The four basic mechanisms of fenestration energy performance that were each addressed previously in the chapter—thermal heat transfer, solar heat gains, air leakage, and daylighting—should all be taken into account but are not independent of many other parameters that influence fenestration annual energy performance. As a result, the annual energy performance of fenestration systems can be accurately determined only when a large number of variables are considered. Building type and orientation, climate (weather, temperature, wind speed), microclimate (shading from adjacent buildings, trees, terrain), occupant usage patterns, and certain HVAC parameters can significantly affect the annual energy impacts of fenestration systems.

For these reasons, the most effective means of establishing fenestration annual energy performance is through detailed, dynamic, hourly computer simulations for the specific building and climate of interest. Since the instantaneous performance of the fenestration will often vary by differing magnitudes as climatic conditions change, the most accurate simulation results are obtained when these variances are accounted for in a building energy simulation computer program. After constructing the building energy simulation model following the procedures defined in Chapters 28 and 29 (for residential and commercial construction, respectively), specific changes to the fenestration system can be modeled, and the annual energy performance changes attributable to fenestration can be quantified. These analytical techniques do not consider issues of performance durability for the various instantaneous indices and should only be used as an initial annual energy performance indicator (Mathis and Garries 1995).

Simplified Techniques for Rough Estimates of Fenestration Annual Energy Performance

While dynamic hourly modeling is certainly the most accurate technique for determining fenestration annual energy performance, it is not readily available to many decision makers and end users of fenestration products simply because it may not be practical or cost-effective. Under these circumstances, it may be useful to assess the relative importance of, or balance the trade-off between, the known instantaneous performance indices of U-factor, SHGC, air leakage, and T_r for any given fenestration system when considering heating, cooling, and lighting loads for many different building types and climates. Mitchell et al. (1999) and Huang et al. (1999) describe personal computer programs that are being developed to run this simplified analysis for residential windows.

Broad generalizations can be made for some classifications of building types and climates. For instance, with large commercial buildings, which require substantial cooling energy use because of high internal loads, significant thermal mass, or high orientation dependency, the primary objective may be to place the most emphasis on low SHGC to reduce the cooling load. Also, an evaluation of commercial fenestration annual energy use can take into account the trade-off between artificial lighting and the natural daylighting benefits associated with a particular fenestration system. Contrary to this, electric lighting loads in low-rise detached residential buildings are typically very small in comparison to the heating and cooling loads because of high envelope-dependent energy use, egress requirements, and occupant usage patterns, and therefore the energy influence of daylighting may be neglected altogether. Yet, despite these generalizations, the problem still exists of balancing and assessing the impact of each of the remaining parameters to establish the seasonal or annual energy performance for cases in which detailed computer modeling is not performed.

Realizing the need for characterization of fenestration annual energy performance, scientists in many different countries have been working over the last several years to develop simplified annual energy performance indices for fenestration. These simplified techniques typically involve using the instantaneous fenestration performance indices to quantify building- and climate-independent scalars of annual or seasonal energy performance for rating purposes. Many of these performance indices have value in that they can be relatively independent of building type, climate, distribution of products, orientation, and other items needed for hourly dynamic building energy analyses. These normalized, scalar-based approaches are also limited in accuracy for the same reasons. A further limitation with the simplified techniques is that they do not have broad applicability to varied building types (commercial versus residential buildings, for example). The usefulness of these scalar-based approaches can be increased when limiting the comparison to a single building type. Currently, the simplified techniques for characterizing fenestration annual energy performance are applicable only to fenestration systems for detached residential buildings and are not appropriate for use with multifamily residential or commercial building fenestration systems.

Simplified Residential Annual Energy Performance Ratings

Annual energy performance ratings can provide a simple means of product comparisons for consumers. Such ratings have been derived with many assumptions, usually to suit local climatic conditions.

The Canadian Standards Association (CSA Standard A440.2) developed a simplified energy rating applicable to residential heating in the Canadian climate, which has been adopted in the 1995 *National Energy Code for Houses*. The standard also provides for specific energy ratings to compare products by orientation and climate.

In the United States, where heating and cooling are both significant, the NFRC is developing a rating system that includes both effects (Crooks et al. 1995, Arasteh et al. 2000).

CONDENSATION RESISTANCE

Water vapor condenses in a film on fenestration surfaces that are at temperatures below the dew-point temperature of the inside air. If the surface temperature is below freezing, frost forms. Sometimes, condensation occurs first, and ice from the condensed water forms when temperatures drop below freezing. Condensation frequently occurs on single glazing and on aluminum frames without a thermal break. The edge-seal creates a thermal bridge at the perimeter of the IGU.

The circulation of fill gas due to temperature differences in the IGU cavity contributes to the condensation problem at the bottom of the indoor glazing (Wright and Sullivan 1995a, 1995b; Curcija and Goss 1994, 1995a). In winter, fill gas near the indoor glazing is warmed and flows up, while gas near the outdoor glazing is cooled and flows down. The descending gas becomes progressively colder until it reaches the bottom of the cavity. There, the gas turns and flows to the indoor glazing, resulting in higher heat transfer rates at the bottom. Thus, the bottom edge of the indoor glazing is cooled both by edge-seal conduction and by fill-gas convection. The combined effect of these two heat transfer mechanisms is shown in [Figure 36](#). The surface isotherms show a wider band of cold glass at the bottom of the window. Typical condensation patterns match these isotherms. The vertical indoor surface temperature profile also shows the effect of edge-seal conduction and that the minimum indoor surface temperature is near the bottom edge of the glass.

Condensation to the fenestration and surrounding structures can cause extensive structural, aesthetic, and health problems. Specific examples include peeling of paint, rotting of wood, saturation of insulation, and mold growth. Ice can render doors and windows inoperable and prevent egress during an emergency.

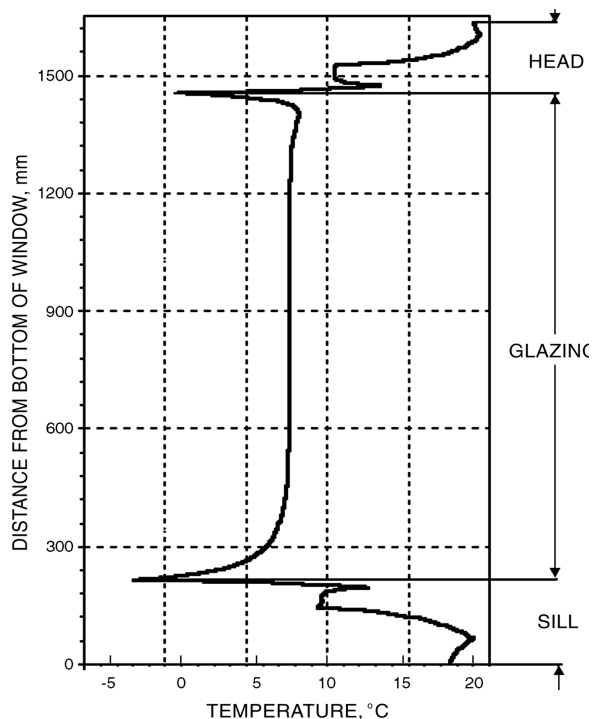


Fig. 36 Temperature Distribution on Indoor Surfaces of Insulating Glazing Unit

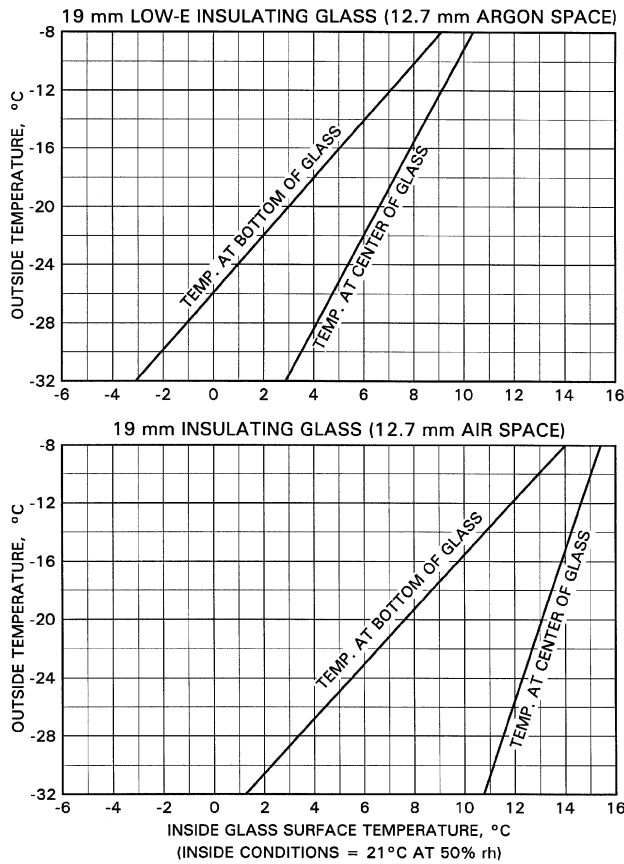


Fig. 37 Minimum Indoor Surface Temperatures Before Condensation Occurs

Energy-efficient housing has been accompanied by reduced ventilation. The resulting increase in indoor humidity has contributed to the condensation problem. However, the solution does not lie in the reduction of humidity levels to a minimum. Relative humidity below 20% and above 70% can increase health risks and reduce comfort. Generally, a minimum of 30% rh should be maintained, and 40% to 50% is more desirable (Sterling et al. 1985).

Minimum indoor surface temperatures can be quantified in a variety of ways. Sullivan et al. (1996), Griffith et al. (1996), Elmahdy (1996), Zhao et al. (1996), and de Abreu et al. (1996) demonstrated good agreement between detailed two-dimensional numerical simulation and surface temperature measurements using thermographs. Wright and Sullivan (1995c), and Curcija et al. (1996) developed simplified simulation models to predict condensation resistance. Estimates of center-glass and bottom-edge surface temperatures that can be expected for two different glazing systems exposed to a range of outdoor temperature are shown in Figure 36. Both glazing systems include insulating foam edge seals. High-performance glazing systems (e.g., low-e/argon and insulated spacers) permit significantly higher indoor humidity levels.

Current measures of condensation resistance of a fenestration system are the **condensation index** (CI) as defined by NFRC (2000a), the **condensation resistance factor** (CRF) as defined by AAMA (1988), or the **temperature index** (I), as defined in CSA Standards A440 and A440.1.

The condensation index is a measure of condensation potential that is based on both area and temperature weighting and is expressed as a minimum of center-of-glazing, edge-of-glazing, and frame CIs. The novelty of this index lies in the fact that it is determined using computer simulation tools unless the overall thermal performance cannot be validated with testing. In the case

that thermal performance cannot be validated, a testing option for determining CI is used.

Computer simulation is done for characteristic two-dimensional cross sections in much the same way that U-factors are determined. The basic difference between U-factor and CI simulations is that more advanced models are used for CI calculations. This is necessary because temperatures are intrinsically local quantities, as opposed to U-factors, which are average quantities, and it is necessary to provide better models for convective heat transfer in glazing cavities and convective and radiative heat transfer on indoor fenestration boundaries. The most general expression of the formula for calculating frame, center-of-glazing, and edge-of-glazing CI is given by the following equation:

$$CI = \left\{ 1 - \left\{ \frac{1}{3} \sum_{j=1}^3 \left[\frac{\sum_i (t_{dpp,j} - t_i)^+ A_i}{(t_{dpp,j} - t_o) A} \right] \right\}^{1/3} \right\} \times 100 \quad (136)$$

where

i = frame, center-of-glazing, or edge-of-glazing section

j = 30%, 50%, and 70% relative humidity

$t_{dpp} = t_{dp} + 0.3 \text{ K}$

t_{dp} = dew-point temperature, °C

$+$ = positive values only

The other two standards define the values by a single dimensionless number as

$$CRF \text{ or } I = \frac{t_h - t_c}{t_h - t_c} \quad (137)$$

where t_h and t_c are the warm and cold side temperatures, respectively. Figure 38 can be used to determine the acceptable range of CRF/I for a specific climatic zone.

The two standards differ in the methods used to determine temperature. The CSA test procedure is based on thermocouple measurements at the coldest location on the frame plus three locations on the glass, each X mm above the bottom sightline. The AAMA procedure specifies two separate factors: one for the frame (CRF_F), which uses weighted frame temperature obtained from surface temperature measurements at predetermined and roving locations on the frame, and one for the IGU (CRF_G), which uses the average of six temperatures measured at predetermined locations near the top, middle, and bottom of the glazed area.

Inside details can significantly alter the potential for condensation on window surfaces. Items such as venetian blinds, roll blinds, insect screens, and drapes increase the thermal resistance between the indoor space and the window and lower the temperature of the window surfaces. These window treatments do not prevent migration of moisture, so they can cause increased condensation. Figure 39 shows different situations that affect the potential for condensation. Note that window reveal plays an important role. If the window is placed near the outside of the wall, the increase in the outdoor film coefficient and decrease in the indoor film coefficient cause colder window surfaces. This effect is more pronounced near the corners of the recess where the indoor film coefficient is locally suppressed because air movement is restricted. Also, blinds should be placed at least 100 mm from the plane of the wall to allow some natural convection between the window and the blind.

Air leakage, especially in operable sections of fenestration, is another important cause of low surface temperature. Leakage near the edge-of-glass sections can further increase the potential for condensation. However, the drier outdoor air decreases the relative humidity near the leakage sites and, in some cases, offsets the

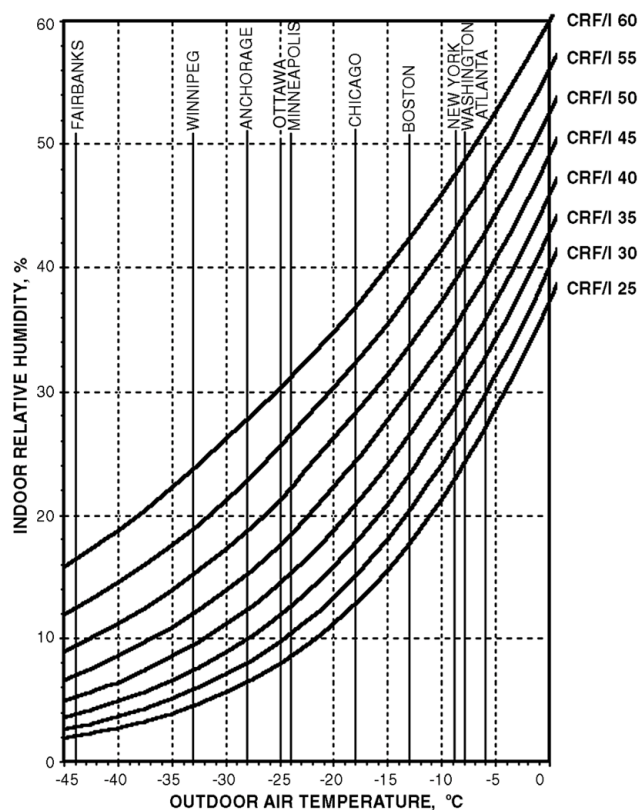


Fig. 38 Minimum Condensation Resistance Requirements ($t_h = 20^\circ\text{C}$)

undesirable effect of the lower surface temperatures. The net effect of air leakage cannot readily be determined experimentally or with simulation.

OCCUPANT COMFORT AND ACCEPTANCE

Human thermal comfort is an immediate sensation that reflects building occupants' perceived response to many physical factors. Unlike much building design that is based primarily on long-term energy and economic considerations, comfort-related design focuses on, and must take heed of, short-term responses of the body's physiology to its surroundings.

Windows influence thermal comfort through a combination of three mechanisms: long-wave radiation exchange, absorption of solar radiation, and convective draft effects (Figure 40). An understanding of these phenomena is important to help designers evaluate the benefits of improved windows and create comfortable buildings. Although it is well understood that high-performance windows can reduce building energy consumption, a better understanding of their impact on comfort might lead to further savings. For example, Hawthorne and Reilly (2000) suggest that significant energy consumption is caused by the standard practice of using perimeter duct distribution in houses to mitigate potential discomfort caused by windows. They found that perimeter heating is often not necessary when high-performance windows are installed and that heating energy savings of 10 to 15% could result from installing a simpler, less expensive duct system. Better windows can allow thermostat settings to be lowered with no loss of comfort. Another simulation study (Lyons et al. 2000) examined the relative magnitudes of a residential window's physical influences under a wide variety of winter and summer climates, glazing parameters, and clothing levels. They found that

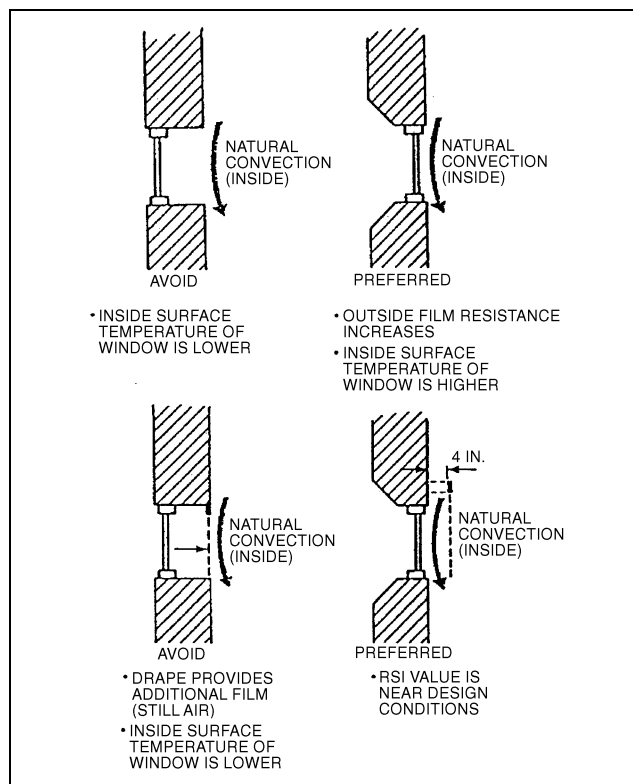


Fig. 39 Location of Fenestration Product Reveals and Blinds/Drapes and Their Effect on Condensation Resistance

- Long-wave, thermal radiation influences of the window dominate unless direct sun strikes the occupant
- Direct solar load has a major influence on perceptions of comfort
- For most residential-size windows, draft effects are generally small

With all but highly insulating windows, the inside surface temperature of the window is heavily influenced by exterior conditions, and this temperature can significantly affect the radiant heat exchange between an occupant and the environment. If this heat exchange moves outside the acceptable range, discomfort will result. Mean radiant temperature (MRT) is commonly used to simplify the characterization of the radiant environment. On a cold day, the inside surface temperature can easily drop below -9°C for a clear single-pane window and below 4°C for a clear, double-pane window. If the occupant is sitting sufficiently near the window, MRT could drop to 13°C for the single-pane case and 17°C for the double-pane case. Based on ASHRAE Standard 55, even the use of the clear double-pane window could result in discomfort. [This example assumes an outdoor air temperature of -18°C , indoor air temperature of 22°C , nonwindow surface temperatures of 22°C , occupant-window view factor of 0.3, 0.9 clo (standard winter indoor clothing), and activity level of 1 met.] In addition to the MRT effect, a cold inside glass surface can induce a downward draft that increases air movement, contributing to further discomfort. If direct solar radiation strikes the glazing or occupant, the situation is much more complex.

In winter, the warming effect of sunlight on skin and clothing is often welcome, depending on the compounding effect of other factors such as air temperature. Windows also absorb and transmit a significant amount of solar radiation. Because of such absorption, a solar-heated window may improve MRT for a nearby person. The premise of passive solar design is that occupants will welcome, or at least tolerate, solar gain in exchange for savings on heating energy. However, it is desirable that the onset of discomfort be able to be

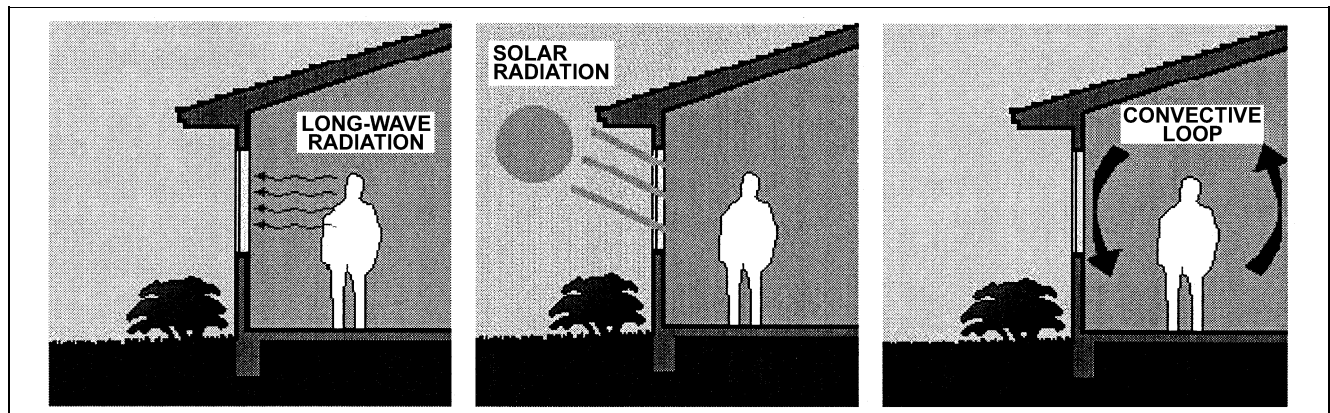


Fig. 40 Fenestration Impacts on Thermal Comfort: Long-Wave Radiation, Solar Radiation, Convective Draft

predicted; otherwise, the energy-saving design may be defeated if occupants draw shades to prevent overheating.

In summer, solar-heated glass may become uncomfortably hot and, in commercial premises, actually devalue rented space near windows. The inside surface of body-tinted, heat-absorbing glass can routinely reach temperatures above 50°C in summer conditions, raising MRT by as much as 8 K. This can be ameliorated with the addition of a second pane of glass on the inside. Transmitted radiation often causes discomfort if it falls directly on the occupant. A person sitting near a window in direct solar radiation can experience heat gain equivalent to a 11 K rise in MRT [Arens et al. (1986)]. Similarly, in residential applications, the perceived need for solar control is affected both by the contribution of window surfaces to MRT and by overheating due to direct solar load.

Advances in window technology, especially high-performance glazings, mean that the designer has a choice of potential glazing systems. On the basis of annual energy performance for heating, cooling, and lighting, these alternatives may give similar outcomes. However, because they represent different combinations of U-factor, SHGC, and inside glass surface temperature, their comfort outcomes may differ considerably. Research continues to develop tools that will help designers evaluate such difficult trade-offs. In the meantime, several general rules of thumb may be followed:

- In heating-dominated climates, windows with the lowest U-factor tend to give the best comfort outcomes. However, there is likely to be a trade-off between the twin goals of maximizing instantaneous comfort and minimizing annual energy consumption.
- In cooling-dominated climates or for orientations where cooling loads are of concern, windows with the lowest rise in surface temperature for a given SHGC tend to give the best comfort outcomes.

Table 26 Sound Transmittance Loss for Various Types of Glass

Type of Glass	Sound Transmittance Loss, dB
3 mm double-strength sheet glass	24
6 mm plate or float glass	27
13 mm plate glass	32
19 mm. plate glass	35
25 mm plate glass	36
6 mm. laminated glass (11 mm plastic interlayer)	30
25 mm insulating glass	32
13 mm laminated glass (11 mm plastic interlayer)	34
Insulating glass, 150 mm air space, 6 mm plate or float glass	40

Sound Reduction

Proper acoustical treatment of exterior walls can decrease noise levels in certain areas. The airtightness of a wall is the primary factor to consider in reducing sound transmission from the exterior. Once walls and fenestration products are tight, the choice of glass and draperies becomes important. Draperies do not prevent sound from coming through the fenestration; they act as an absorber for sound that does penetrate. Table 26 lists average sound transmission losses for various types of glass. These averages apply for the frequency range of 125 to 4000 Hz and were determined by tests based on ASTM Standard E 90.

Strength and Safety

In addition to its thermal, visual, and aesthetic functions, glass for building exteriors must also perform well structurally. Wind loads are specified in most building codes, and these requirements may be adequate for many structures. However, detailed wind tunnel tests should be run for tall or unusually shaped buildings and for buildings where the surroundings create unusual wind patterns. The strength of annealed, heat-strengthened, tempered, laminated, and insulated glass is given in ASTM Standard E 1300.

Thermal expansion and contraction of glass can result in breakage of ordinary annealed glass. This expansion and contraction can be caused by solar radiation onto partly shaded glass, by heat traps from drop ceilings and tight-fitting drapes, or by HVAC ducts incorrectly directed toward the glazing. High-performance tinted and reflective glasses with low-e coatings are usually more vulnerable to thermal stress breakage than clear glass. Heat treating (heat strengthening or fully tempering) the glass resists thermal stress breakage. Heat-strengthened glass, although not a safety glass, is usually preferred to tempered (safety) glass because it typically has less distortion and is much less likely to have spontaneous breakage. Spontaneous breakage can occur on very rare occasions in tempered glass. The glass manufacturer or fabricator should be consulted for information on thermal stress performance.

Building codes may require glass in certain positions to perform with certain breakage characteristics, which can be satisfied by tempered, laminated, or wired glass. In this case, glass should meet Federal Standard 16 CFR 1201 or other appropriate breakage performance requirements.

Life-Cycle Costs

Alternative building shells should be compared to ensure satisfactory energy use and total energy budget compliance, if required. ASHRAE Standards 90.1 and 90.2 should be used as a starting point. A life-cycle cost model should be developed for each system considered. See Chapter 36 of the *ASHRAE Handbook—Applications*.

DURABILITY

The service life and long-term performance of fenestration systems depend on the durability of all the components that make up the system. Representative samples of IGUs are usually tested (for seal durability) according to test methods to ensure the integrity of the seal. Failure of IGUs is usually indicated by loss of adhesion of sealant to the glass; as a result, fogging occurs inside the glazing cavity.

In the case of argon-filled units, the seal failure means the loss of argon and, hence, degradation in the thermal characteristics of the unit. Extensive work was done at the National Research Council of Canada to study the durability of IGUs filled with argon gas (Elmahdy and Yusuf 1995). The results indicated that, under normal conditions, argon loss due to diffusion through the sealant is very small. However, when cracks or pinholes exist in the sealant, most of the argon gas escapes from the unit, which implies that the implementation of stringent quality control procedures is essential for the production of durable IGUs.

The degradation of organic materials and other chemical components in the IGUs, as a result of exposure to ultraviolet radiation, is also among the factors affecting the durability and service life of fenestration systems. The use of low-e coating on glass tends to enhance the appearance of chemical deposits on the glass surface. Also, the insertion of muntin bars in the glazing cavities may result in excessive rate of unit failure during the ultraviolet volatile (fogging) test unless strict quality assurance processes are implemented. The current ASTM (United States) and CGSB (Canada) durability standards are being reviewed to reflect the emergence of new technologies in the fenestration industry.

Insulating glass products have been studied in a 15-year correlation study by the Sealed Insulating Glass Manufacturers Association (SIGMA). During this study, it was found that long-term performance and durability of insulating glass correlated well with the test level to which such a unit's construction had been manufactured with regard to the ASTM *Standard E 773* test method and ASTM *Standard E 774* specification for sealed insulating glass. The units showing the highest percentage of resistance to seal failure were those that were tested in conformance with the ASTM *Standard E 774* Class CBA standard. Units that did not qualify to the A level showed a definite correlation to a higher percentage of failure. During the field correlation studies, it was found that units glazed in compliance with the SIGMA recommendations perform for longer periods than units not constructed properly, having deficiencies in the glazing system, or not meeting the ASTM requirements.

The durability of fenestration systems is also dependent on the durability of other system components such as the weatherstripping, gaskets, glazing tapes, air seals, and hardware. The wear and tear of these elements with time and use may result in excessive air and water leakage, which will affect the overall performance and the service life of the system. Excessive water leakage may result in damage to the fenestration product, especially the edge seal, as well as the wall section where the product is mounted. Excessive air leakage may lead to frost buildup and condensation on the fenestration surfaces.

Studies conducted at the National Research Council of Canada (Elmahdy 1995) and elsewhere (Patenaude 1995) showed that when windows are tested at high pressure and temperature differentials, they experience air leakage rates which exceed those determined at 75 Pa and zero temperature differential (these conditions are used in rating the window air leakage in U.S. and Canadian standards). In other studies (CANMET 1991, 1993), the effect of pressure and motion cycling on windows resulted in excessive degradation in almost all the window performance factors, particularly the condensation resistance, ease of operation, air leakage, and water leakage.

In order to predict long-term performance, the unit construction for insulating glass should be subjected to a test and certification

program such as ASTM *Standard E 774* Class CBA level and the requirements of SIGMA or CGSB *Standard 12.8* certified by the Insulating Glass Manufacturers Association of Canada (IGMAC) or equivalent.

In addition to affecting the fenestration performance factors mentioned above, durability may also affect long-term energy performance.

CODES AND STANDARDS

National Fenestration Rating Council (NFRC)

The National Fenestration Rating Council (NFRC) was formed in 1989 to respond to a need for fair, accurate, and credible ratings for fenestration products. NFRC has adopted rating procedures for U-factor (NFRC 100), solar heat gain coefficient and visible transmittance (NFRC 200), optical properties (NFRC 300), emissivities (NFRC 301), and air leakage (NFRC 400). To provide certified ratings, manufacturers follow the requirements in the NFRC *Product Certification Program* (PCP) which involves working with laboratories accredited to the NFRC *Laboratory Accreditation Program* (LAP) and independent certification and inspection agencies accredited through the NFRC *Certification Agency Program* (CAP).

NFRC 100 was the first of the NFRC rating procedures approved and thus the first NFRC procedure adopted into energy codes in the United States. NFRC 100 requires the use of a combination of state-of-the-art computer simulations and improved thermal testing to determine U-factors for the whole product. The next step is product certification. NFRC has a series of checks and balances to ensure that the rating system is accurately and uniformly employed. Products and their ratings are authorized for certification by an NFRC-licensed independent certification and inspection agency (IA). Finally, two labels are required: the temporary label, which contains the product ratings, and a permanent label, which allows tracking back to the IA and information in the NFRC *Product Directory*. In addition to informing the buyer, the temporary label provides the building inspector with the information necessary to verify energy code compliance. The permanent label provides access to energy rating information for a future owner, property manager, building inspector, lending agency, or building energy rating organization.

This process has a number of noteworthy features that make it superior to previous fenestration energy rating systems and correct past problems:

- The procedures provide a means for manufacturers to take credit for all the nuances and refinement in their product design and a common basis for others to compare product claims.
- The involvement of independent laboratories and the IA provides architects, engineers, designers, contractors, consumers, building officials, and utility representatives with greater confidence that the information is unbiased.
- Requiring simulation and testing provides an automatic check on accuracy. This also remedies a shortcoming of previous energy code requirements that relied on testing alone, which allowed manufacturers to perform several tests and then use the best one for code purposes.
- The certification process indicates that the manufacturer is consistently producing the product that was rated. This corrects a past concern that manufacturers were able to make an exceptionally high quality sample and obtain a good rating in a test but not consistently produce that product.
- There is now a readily visible temporary label that can be used by the building inspector to quickly verify compliance with the energy code.
- There is now a permanent label that enables future access to energy rating information.

While the NFRC program is similar for other fenestration characteristics, there are differences worth pointing out. The solar heat gain coefficient and visible transmittance ratings (NFRC 200), which have been referenced in several codes, are based on simulation alone. Optical properties (NFRC 300) and emissivity (NFRC 301) are based on measurements by the manufacturer, with independent verification. The air leakage ratings (NFRC 400) are based on testing alone. For site-assembled fenestration products (such as curtain walls and window walls), there is an NFRC label certificate that fulfills the labeling requirements and serves the certification purpose. There must be a separate NFRC label certificate for each "individual product" in a particular project.

United States Energy Policy Act (EPAAct)

In the United States, the 1992 Energy Policy Act (EPAAct) required the development of national fenestration energy rating systems and specified NFRC as the preferred developer. (The U.S. Department of Energy was to establish procedures if the NFRC did not.) While this recognition provided an impetus for NFRC to develop the desired procedures and programs, the EPAAct sections on energy codes have been a key factor in their implementation.

EPAAct set energy code baselines for state energy codes. The ICC 2000 *International Energy Conservation Code* (IECC) and ASHRAE/IESNA *Standard* 90.1-1999, *Energy Standard for Buildings Except Low-Rise Residential Buildings* are the current successors to the versions cited in the 1992 legislation. The majority of states have adopted the predecessors to the 2000 *IECC* (including the 1998 *IECC* and the CABO 1995 *Model Energy Code*) and to ASHRAE/IESNA *Standard* 90.1-1999 (i.e., ASHRAE/IESNA *Standard* 90.1-1989) into their codes either directly or by reference when adopting a building code published by one of the three national code organizations in the United States. The ICC 2000 *International Building Code* (the U.S. model building code jointly developed by ICBO, BOCA, and SBCCI) references the 2000 *International Energy Conservation Code*.

The ICC 2000 International Energy Conservation Code

The ICC 2000 *International Energy Conservation Code* (IECC) references NFRC 100 for U-factor (as did the 1998 *IECC* and the 1995 *Model Energy Code*) and NFRC 200 for solar heat gain coefficient (SHGC) (as did the 1998 *IECC*). Section 102.3, which applies to all occupancies, requires U-factors of fenestration products (windows, doors, and skylights) to be determined in accordance with NFRC 100 by an accredited independent laboratory and labeled and certified by the manufacturer. While the language does not specify NFRC accreditation, it both requires the use of the NFRC rating procedure by an independent entity and requires labeling and certification.

ASHRAE/IESNA Standard 90.1-1999

In 1999, ASHRAE and IESNA published a comprehensive update to the 1989 version of *Standard* 90.1. The fenestration rating, labeling, and certification criteria are in Sections 5.2.2 and 5.2.3. U-factors are to be determined in accordance with NFRC 100, solar heat gain coefficient in accordance with NFRC 200, visible transmittance in accordance with NFRC 300, and air leakage in accordance with NFRC 400.

For further information on U.S. energy codes, the Building Codes Assistance Project (BCAP) publishes a bimonthly summary entitled "Status of State Energy Codes," which provides information on current codes and pending legislation. For additional information, contact BCAP at 1200 18th Street NW, Suite 900, Washington DC 20036; voice: 202-530-2200; fax: 202-331-9588; e-mail: bcap@ase.org; website: <http://solstice.crest.org/efficiency/bcap/update.html>.

Canadian Standards Association (CSA)

In Canada, the Canadian Standards Association (CSA) promulgates fenestration energy rating standards. CSA *Standard* A440.2

addresses most fenestration products, and CSA *Standard* A453 addresses doors. These are companion standards to NFRC 100. NFRC and CSA have established a Thermal Harmonization Task Force to attempt to harmonize their fenestration energy rating standards.

SYMBOLS

a	= absorptance in a layer, considered as an isolated layer
A	= apparent solar constant
A	= total projected area of the fenestration product
AST	= apparent solar time
B	= atmospheric extinction coefficient
C	= sky diffuse factor
e	= hemispherical emissivity
E_{DN}	= direct normal irradiance
E_D	= direct irradiance
E_d	= diffuse sky irradiance
E_r	= diffuse ground reflected irradiance
E_t	= total irradiance
ET	= equation of time
h	= surface heat transfer coefficient
H	= fenestration product height
H	= hour angle
k	= thermal conductivity
L	= latitude
LON	= longitude
LSM	= local standard meridian
LST	= local standard time
n	= refractive index
P_V	= vertical projection depth
P_H	= horizontal projection depth
q	= instantaneous energy flux
Q	= instantaneous energy flow
R	= reflectance of a layer or collection of layers (system or subsystem)
R_H	= height of opaque surface between fenestration product and horizontal projection
R_W	= width of opaque surface between fenestration product and vertical projection
SHGC	= solar heat gain coefficient
t	= relative temperature
T	= absolute temperature
T	= transmittance of a layer or collection of layers (system or subsystem)
U	= overall coefficient of heat transfer
W	= fenestration product width
Y	= ratio of vertical/horizontal sky diffuse
α	= material absorptivity
β	= solar altitude
δ	= declination
Δ	= vertical projection profile angle
ϕ	= solar azimuth
γ	= surface solar azimuth
η	= day of year
λ	= wavelength
θ	= incident angle
ρ_g	= ground reflectance
ϖ	= solid angle
Ω	= horizontal projection profile angle
ξ	= refractive angle
ψ	= surface azimuth
Σ	= surface tilt
A	= absorptance in a layer or a collection of layers (system or subsystem)

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