Fenestration Solar Gain Analysis

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Abstract

This publication is a tutorial treatment of solar heat gain through fenestration systems, focusing mainly upon the glazing elements of such systems. It describes the basic physical, radiometric, and photometric processes involved in the transfer of solar radiant flux through the fenestration to the inside of the building. Included are discussions of the shading coefficient method of determining solar gain, and the new spectrally-based solar heat gain coefficient method that has been adopted by the National Fenestration Rating Council for its national system for window energy performance rating, certification, and labeling, and which is being adopted by the American Society of Heating, Refrigerating, and Air Conditioning Engineers.

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Preface

The National Fenestration Rating Council was created to develop and promulgate a voluntary consensus program for the energy performance rating, certification, and labeling of windows and other fenestration systems sold in the United States. A dramatic increase in energy performance of modern, commercially available "super windows" over the last two decades has led to a corresponding increase in the sensitivity of these new windows to changing environmental conditions. The solar radiant heat gain through modern angularly and spectrally selective windows and attachment products, for example, involves several optical and thermal processes that cannot be properly characterized by the simplified engineering methods of the past.

The purpose of this publication is to describe technical concepts involved in analyzing the solar radiant heat gain through fenestration systems, to enable building designers, specifiers, and energy engineers interacting with the new NFRC and ASHRAE methods better to understand the technical issues upon which the methods are based. It is intended for a technically trained audience but should be understandable by professionals in the field without extensive scientific or engineering backgrounds.

Readers are encouraged to scan the Contents so that material with which they are already familiar can be skipped or read quickly to refresh their familiarity.

This document adheres to international standard terminology in the fields of radiometry and photometry. Early sections on the terminology of radiometry, photometry, and material optical properties are provided as background material for the sections that follow.

FENESTRATION SOLAR GAIN ANALYSIS

Ross McCluney

Introduction

Windows, skylights, clerestories, sliding glass doors, sloped roof glazings, and glazed doors all fall into a general category called *fenestrations*. The fenestration system, including any shading devices attached to it, as well as its frame and other opaque elements, limits the admission of solar radiation and daylight. The limiting action includes the effects of the edges of the aperture and other opaque elements of the system that block solar radiation and daylight as well as the processes of transmission, absorption, and reflection by the glazings and other elements. There are several physical mechanisms involved in these actions. The purpose of this introduction is to describe the basic concepts.

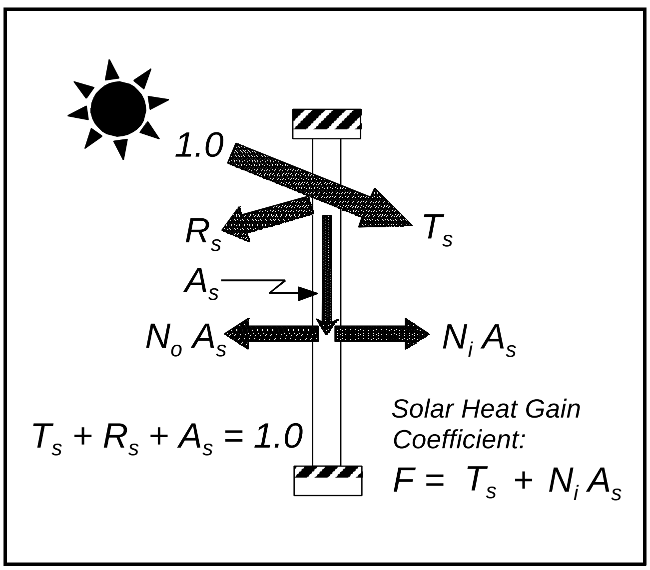

Figure 1. Illustration of glazing system solar radiant heat gain components.

The fundamental mechanisms involved in solar radiant heat gain are diagramed in Fig. 1 for single pane glass. The effects of the frame and other opaque elements are not shown in this diagram but will be discussed subsequently.

Most of the solar gain through single pane clear glass comes from the large fraction T_s of the incident radiation that is transmitted directly through the glass as solar radiation. The remaining radiation is taken away by absorption and reflection. Of the absorbed radiation, a portion, called the *inward flowing fraction*, N_i, propagates inside, adding to the directly transmitted component a fraction of the incident radiation. Another portion, N_o, is the outward flowing fraction. The propagation mechanisms for inward and outward flowing fractions are conduction, convection, and radiation.

As shown in Fig. 1, the directly transmitted fraction of the incident solar radiation is called the *solar transmittance*, T_S, of the glazing. This is one of several *solar optical properties* of fenestration system components that will be defined and used subsequently. The fraction of incident solar radiation that is absorbed by the glazing is called its *solar absorptance*, A_S. The fraction of incident solar radiation reflected by the glazing is its *reflectance*, R_S. Since the incident solar radiation can only go into these three fractions, the sum of them is 1.0:

$$T_S + A_S + R_S = 1.0 \tag{1}$$

If we know any two of these quantities we can determine the third one by subtracting their sum from 1.0. Turning to the absorption coefficient, A_S, the inward flowing fraction of it is given the symbol N_i. The fraction of incident solar radiation entering the building as total solar gain, called the Solar Heat Gain Coefficient, *SHGC*, is represented by the symbol *F* in editions of the *ASHRAE Handbook of Fundamentals* prior to the 1997 one, and in other relevant literature. *SHGC*, or *F*, is given by the equation:

$$F = T_S + N_i A_S \tag{2}$$

Use of the SHGC in determining solar gain, in W or Btu/hr, is discussed subsequently. It is important to note that Equation 2 applies only to the glazing portion of a fenestration system. The optical properties T_s and A_s in Eq. 2 in general depend on both the direction of incidence and the wavelength of the incident radiation. The angular and spectral dependencies of the solar heat gain coefficient are very important and are discussed subsequently. When the *angular transmittance* of a glazing system varies more strongly than that of clear plate glass, the system is called *angularly selective.* When the *spectral transmittance and/or reflectance* of a glazing system varies more strongly than that of clear plate glass, the system is called *spectrally selective*. These important selectivities are discussed at length subsequently.

In addition to the *glazing* system solar gain, there is also some fraction of the solar radiation absorbed by the *opaque* elements of a fenestration system that conducts through these elements and enters the room as solar gain, through the mechanisms of conduction, convection, and radiation from the room-side surfaces of those elements. While this is usually a small portion of the total solar gain, it must be added to the glazing system solar gain to obtain a total fenestration system solar gain.

The two cases of glazing and frame solar gain are distinguished in the National Fenestration Rating Council and the American Society of Heating, Refrigerating, and Air Conditioning Engineers, with the subscripts "*g*" for "glass" and "*f*" for "frame", the latter applying to the frame and other opaque elements such as munton bars and true dividers. If A_f is the area of the frame portion of a fenestration system and A_g is the area of the glazed portion of a fenestration system, then the total fenestration system solar heat gain coefficient F will be given by

$$F = \frac{F_g A_g + F_f A_f}{A_g + A_f} \qquad \textbf{(3)}$$

(A glance at document NFRC 200-95 will show that the frame and glazing areas are further subdivided into additional areas, but the principle shown in Eq. 3 is the same.) The F_f of the opaque, framing elements of a fenestration system can be calculated with the equation

$$F_f = \frac{A_f U_f}{h_f} \qquad \textbf{(4)}$$

where U_f is the U-factor of the opaque framing elements of the window, A_f is the area of these elements, and h_f is the convective film coefficient for the air-to-frame interface. (Equations for convective film coefficients are provided in the ASHRAE Handbook of Fundamentals.) The total solar gain, q, in Watts, through a fenestration system of area A and solar heat gain coefficient F irradiated by solar radiation having irradiance E_S is given by

$$q = E_S F A \qquad \textbf{(5)}$$

When the directly transmitted radiation is absorbed by the interior surfaces of the building, it turns into heat--all of it (including UV, visible, and infrared portions of the spectrum) and produces solar heat gain. In most situations only a very small portion of the directly transmitted radiation is reflected back out through the window by the interior surfaces of the room. There are cases, however, where this reflected radiation can be significant, reducing the solar gain somewhat from the amount calculated using the solar heat gain coefficient defined above.

For the purposes of *rating* windows and other fenestration systems, independently from any room into which they might be installed, it is assumed that the room surfaces are essentially black, totally absorbing over the solar spectrum, so that none of the directly transmitted radiation can reflect back outside through the window. Re-radiation of

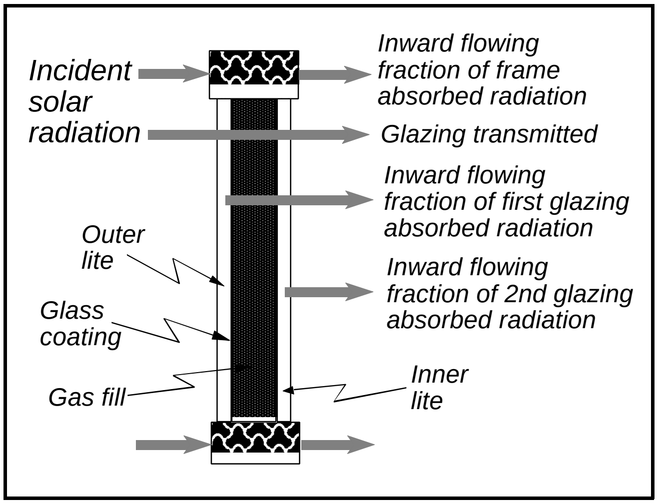

Figure 2. Components of solar radiant heat gain with a double pane window, including both frame and glazing contributions.

absorbed heat from the room surfaces back toward the window is likewise ignored in this rating system. Reflected and radiated energy is important in the operation of *real* buildings, however, and special *low-e* coatings have been devised for multiple pane windows intended for use in cold climates, to prevent the escape of interior heat radiated toward the window (or between the panes of a multiply glazed window). This is discussed in subsequent sections.

The glazing's *total solar radiant heat gain*, in this approximation, is a combination of the directly transmitted solar radiation and the inward flowing fraction of the absorbed solar radiation. These contributions must be added to get the total solar gain. If the clear glazing used in our example window is replaced by tinted glass, then it will absorb a larger fraction of the incident radiation and the inward flowing fraction of the absorbed radiation will be a larger portion of the total solar gain. For very strongly tinted single pane glass, the inward flowing fraction of absorbed radiation can exceed the directly transmitted solar gain.

The same physical effects are in operation when more than one pane of glass is present in the glazing system and the resulting multi-pane insulated glazing unit (*IGU*) is surrounded with an insulated frame. The combined effects are shown in Fig. 2. A modern sealed two-pane glazing unit with an insulating gas fill and a spectrally selective coating on the inner surface of the outer lite is shown. (Numbering the glass surfaces from the outside to the inside, the coating is placed on surface number 2 in Fig. 2.)

Solar radiation is shown schematically as incident upon both the glass and the frame. Some of the radiation incident on the glass is transmitted directly. Another portion is absorbed by both glazings. Each glazing produces its own inward flowing fraction of the absorbed radiation. Some of the radiation absorbed by the framing elements is conducted through those elements and enters the building as heat gain. This component must also be accounted for.

In the case of multipane glazings, Eq. 2 has to be modified to account for the different inward flowing fractions from the different glazings. This is discussed explicitly in the subsequent section titled "Solar Heat Gain Coefficient".

T_S and A_S in Eq. 2 are in general dependent upon the spectral (wavelength) and angular distributions of the incident solar radiation. These dependencies are accounted for in the NFRC standard procedure for determining solar gain outlined in NFRC 200-95 and it is important to know something about the symbols, units, terminology, and basic concepts needed to describe these distributions.

To understand the angular and spectral dependencies of the SHGC and its constituent optical properties it is important first to describe some fundamental concepts in the fields of optics and radiometry that deal with these optical properties. This is necessary not only for full understanding but also to insure that simulations performed with the Window 4 and 5 programs[1] are done with proper attention to the spectral and angular variations in both the optical properties and the incident radiation.

The spectral optical properties of glazing systems will be discussed first and this will be followed with a treatment of angular effects.

The Electromagnetic Spectrum

Terrestrial solar radiation results from the emission of electromagnetic radiation from the sun. The propagation of oscillations of electric and magnetic fields together is called *electromagnetic radiation*, since both the electric and magnetic fields are involved and the process radiates energy away from the source.

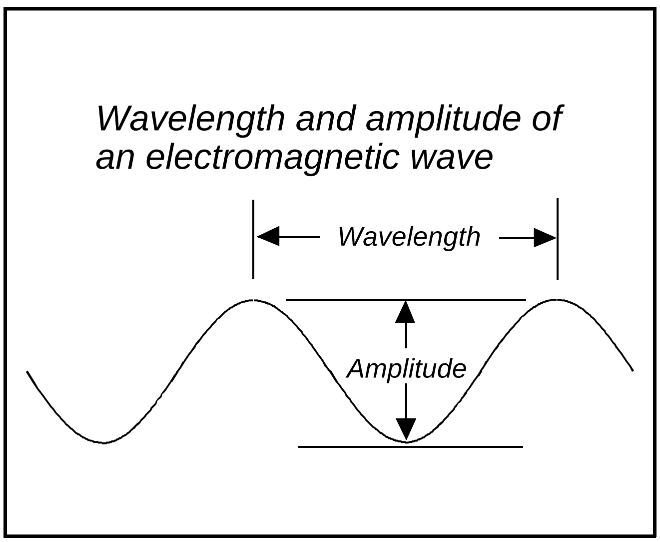

Figure 3. Illustration of the wavelength and amplitude of a monochromatic electromagnetic wave.

Apart from the strength of the oscillations, called their amplitude or energy density, the most important characteristic of the oscillations in electromagnetic radiation is their *frequency*, how many times the electric and magnetic fields reverse direction (or rotate) in a second. One oscillation in one second, one cycle per second, is called the Hertz by international agreement.

An oscillating electromagnetic field propagating away from a source, whether it be a radio antenna, a light bulb, or the sun, has both frequency and wavelength, the latter being the distance between the crests or maximums in the instantaneous field strengths of either the electric or magnetic field. This is illustrated in Fig. 3, which can be considered a snapshot in time of the variation of the electric field strength along the direction of propagation of a monochromatic (single frequency and single wavelength) electromagnetic wave.

There is an important relationship between the frequency and wavelength of electromagnetic radiation, a relationship that comes out of some important equations in James Clerk Maxwell's theory of electricity and magnetism. This relationship is

$$c = \lambda \nu \qquad \textbf{(6)}$$

where λ is the wavelength in meters, ν is the frequency in Hertz, and c is the speed of light in the medium through which the radiation is propagating, in meters per second. In a vacuum the speed of light is 2.9×10^8 m/s. It is clear from Eq. 6 that there is an inverse relationship between frequency and wavelength in electromagnetic radiation.

The range of frequencies and their corresponding wavelengths, from very low frequencies below one Hertz to very high frequencies, above 10^{24} Hertz, is called the *electromagnetic spectrum*.

The frequency of electromagnetic radiation is very important in determining how that radiation interacts

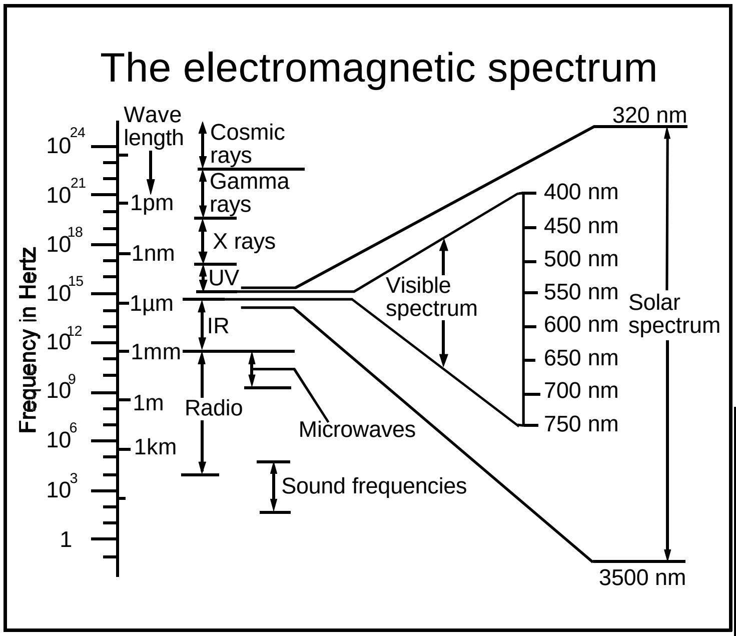

Figure 4. Illustration of major wavelength and frequency ranges in the electromagnetic spectrum.

with matter. Electromagnetic radiation over one range of frequencies behaves quite differently in many respects from electromagnetic radiation at other frequencies. Thus different portions of the spectrum have been given different names. The names of the parts of the electromagnetic spectrum are shown in Fig. 4. The approximate wavelengths of the colors of the visible spectrum, and the wavelength ranges of the ultraviolet and infrared portions of the spectrum are given in Table 1.

Blackbody Radiation and the Solar Spectrum

In studying the physics of fenestration solar gain we are interested in the portion of the spectrum covered by both solar radiation, from about 350 nanometers to about 3500 nanometers in wavelength, and a longer wavelength portion, from 3500 nanometers to above 50,000 nanometers. One nanometer, abbreviated nm, is 10^{-9} m. 1000 nm is equivalent to 1 micro meter, abbreviated µm, or 10^{-6} m. (When speaking of wavelength, two previously common units of length, the Angstrom (0.1 nm) and the micron (1 µm) have been discontinued and their use is deprecated by national and international standards organizations.) In discussing these topics it is helpful to have some knowledge of what is called *blackbody radiation*.

Table 1. Wavelength Ranges of Optical Spectral Regions*

Name	*Wavelength range*
UV-C	100 to 280 nm
UV-B	280 to 315 nm
UV-A	315 to 400 nm
VIS	Approx. 360-400 to 760-800 nm
Purple	360 to 450 nm
Blue	450 to 500 nm
Green	500 to 570 nm
Yellow	570 to 591 nm
Orange	591 to 610 nm
Red	610 to 830 nm
IR-A, "Near IR" or NIR	780 to 1,400 nm
IR-B	1.4 to 3 µm
IR-C, "Far IR"	3 µm to 1 mm

*CIE, **International Lighting Vocabulary**, CIE Publ No. 17.4 IEC Publ. 50(845), Central Bureau of the *Commission Internationale de l'Eclairage*, Kegelgasse 27, A-1030 Vienna, P. O. Box 169, Austria, and *Bureau Central de la Commission Electrotechnique Internationale, 2, rue de Varembe*, Geneva, Switzerland, 1987. Also available from the national committees of the CIE. In the U. S. this document can be obtained from TLA-Lighting Consultants, Inc., 7 Pond Street, Salem, MA 01970-4893.

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

$$M = \epsilon \sigma T^4 \qquad \textbf{(7)}$$

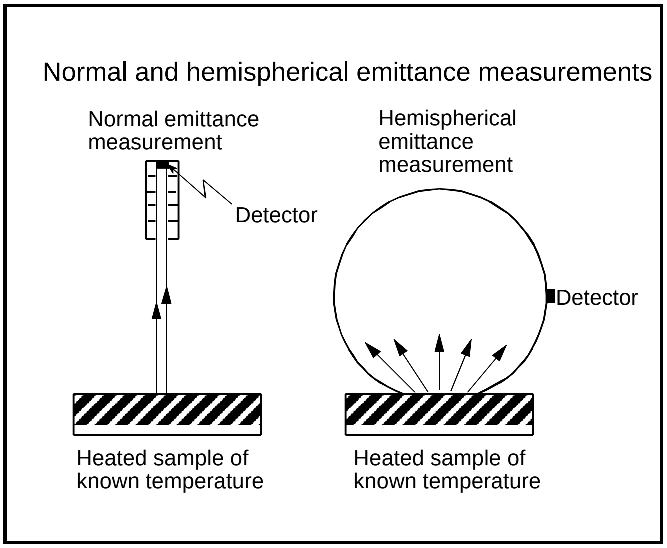

Figure 5. Illustrating the difference between normal and hemispherical emittance of a material. The *integrating sphere* on the right is a highly reflective sphere that delivers a fixed fraction of the flux from the heated sample to the detector, including all emitted radiation in a hemispherical solid angle from each point on the sample. Solid angles are discussed in the text.

where M is the exitance of the material in watts per square meter, written as $W \cdot m^{-2}$, T is the temperature in degrees Kelvin, σ is the Stefan-Boltzmann constant, whose value is $5.67032 \times 10^{-8}\ W \cdot m^{-2} \cdot K^{-4}$, and ϵ is the *hemispherical emittance* of the material. (On the Celsius temperature scale, water freezes at 0 degree and boils at 100 degrees. The Kelvin scale moves the zero to absolute zero, about 273 Celsius degrees below the freezing point of water. Thus water freezes at about 273 K and boils at about 373K.)

The maximum value the hemispherical emittance can have for any material is 1.0, in which case the surface emits the theoretically 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.*

One occasionally hears about a related quantity, called *normal emittance*. The relationship between them is illustrated in Fig. 5. Bodies with emittances below 1.0 are sometimes called *greybodies*, whentheir emittances do not vary with wavelength. There are many surfaces, however, whose emittances do vary with wavelength, giving rise to a quantity called the *spectral emittance*, ϵ_λ. These surfaces are called *nonblackbodies*.

There is an equation for calculating the spectral distributions of blackbody radiation. It can be found in most any textbook on radiometry and photometry, optics, or electricity and magnetism[1]. The resulting spectral distributions are illustrated in Fig. 6 for blackbodies ranging in temperature from 300 degrees Kelvin (approximately room temperature) to 20,000 deg K

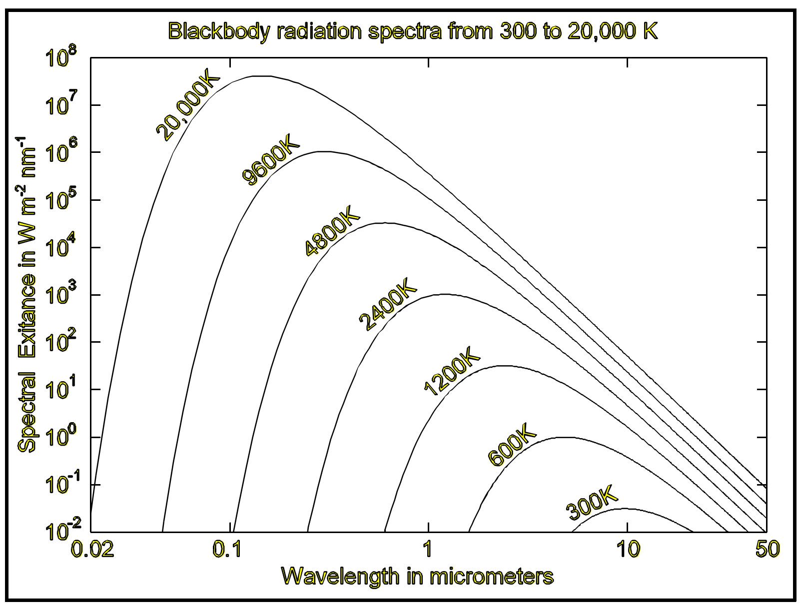

Figure 6. Spectral distributions of blackbody radiation at different source temperatures.

The reason for our interest in the spectral range from 350 nm to over 50 μm is that it contains the wavelength ranges of radiation from both the sun and sky incident upon fenestration systems and the longer wavelength "thermal" radiation emitted by warm bodies both outside and inside the building, at temperatures ranging from about 0° F to over 160° F (-17.8 C to 71.1 C). A reason for our interest in this portion of the spectrum is illustrated in Fig. 7. As this diagram shows, it is desirable for glazings intended for hot climates to have high transmittance over the visible portion of the spectrum, letting daylight in for both illumination and view, and low transmittance over all other portions of the spectrum, to reduce solar heat gain. In comparison, glazings intended for very cold climates should have high transmittance over the whole solar spectrum, from 380 nm to over 3500 nm, for maximum admission of solar radiant heat gain and light, and they should have low transmittance over the long-wavelength infrared portion of the spectrum, in order to block this form of radiant heat emitted by the relatively warm interior surfaces of buildings from escaping back outside through the glazings.

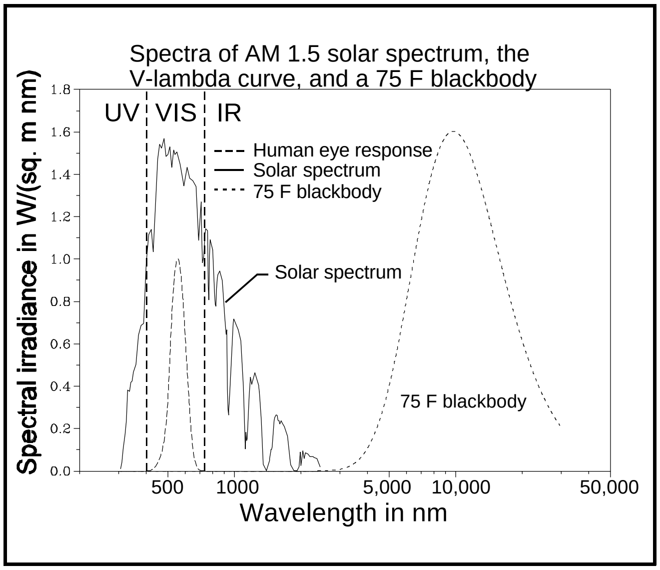

Figure 7. Spectral distributions of solar radiation, the human eye response, and a room temperature blackbody. Human eye response and blackbody curves have been scaled vertically for comparison purposes.

More is said about the effects illustrated in Figure 7 in subsequent sections, but introducing the information here provides part of the motivation for the material that follows.

The next step is to learn how to describe the propagation of solar radiant heat through a fenestration system more precisely, using the system of terminology and units used world-wide in the field of radiometry. An introduction to the concept of solid angle is needed first. This leads us to the angular selectivity of fenestration system optical and solar gain properties.

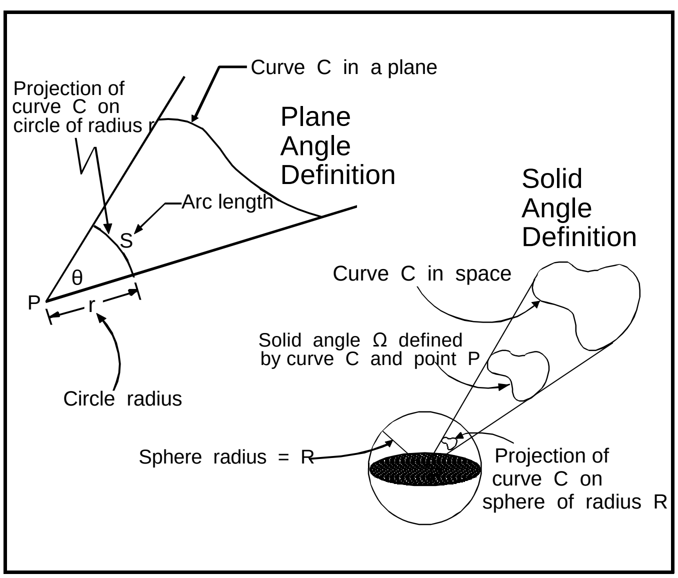

Figure 8. Plane and solid angle definitions.

Solid Angles and Directional Measurements

The discussion begins with the definition of a *plane angle*. A plane angle can be thought of as the space between two lines that intersect in a plane. Alternatively, it can be described as the arc length *s* of the projection of a curve between two points in the plane onto a circle of radius *r* centered at the point of definition of the angle, divided by the radius:

$$\theta = \frac{s}{r} \qquad \textbf{(8)}$$

See Fig. 8. As defined in Eq. 8, the plane angle is unitless. However to aid in discussions and understanding, the unit of the plane angle θ defined in Eq. 8 is the *radian*. There are 2π radians in a circle. The degree is another unit of plane angle measure. There are 360 degrees in a circle. Thus the conversion factor for converting angles in radians to degrees is 2π/360 or π/180.

A solid angle is a kind of three-dimensional angle, and it is defined similarly. A *solid angle* is the area of the projection of a closed curve in space onto a sphere of radius *R*, divided by the square of that radius:

$$\Omega = \frac{A}{R^2} \qquad \textbf{(9)}$$

The solid angle is likewise unitless as defined in Eq. 9. However, to aid in discussions and understanding, the unit of the solid angle Ω defined in Eq. 9 is the *steradian* abbreviated *sr*. There are 4π sr in a sphere, 2π in a hemisphere.

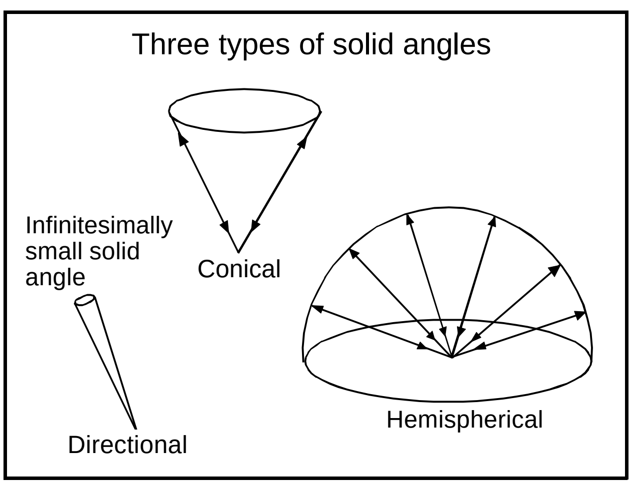

Figure 9. Illustration of three different sizes of solid angle commonly used.

There are three different kinds or sizes of solid angles that are found frequently in the literature and in standards dealing with the measurement of optical properties: directional, conical, and hemispherical. They are illustrated in Fig. 9. These become important when talking about the optical properties of materials because it matters in such discussions how the materials are illuminated and how the reflected or transmitted radiation is collected. This information is needed for discussions of the optical properties of materials, and in the definitions to follow.

The *directional* term refers to infinitesimally small solid angles used primarily for mathematical treatments in radiometry and photometry. *Conical* solid angles are finite solid angles subtended by generally small circular apertures and are the most common solid angles involved in the incident beam with spectrophotometric measurements of samples of glazings and other fenestration components. A *hemispherical* solid angle is generally used for the collection of transmitted radiation in a spectrophotometric measurement using an integrating sphere attachment. The transmittance so measured is commonly referred to as the *conical-hemispherical transmittance*. For more information about this terminology, see Chapter 6 of Ref. 2. It is the conical-hemispherical transmittance and the reflectances of glazing systems that are determined by the Window computer program developed by Lawrence Berkeley Laboratory.

Radiometry

Radiometry is the field of physics dealing with the measurement and description of radiant flux. It includes the definition and measurement of optical properties of materials. A fundamental quantity in radiometry is the *flux* or power (rate of flow of energy per unit time) contained in a defined beam of

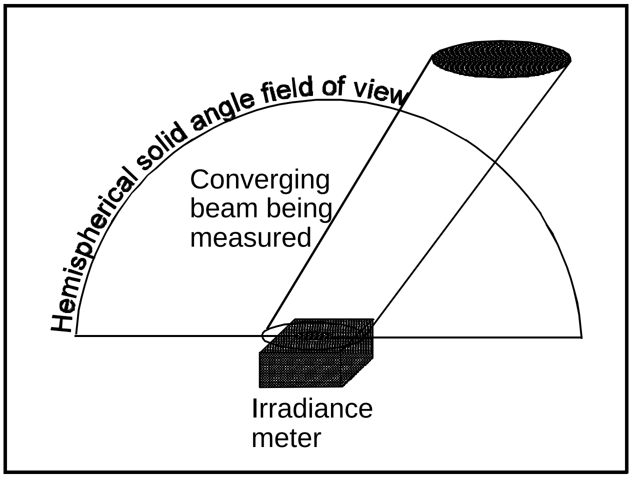

Figure 10. An irradiance meter views a whole hemispherical solid angle but it may measure flux coming from only a limited portion of that field of view.

radiation. The *radiant flux* is measured in watts. The flux per unit area on a defined surface at a point in a beam of radiation is called the *irradiance*. Irradiance is flux per unit area and has the units of watts per square meter.

In radiometry the term *intensity* is reserved for the flux per unit solid angle emanating from (or converging to) a point in space, in units of watts per steradian. While it may be an appropriate quantity for describing the flux produced by a small filament light source, it has little use in the fenestration industry and we will avoid its use in the remainder of this discussion.

The fourth and final quantity found often in radiometric discussions is the *radiance*. Radiance is the quantity to use when one desires to describe the directional distribution of flux emanating from a surface, such as the wall of a room or the downwelling diffuse sky radiation from the sky "dome". Radiance is flux per unit area and per unit solid angle. It has units of $W \cdot m^{-2} \cdot sr^{-1}$.

When you look at the wall of a room, the flux received by the tiny pupil of your eye from a point on the wall fills a small solid angle and the apparent "brightness" of the point on the wall is related to the radiance of that point in the direction toward your eye. Radiance is an important quantity, but there is little need for it in this publication.

In discussing fenestration energy performance, especially the solar gain part of that, we need to speak of the total flux and the flux per unit area incident on the fenestration aperture as well as the portion of that which enters the window as heat gain. The symbol for radiant flux is the Greek letter uppercase phi: Φ, and the symbol for irradiance is E. Thus, if A is a small area at a point in a surface emitting radiation or through which radiant flux is passing, then the irradiance at that point (the average over the small area) is $E = \Phi/A$, and it has units of watts per m^2, abbreviated $W \cdot m^{-2}$.

Suppose a beam of radiation falls on an irradiance meter. The situation is illustrated in Fig. 10. The Figure shows that the field of view of an irradiance meter is the whole 2π steradian solid angle of a hemisphere. The flux on the sensitive surface of the meter may only come from a small portion of that field of view. An accurate irradiance meter will record the flux per unit area falling on it no matter how it is distributed over the hemisphere.

Optical Properties of Materials

With this short background on radiometry we can move to the subject of the optical properties of materials. The main optical properties of interest here are the *transmittance, reflectance, and absorptance*. These quantities are distinguished from the related quantities *transmissivity*, *reflectivity*, and *absorptivity*, as follows.

The "*-ivity*" ending refers to the inherent properties of a bulk sample of material. The "*-ance*" ending refers to the property of a specific thickness or sample of a substance or combination of substances.

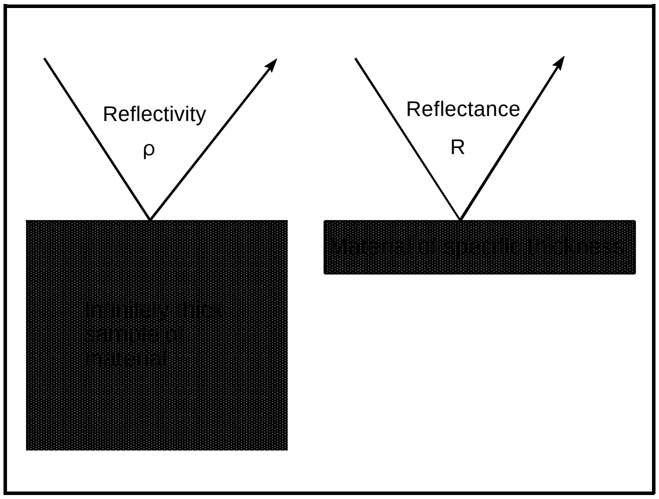

Figure 11. Illustration of the differences between "-ivity" and "-ance" quantities.

See Fig. 11. An analogy is with electrical resistivity, which is the electrical resistance per unit length of a material. Once you put wires on either end of a specific length or thickness of an electrically resistive material, the resultant electrical property, measured between the ends of the length of material, i.e. at the wires, is the resist*ance* of the particular *resistor* you have just made.

Thus, the *reflectivity* of a material is the faction of flux incident upon the polished surface of an infinite slab of that substance that is reflected. If the substance is formed into a parallel plate with polished surfaces a fixed distance apart, then one can determine the *reflectance* of the particular plate. One often speaks of the portion of the reflectivity of a polished surface due only to reflection from the interface, as if the volume of material below the interface returns none of the incident radiation to the surface. This will be used later when talking about glazing optical properties.

The *transmissivity* of a substance can be defined as the fraction of flux transmitted inside the substance per unit length along a ray of propagation. Once the substance is made into a parallel plate with polished sides, it can have an overall *transmittance*. The *absorptivity* of a material is correspondingly the absorptance per unit length. A parallel plate of the material can have an overall *absorptance.*

There is a formula attributed to Augustin J. Fresnel for calculating the interface reflectivity of transparent substances such as glass and plastic, if the refractive index of the transparent material is known. When the substance is made into a parallel plate with polished surfaces the overall transmittance and reflectance can be calculated from knowledge of the reflectivity of the surfaces and the absorptivity of the substance. The reflectance and transmittance of such a plate with a refractive index of 1.55 that is 3 mm thick and has an absorptivity of 0.01 per meter are plotted in Fig. 12.
At a given wavelength, or over a defined range of wavelengths, the transmittance of a glazing system is the same in both directions through the system (left-to-right or right-to-left). The reflectances, however,

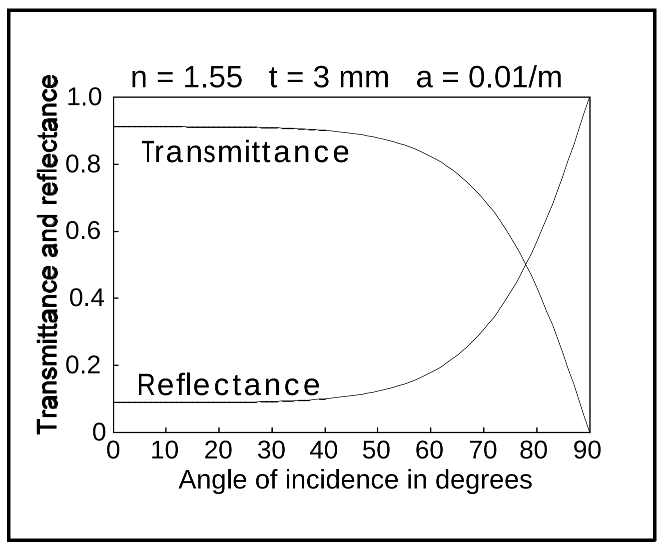

Figure 12. Fresnel transmittance and reflectance of a plane parallel plate of glass. n = refractive index, t = thickness, a = absorptivity

are not necessarily the same on both sides! The Window 4 program calculates one transmittance for a glazing system and two reflectances, one each for the "front" and "back" sides. One side of a sheet of glass can be a mirror with high reflectance and the other a dark black ink with low reflectance, even though the transmittance is the same in both directions.

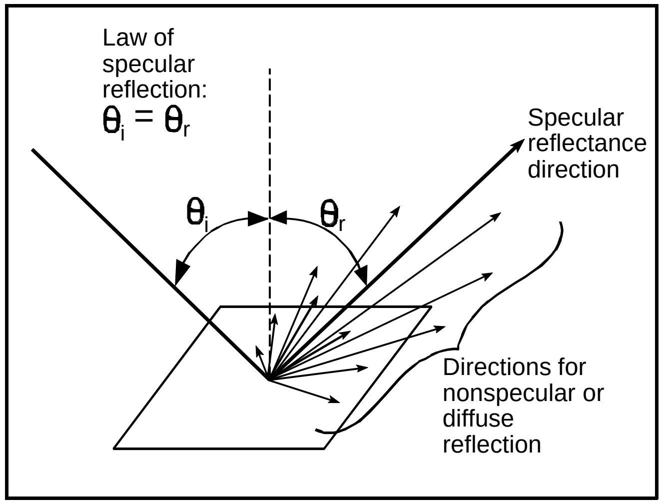

Figure 13. Illustration of diffuse and specular reflection.

This is how a "one-way" window works. It's not really one-way in transmission. It is just that the “secret” room is kept dark and the observation room is bright. There is much more light reflected from the window between them back into the brightly lit room being observed than is transmitted by the window from the darkened “secret” room. Thus persons in the observation room see only their reflection in the window, not the very small amount of light passing through the window from the other side.

This effect works in a similar fashion with ordinary tinted or reflective windows in buildings, making it difficult to see inside during the daytime (but easy to see out) while easy to see well-lit interiors at night from the outside (but difficult to see out from the inside at night).

The properties shown in Fig. 12 are what are called *specular* optical properties, because they relate to what happens to a *collimated* (parallel rays) beam of radiation reflected and transmitted according to the laws of geometrical optics, namely that the angle of reflection equals the angle of incidence and that the angle of refraction θ_{rf} from air into a polished slab of material follows Snell’s law:

$$\sin(\theta_{rf}) = n \sin(\theta_i) \qquad \textbf{(10)}$$

where n is the refractive index of the material and θ_i is the angle of incidence.

Many materials do not exhibit specular optical properties. These are materials for which an incident beam is scattered into many directions upon reflection or transmission. Liquid milk is an example of such a substance. Most materials have both specular and non-specular (called *diffuse*) properties, as illustrated in Fig. 13 for reflection. A similar diagram could be drawn for transmission, showing both a specular and a diffuse component to the transmitted radiation.

The NFRC solar gain standard, NFRC 200-95, provides a procedure for calculating the solar heat gain coefficient of fenestration systems containing glazing systems with only specular optical properties. If a window has one or more glazings or other elements, such as integral shades or louvers, with even a modest diffuse component, that window is excluded from the NFRC 200 calculations.

Glazing systems, including any integral shading or beam-controlling layers, that are designed for re-directing incident radiation, differently from simple specular reflection and transmission, are termed *angularly selective* systems. Angularly selective fenestrations are also excluded from the calculation procedure described in NFRC 200-95.

An example of a strongly angularly selective glazing system that is specifically excluded from calculations with NFRC 200 is shown in Fig. 14.

In preparation for discussing the optical properties of materials, including both angular and spectral selectivity effects, it will be helpful to describe the spectral versions of the radiometric quantities introduced earlier.

Spectral Quantities in Radiometry

If we consider the amount $\Delta\Phi$ of radiant flux in a small wavelength interval $\Delta\lambda$ centered at wavelength λ, then a quantity called the *spectral radiant flux* Φ_λ can be defined as $\Delta\Phi/\Delta\lambda$, if $\Delta\lambda$ is made to be arbitrarily small. The units of Φ_λ are W/nm.

The *spectral irradiance*, E_λ can similarly be defined as $\Delta E/\Delta\lambda$ in the limit as $\Delta\lambda$ is made arbitrarily small. It will have units of $W{\cdot}m^{-2}{\cdot}nm^{-1}$, or watts per square meter and per nanometer.

Spectral intensity and *spectral radiance* have similar definitions and units. For more information, consult textbooks dealing with radiometry and photometry[2]. The optical properties of transmittance, reflectance, and absorptance vary with wavelength over the solar spectrum for most glazings. In consequence, the Window 4 program must perform its calculations of solar gain on a wavelength-by-wavelength basis. If we designate the spectral transmittance as $T(\lambda)$ and the incident solar spectral irradiance as E_λ then the directly transmitted portion of the solar gain, at wavelength λ, is given by $T(\lambda)\,E_\lambda$ and the directly transmitted portion of the solar heat gain coefficient over the solar spectrum is

$$T_s = \int_{350}^{3500} T(\lambda)\, E_\lambda\, d\lambda \qquad \textbf{(11)}$$

Replacing the integral with a sum we have the equivalent approximate equation

$$T_s = \sum_{i=1}^{N} T(\lambda_i)\, E_{\lambda i}\, \Delta\lambda_i \qquad \textbf{(12)}$$

This "solar spectrum weighting" process is the one used by Window 4 to calculate the solar transmittance of a glazing system. Eqs. 11 and 12 show how the interaction of incident spectral irradiance with spectral transmittance can produce different solar transmittances, when the spectral shapes of either the incident solar spectrum or the spectral transmittance vary. This brings up the question of solar weighting, solar spectral variations, and the effect on SHGC.

Figure 14. Angularly selective glazing system that cannot be simulated with Window 4.

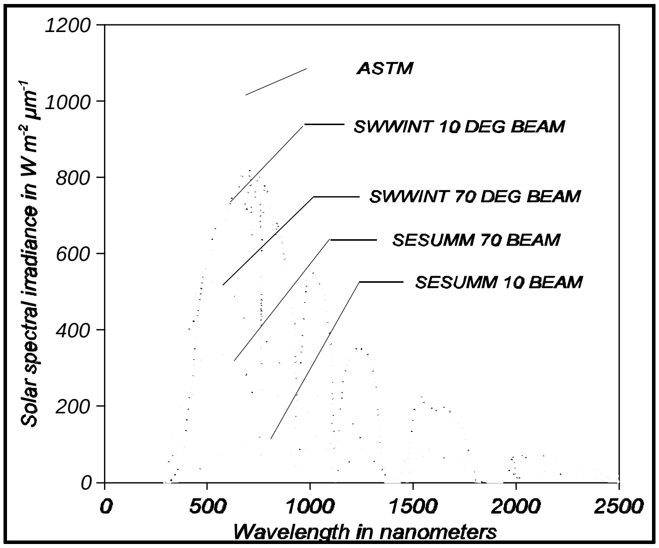

Figure 15. Direct beam solar spectral irradiances for four different clear sky atmospheric conditions and for an ASTM standard. 10° and 70° solar altitude angles were used.

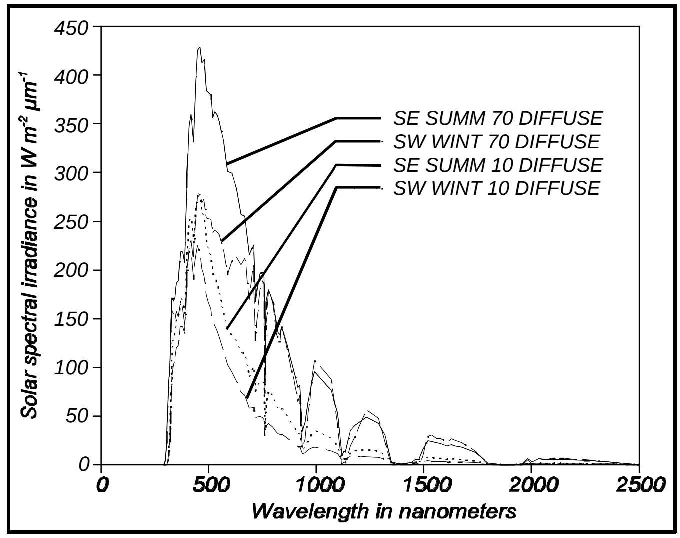

Figure 16. Four cloudless sky diffuse spectral irradiance distributions.

Solar Spectrum Variations

I have studied the sensitivity of the solar heat gain coefficient to variations in both the shape of the incident solar irradiance spectrum and the angle of incidence[3]. The spectral shapes of the ASTM standard spectrum used by the Window 4 program and various direct beam and diffuse sky spectra were compared. The comparisons are shown in Figs. 15 and 16.

It can be seen that there are significant differences between the shapes of these spectra, differences that are of little consequence for most normal window glass, having a relatively small amount of spectral selectivity--with spectral transmittances varying little over the solar spectrum.

For strongly selective glass, such as some tinted glazings and those with a "low-e squared"-type coating, however, these solar spectral differences can produce shifts in the calculated solar heat gain coefficients for the glazing systems involved. When the sun is lower in the sky its spectral shape is shifted toward the red (high wavelength) portion of the spectrum and blue sky light has a spectrum that is considerably shifted toward the blue end of the spectrum. These shifts alter the SHGC of glazing systems with strong red or blue spectral selectivity.

Figure 17 shows a comparison of the spectra of direct beam sunlight and diffuse sky light incident on a vertical west-facing window, with the sun close to the horizon in a southeastern U.S. summer sky.
In analyzing the effects of changing source spectra on glazing system SHGC values, one can use the Window 4 program. It is possible to change the solar spectrum used by Window 4 to calculate SHGC. The Window 4 operating manual should be consulted for details about substituting other solar weighting functions. It is anticipated that Window 5 will be designed to make substitution of solar weighting functions easier.

The SHGC of a spectrally selective glazing system can be quite different for different spectra, as discussed next.

The procedure used in Window 4 is being standardized by the American Society of Heating, Refrigerating, and Air Conditioning Engineers (Special Project Committee 142P).

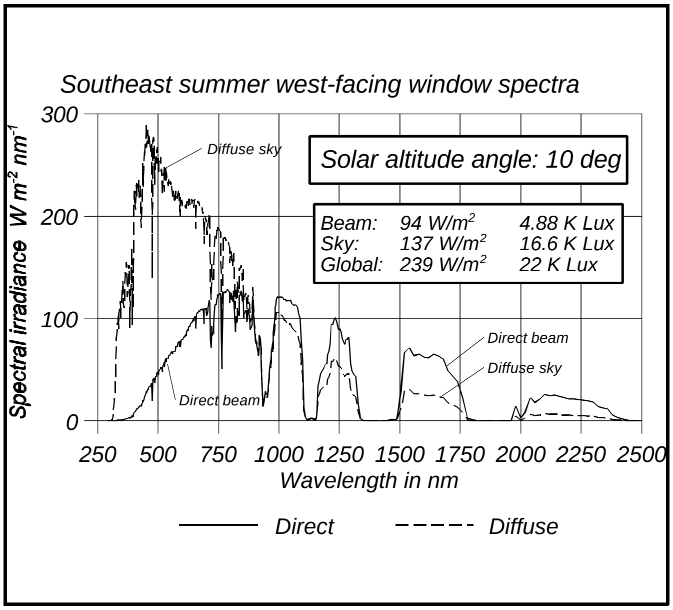

Figure 17. Direct and diffuse solar spectra for a low sun angle, showing the strong red shift of the setting sun.

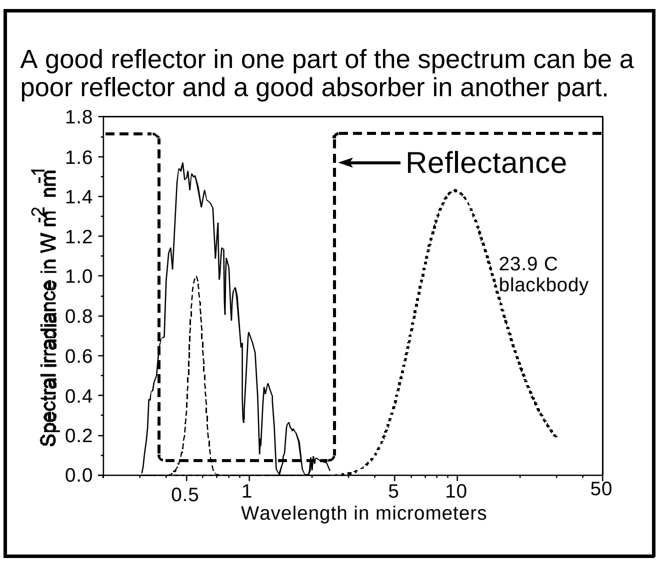

Figure 18. Illustration of one form of idealized spectral selectivity, for solar heat gain admission and trapping.

The Window 4 program can be used to estimate the actual solar heat gain of a window for a real spectral distribution of incident radiation. For this purpose one can replace the default standard solar spectrum used in Window by another more realistic spectrum for the conditions involved in making the estimate. For strongly spectrally selective glazing systems, as we will see, changes in the spectral distribution of incident radiation can cause a noticeable change in the solar heat gain coefficient of the glazing system. Before discussing this, additional information about optical properties and glazing design is needed.

Recall that the sum of the transmittance, reflectance, and absorptance is 1.0. There is another relationship amongst the optical properties that is of interest and importance. It is called Kirchhoff's Law:

$$A(\lambda, \theta, \phi) = \epsilon(\lambda, \theta, \phi) \qquad \textbf{(13)}$$

where θ and ϕ are angles defining the directional dependence of the spectral absorptance $A(\lambda)$ and the spectral emittance $\epsilon(\lambda)$. A consequence of Eqs. 1 and 13 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.

Spectral Selectivity in Windows

Figure 18 illustrates the basic concept of *spectral selectivity*. A good reflector in one part of the spectrum (the infrared portion) can be a poor reflector (and a good transmitter) in another part (the solar portion). A high reflectance in the long-wavelength infrared portion of the spectrum, because of the conservation of energy ($T + R + A = 1.0$) means a low transmittance and absorptance and, because of Kirchhoff’s Law, therefore, a low emittance as well.

This is the principle of operation of the *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 inwards. The "low-e" in "low-e coating" refers to a low emittance over the long-wavelength portion of the spectrum. It doesn't matter, for the purposes of reflecting thermal infrared radiation, what the emittance is over the solar spectrum. It could be high or low, but on most windows it is relatively high over the solar spectrum. "Low-e" means low emittance over the range from 3 to 50 micrometers.

Figure 19 shows how the concept of spectral selectivity can be carried still further, to generate a glazing system with improved performance for hot climates. In this case the sharp *reflection edge* that the ideal low-e coating exhibited just past the end of the solar spectrum in Fig. 18 is shifted closer to the edge of the visible portion of the spectrum, seen in Fig. 19 as a drop in the transmittance at the right side of the visible portion of the spectrum. The effect is to reflect the near infrared portion of the solar spectrum back outside, *reducing solar gain*, while still admitting visible light in the wavelength region below about 800 nm.

The reduced IR transmittance in Fig. 19 is ideally accomplished by high reflectance and low absorptance (meaning low emittance), but it can also be accomplished by high IR absorptance, if some means can be found for reducing the inward flowing fraction

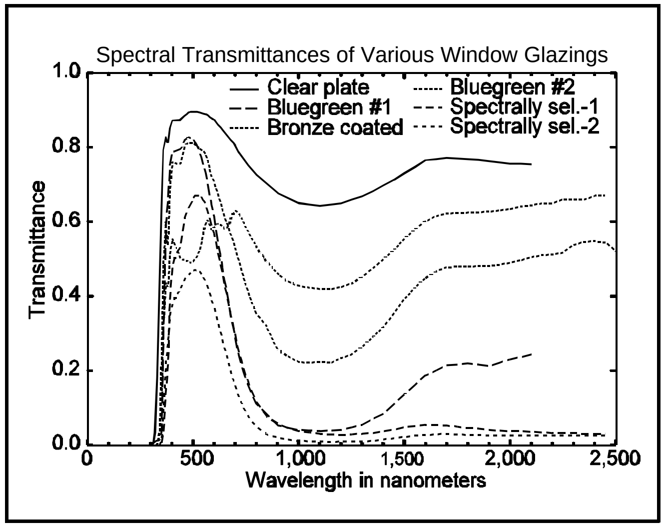

Figure 20. Spectral transmittances of several commercially available glazing systems.

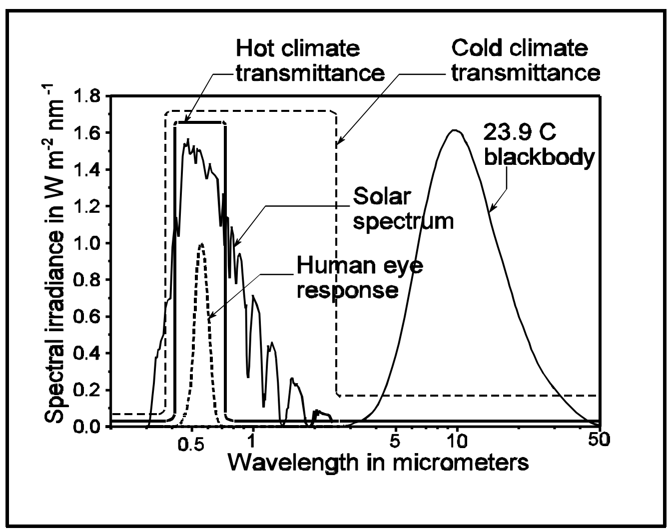

Figure 19. Illustration of spectral selectivity for hot and for cold climates.

of the absorbed solar radiation*. Because the coating for hot climate glazings has an emittance which is low over both the near (solar) infrared and far (thermal) infrared portions of the spectrum, one manufacturer calls this coating "low-e squared."

How well do real glazing systems approach the ideals detailed above? A sample of the spectral transmittances for some commercially available glazing systems is shown in Fig. 20. This shows a fairly gradual trend from a transmittance that exhibits little spectral selectivity to one which is strongly peaked over the visible portion and nearly zero everywhere else.

Even stronger spectral selectivities are possible, and glazings with what can be called *inverted spectral selectivity* are possible. These are glazing systems whose transmittances over the visible are significantly less than their infrared transmittances. Examples of more strongly spectrally selective glazing optical properties will be shown in a subsequent section. The ratio of visible transmittance to solar heat gain coefficient, which I call the *light-to-solar gain* or *LSG* ratio, is a measure of the spectral selectivity of a glazing system. The more this ratio departs from a value of 0.8, the stronger is the spectral selectivity. This is discussed more subsequently.

*One means of having a low solar gain with a spectrally *absorbing* window pane is to *insulate* the interior of the building from this hot, solar-absorbing outer glazing by the use of an insulating dead-air space, plus a second interior clear pane of glass. If a low-e coating is applied to the inside of the hot outer lite, radiation from it to the interior will be reduced and conduction and convection of heat from it is reduced by both the insulating gas space and the second pane. Several manufacturers offer this kind of non-reflecting spectrally selective glazing system for commercial buildings having large loads on their cooling systems, even in winter months.

Solar Heat Gain Coefficient

Let M be the number of glazings in a multipane glazing system. The glazing system solar heat gain coefficient $SHGC_g$ is given by

$$\begin{aligned} SHGC_g &= T_s + N_{i1} A_{s1} \\ &+ N_{i2} A_{s2} + \ldots + N_{iM} A_{sM} \end{aligned} \qquad \textbf{(14)}$$

which can be written as

$$SHGC_g = T_s + \sum_{j=1}^{M} N_{ij} A_{sj} \qquad \textbf{(15)}$$

Window 4 calculates the solar heat gain coefficient using a version of this equation. The optical properties T_s and A_{sj} are determined spectrally, on a wavelength-by-wavelength basis as described above. The inward flowing fractions N_{ij} are determined using a one-dimensional heat transfer algorithm that accounts for the flux absorbed in each layer, and the convection transfers across the gas spaces between the layers.

For spectrally selective glazing systems, spectral calculations are particularly important.

Although the NFRC specifies SHGC at normal incidence, at an incidence angle of zero degrees, one can see from the plots in Fig. 21 that for specular glazing systems the SHGC is nearly constant from 0 to about 40 degrees, but it then varies substantially for angles of incidence greater than about 50 degrees.

ASHRAE Solar Gain Historical Background and the Limitations of the Shading Coefficient

Before modern complex windows were marketed, 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, in watts per unit area, in tables of what were called *solar heat gain factors* (SHGF). These factors, having units of watts per square meter or Btus per hour and per square foot, 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 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 was relatively easy. He or she first figured out the angle of direct beam incidence on the glass for a typical peak solar gain date and time. This was done using equations provided in the ASHRAE Handbook of Fundamentals or 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 a set of tables provided for the purpose in the ASHRAE Handbook. These same tables provided the solar heat gain factor for clear single pane glass (the so-called *standard reference glazing*) under these conditions. The procedure has been computerized by David Tait of Phoenix, Arizona, and the latest version of his program is called WinSARC.

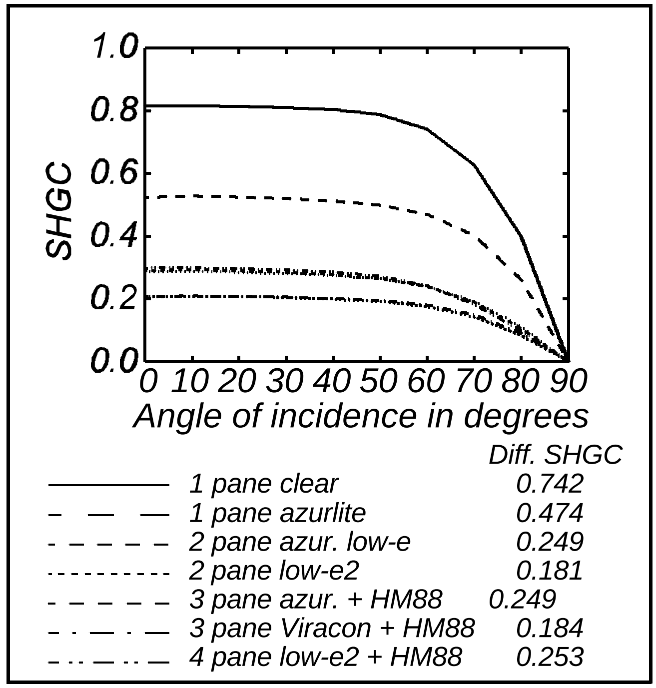

Figure 21. Plots of SHGC versus angle of incidence for 7 commercially available glazing systems.

The next step was simply a matter of multiplying the solar heat gain factor by the area of the glazing, producing the solar gain expected in watts or in Btu's per hour. This provided very directly the solar gain for single pane clear glass.

When tinted glazings came along, the procedure was modified a little, and the concept of *shading coefficient* was introduced. The idea behind the shading coefficient was to find a multiplicative factor for tinted glass that allowed the engineer to correct his previously determined solar gain number in Btu's or watts through clear glass to the correct value through the tinted glass being specified.

This plan worked just fine, as long as it was used for single pane tinted glass whose angle-dependent optical properties varied with both angle and incident spectrum the same way the optical properties of single pane clear glass did. The method of determining SHGF for multiple pane clear and non-spectrally selective tinted glass was modified somewhat so that the shading coefficient method could be retained. When modern windows with coatings and other complexities came along, however, the old shading coefficient method proved inadequate (even though it still continues to be widely used). Here's why.

Glazing optical properties are in general both wavelength and angle dependent. This makes the SHGC a wavelength and angle-dependent quantity, as expressed in the equation

$$F(\lambda, \theta) = T_s(\lambda, \theta) + N_i A_s(\lambda, \theta) \qquad \textbf{(16)}$$

where λ is the wavelength and θ the angle of incidence.

The shading coefficient is 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 and spectral distribution of incidence:

$$SC = \frac{F(\lambda, \theta)_{Test}}{F(\lambda, \theta)_{Ref}} \qquad \textbf{(17)}$$

The beauty of the shading coefficient concept is that this ratio remains constant as the solar spectrum varies and as the angle of incidence varies, at least for single pane clear, many single pane tinted glazings, and some double pane systems. In such cases a single number can be used to convert from the reference SHGC found in the ASHRAE Handbook of Fundamentals to the SHGC for the selected system at the angle of incidence of interest.

In consequence, since the SHGC for the standard reference glass is 0.87 at normal incidence and for ASHRAE standard summer conditions, the relationship between SHGC and SC at normal incidence is easy to calculate. The SC is 1.15 times the SHGC of the glass at normal incidence and with a standard solar spectrum. (The value of the SC for standard reference glass is 1.0, but the SHGC for this glass is 0.87 at normal incidence and a standard solar spectrum.) Thus, if one is given a value for the SC of a glazing system at normal incidence and for a standard solar spectral distribution, the SHGC of that glazing system will be 0.87 times its SC, *but only for normal incidence and for the standard solar spectral distribution*.

When more spectrally and angularly selective multiple pane and coated glazings are introduced, the simple relationship between shading coefficient and solar heat gain coefficient is no longer valid and the shading coefficient becomes a variable rather than a constant.

This is because these more complicated glazing systems do not have the same angular response as single pane clear glass, nor do they have the same spectral response, in general. Thus the ratio of solar heat gain coefficients that defines the shading coefficient in Eq. 17 is no longer constant. Rather than introduce a whole new table of shading coefficient dependencies on angle of incidence and solar spectrum, it was decided by NFRC and ASHRAE to work with the SHGC directly. SHGC has the added advantage of being applicable to opaque framing elements as well.

Window 4 does calculate the SC for a glazing system after calculating the SHGC, but the value given is only for normal incidence and with the standard solar spectral distribution built into Window 4.

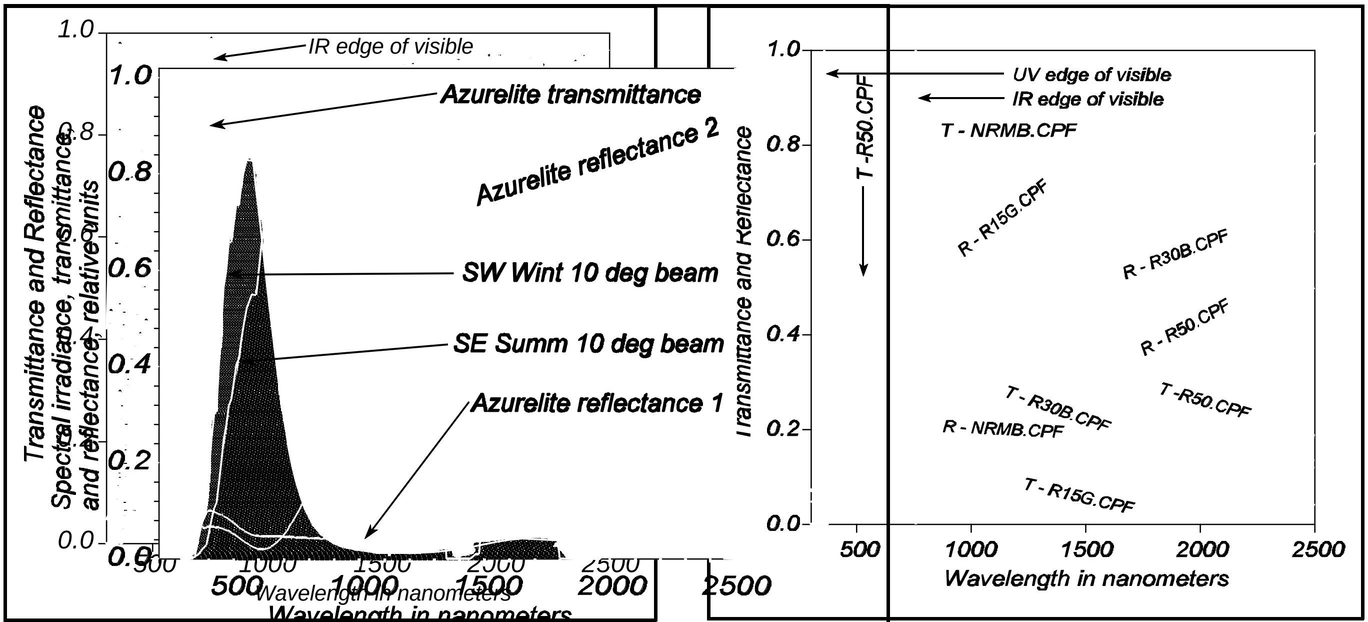

Figure 22. Spectral transmittances and reflectances of several commercially available glazings.

Figure 23. Spectral transmittances and reflectances of several glazing systems, including some with what might be called *inverted spectral selectivity*.

Figure 25. Comparison of the spectral optical properties of single pane azurelite glass with the irradiance spectra of direct beam radiation at a solar altitude angle of 10 degrees, through two different atmospheres. All curves except the reflectance curves are normalized to 1.0.

The study cited in Ref. 3 examined the dependency of SHGC on changes in the shape of the solar spectrum and on incident angle in some detail.

Figures 22 and 23 show the spectral optical properties of several of the spectrally selective glazing systems examined. For each of the 18 glazing systems looked at in that study, the maximum SHGC variation covering the 5 direct beam solar spectra used was divided by the average SHGC for that glazing system, and the result was plotted versus the light-to-solar-gain ratio, LSG, defined previously. The results are presented in Fig. 24. For more details about this study, consult Ref. 3.

It is seen that the SHGC variation with incident spectral variation is significant for strongly spectrally selective glazing systems, as indicated by departures of the LSG ratio from 0.8. For those that are not spectrally selective, like the clear, “water-white” glass labeled STRPH_2.PPG in Fig.22, having almost constant spectral

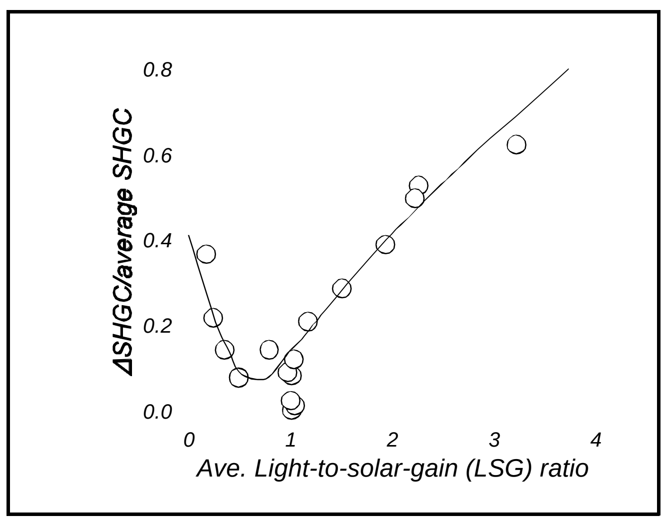

Figure 24. Variation of glazing system solar heat gain coefficient with changes in incident beam solar spectral irradiance distribution, as a function of glazing spectral selectivity, indicated by the LSG ratio.

transmittance, it doesn't matter what the incident spectrum is. The SHGC is the same across a variety of solar spectra.

For glazings with stronger spectral selectivity, as indicated by the LSG ratio, it *does* matter what spectrum is incident on the glazing. The fractional change in SHGC can be as high as 0.6, meaning a variation by as much as 60% in the SHGC as the solar spectrum changes.

Figure 25, taken from Ref. 3, is provided to answer the question of how such wide variations in SHGC can be produced with relatively modest changes in solar spectral distribution.

The optical properties of this glazing are plotted along with two 10-degree sun angle beam spectra, all normalized to 1.0. It is clear from this that this azurlite glazing is strongly spectrally selective, passing the short-wavelength components and rejecting the long-wavelength ones. Low sun angles were used to accentuate the spectral differences between the two atmospheres. Since the southeast summer low sun spectrum is substantially shifted toward the red end of the spectrum, compared to the southwest winter one, the former will produce a substantially lower SHGC, and this is observed clearly in the SHGC values for this glazing with the two different spectra.

- ● *Single pane clear*
- ■ *1 pane blue tint*
- ▲ *1 pane green tint*
- ▼ *1 pazure-ssabs*
- ◆ *3 p1-ssrefl*
- ● *3 p2-ssrefl*
- ● *2 pane with low-e coating*
- ■ *3 pr50-ssinv*
- ▲ *3 pnrmb-jag*
- ▼ *3 pr16g-jag*
- ◆ *3 pr30b-jag*
- ● *1 pane Ultima1 idealized glass*
- ● *1 pane Ultima2 idealized glass*
- ■ *2 pane blue and loe glass*
- ▲ *2 pane bronze and low e glass*
- ▼ *2 pane green + specsel*
- ◆ *2 pane low-e plus sharp cut-off glass*

Figure 27. Key to line types shown in Fig. 26 and 28. Codes are from the Window 4 Glazing library.

Changes in SHGC with angle of incidence for a single solar spectral distribution (the ASTM standard spectrum) were presented for a few glazings in Fig. 21. Using the 18 glazing systems examined in Ref. 3, and normalizing the plots to a SHGC value of 1.0, we see in Fig. 28 the changing shapes that different glazing systems have. The topmost curve in Fig. 26 is for two hypothetical glazings, called "ultima1" and "ultima2" having solar transmittance approximately 1.0 over the visible portion of the spectrum, very low outside, and with solar reflectance the inverse of this, near zero over the visible and nearly 1.0 outside the visible. Because of the lack of absorption in these glazings, the drop of SHGC with increasing angle of incidence occurs at larger angles of incidence.

A final way of looking at SHGC variations with angle is to divide the SHGC for each glazing by the SHGC of single pane clear glass at that same angle, using ordinary clear plate glass as the base case. The resulting ratio is equivalent to the shading coefficient, since it is defined to be this ratio.

The resulting ratios are plotted in Fig 28, providing a test of the constancy of the shading coefficient with changing angle of incidence. It is clear that SC is not constant for some glazings at angles of incidence exceeding about 40 degrees.

Several conclusions can be drawn from these results. First of all, any attempt to retain the shading coefficient method for calculating the solar gain of these advanced glazing systems must accommodate SC variations with incident spectral distribution and changing angles of incidence above 40 degrees. The

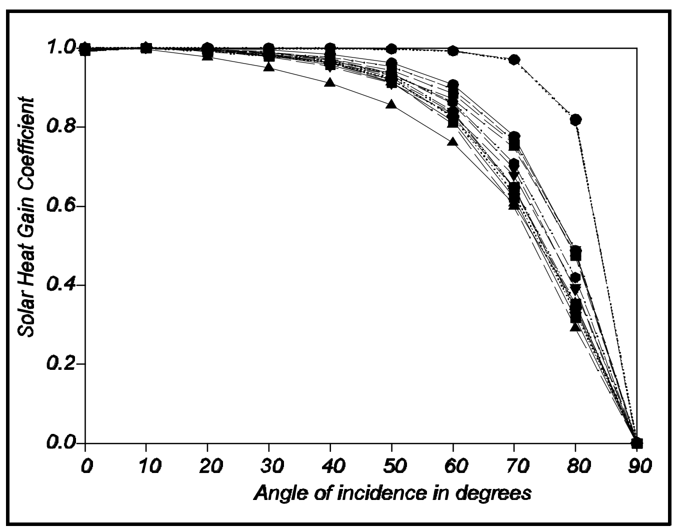

Figure 26. Variation of SHGC with angle of incidence, normalized to 1.0, for a variety of glazing systems.

Window 4 program has been widely accepted by the window industry in the U.S., and has been adopted as the official means of determining the solar gain properties of windows rated by the NFRC.

A better alternative to retaining the shading coefficient method would seem to be use of the Window 4 program directly, for calculations of fenestration solar heat gain. Window 4 properly performs its calculations on a wavelength-by-wavelength basis.

It is suggested that the program be modified to make it easier for the user to enter any of a variety of incident solar irradiance spectra, either from a fixed set of "standard" files of such data or from a separately adopted cloudless sky solar spectrum calculational procedure, such as the one used in performing the calculations reported in Ref. 3. It would also aid the user if a specified angle of incidence could also be entered for solar gain calculations, in addition to the default normal incidence case used for rating windows. This enhanced capability would allow the design engineer to choose the solar spectrum best representing the atmospheric conditions present for the situation being simulated. The Canadian "Vision" program performs calculations similar to those of the Window program[4].

Examining the angle-dependent results presented in Ref. 3 and above, it is clear that SHGC remains essentially constant for incident angles below about 40 degrees. Vertical windows, sloped glazings, and roof skylight windows in general receive significant quantities of beam radiation at angles greater than this over the course of a year[5], especially during summer months for vertical glazings and for nearly every clear day for sloped and horizontal glazings. Any calculations of solar gain above 40 degrees, therefore, must account for the reduced SHGC values at those angles.

The recommendations of Ref. 3, based on these results, are worth repeating here:

It is recommended that approaches to fenestration solar radiant heat gain calculation, relying upon constant, immutable, values of the shading coefficient for each glazing system, be abandoned for all fenestration systems employing strongly spectrally selective glazings and for those whose SC changes with angle of incidence.

A broadband SC method can be retained as an interim measure, for applications not requiring high accuracy, as long as the limitations of this approach are understood.

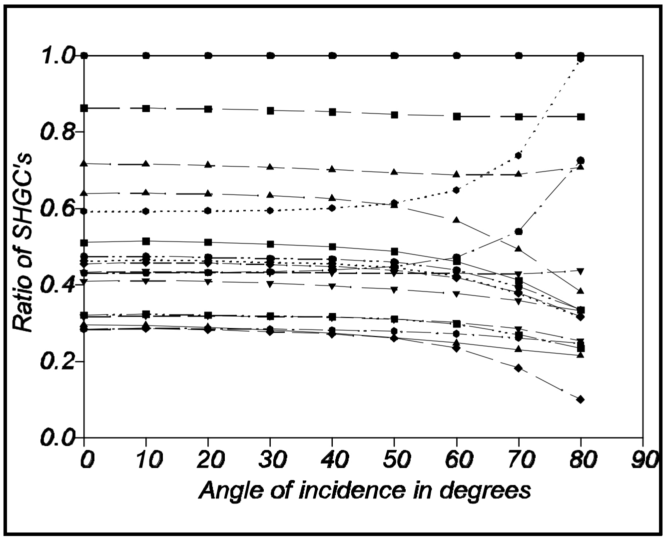

Figure 28. Ratio of SHGC to that for clear pane standard reference glass (equal to the shading coefficient) versus angle of incidence for a variety of glazing systems. A key to the different glazing types is shown in Fig. 27.

For more exacting calculations, a wavelength-by-wavelength and angle-by-angle calculational method, such as is performed by the Window 4 program[1], and described in forthcoming ASHRAE standard 142, should be used. With this approach it is possible for the user to replace the standard solar spectral distribution used by the computational procedure with any of a variety of other possible spectra more representative of the atmospheric conditions of the intended calculation. With this solar spectrum replacement, the transmitted spectral flux in Watts (or Btu/hr) per nanometer of wavelength interval is calculated directly and then integrated to yield the Watts (or Btu/hr) of directly transmitted radiation. To this the program then adds the inward flowing fraction of the absorbed radiation, to provide the total solar radiant heat gain in Watts (or Btu/hr) with greater accuracy than is possible with the broadband methods. This approach has the advantage of being able to perform these calculations for any angle of incidence as well, as long as the angle-dependent optical properties of the fenestration system are known.

There is a significant limitation in this proposed procedure. As mentioned previously, the method of determining angle-dependent optical properties presently employed by the Window 4 program does not fully account for certain interference and other effects in the layers of coated glasses, introducing possible errors in the calculation. Experimental angle-dependent measurements on a few selected coated glazings have been performed by M. Rubin at LBL and he reports that the residual errors in the Window 4 calculational algorithm are modest in magnitude[5]. Planned future additional measurements are expected to produce improved formulae for the calculation of angle--dependent optical properties of coated glazings in a future version of the Window 4 program.

New Approach to Solar Gain Analysis

Due to the limitations mentioned above, and the prevalence of spectrally selective multipane windows in the marketplace, the Handbook Subcommittee of ASHRAE's Fenestration Technical Committee (TC 4.5) has decided to phase out the old shading coefficient method of calculating solar gain[6] and to replace it with a SHGC method, called here the "spectral method" since it relies basically upon the calculation of solar gain on a wavelength-by-wavelength basis, as the calculation is performed by the Window 4 (or Vision) program.

The old broadband shading coefficient method will still be permitted for single and double pane clear and tinted glazings exhibiting little spectral selectivity. In the future, the reader will be referred to previous editions of the ASHRAE Handbook or to any of a variety of textbooks for information about the shading coefficient method.

For all other glazing systems and for the most precise calculations, with windows known to exhibit strong spectral selectivity, the practitioner will be encouraged to calculate solar heat gain using the spectral method, and to use a solar spectral distribution approximating that expected for the environmental conditions being simulated.

Hourly building energy simulation computer programs such as BLAST and DOE-2 (presently being combined into one future federally sponsored building energy performance simulation program) in the future can be expected to use a spectral procedure for accurate calculations of solar gain with spectrally selective glazings. The approach will be to change the spectral distribution of the incident radiation as the sun moves through the sky and as the atmosphere changes from hour to hour during the simulation. Spectrally selective glazing systems will respond to these hourly changes in incident spectrum by changing their effective solar heat gain coefficient correspondingly. Dynamic variations in the effective SHGC will more closely simulate the actual conditions experienced by fenestration systems on real buildings in real situations.

Selecting Windows

With the complexities of performance introduced by the wide range of different fenestration types on the market today comes an increasing complexity and the resulting difficulty in deciding what is the "best" window for a given situation. Parameters of interest in selecting a window for either residential or non-residential buildings include:

- Appearance, attractiveness
- Ease of operation, functionality
- Visible transmittance, how much daylight the window lets in and how easy it is to see out
- Color of the glass, as viewed from the inside and outside
- U-factor, ability to transmit conductive heat flows through the fenestration system
- Solar heat gain coefficient, ability to pass solar radiant heat gain
- Condensation resistance, resistance to interior water condensation on cold winter nights and exterior condensation on hot humid days
- Durability, permanence of the above properties over time

It should be obvious that different purchasers, building types, climates, and window orientations will produce differences in purchaser desires for the above properties. A high solar gain window to provide passive solar heat gain for northern Maine would be a disaster for the hot, humid climate of southern Florida. Increased insulation to prevent heat escape on long cold winter nights in northern climates might be a waste of money or even a detriment to thermal performance in mild climates with very modest temperature differences between the inside and outside over most of the year.

Choosing the "right" window for one's taste, climate, and building type has not been made easier by manufacturers increasing their window selections to better meet the differing needs of different buyers. One of the goals of the National Fenestration Rating Council is to develop information and data on fenestration performance to at least ease the selection process for most buyers. The Council has standards in existence or under development on the optical properties, insulating ability, solar gain property, condensation resistance, and long-term energy performance of fenestration systems. A major new publication is nearing completion under Lawrence Berkeley National Laboratory sponsorship that promises simple information and guidance to aid in the selection of fenestration systems for residential applications[7].

Understanding all aspects of fenestration performance, including the physics of fenestration energy performance, especially the solar gain performance, is important for fenestration industry professionals both to understand the problems and opportunities available and better to advise buyers concerning how to choose the right fenestration system for their needs.

The thrust of this publication is on the solar gain properties of fenestration systems. In the past, reduced solar gain generally meant substantially reduced visible transmittance as well. This is no longer true for all situations, but it is important to understand the important role that visible transmittance plays in the selection of fenestration systems. This is addressed in the next section.

Visible Transmittance and the Light-to-Solar Gain (LSG) Ratio

The primary purpose of a window is not just to save energy but to see out of it. One sees out of a window by virtue of the light from the outside coming through that window into the person's eyes. The light from outside is valuable not only for views of the outdoors but for providing daylight illumination of the interior.

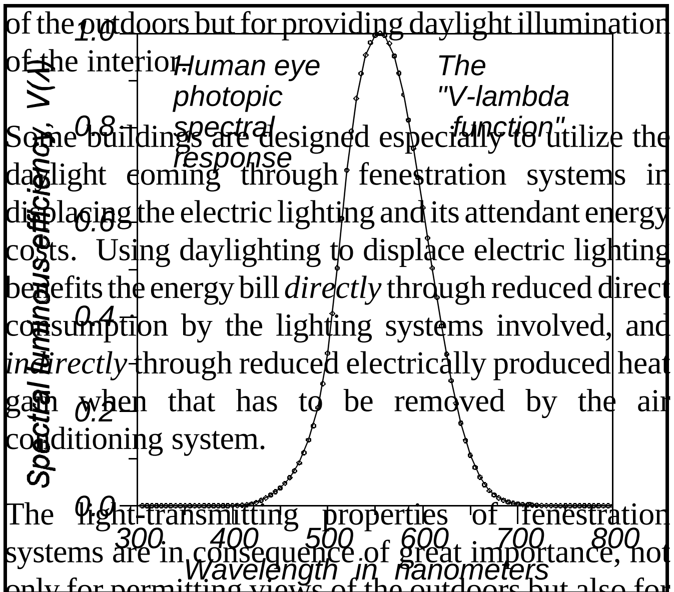

Figure 29. Standardized human eye spectral response function.

Some buildings are designed especially to utilize the daylight coming through fenestration systems in displacing the 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 when that has to be removed by the air conditioning system.

The light-transmitting properties of fenestration systems are in consequence 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 window with excellent solar heat gain performance for hot climates, meaning a very low solar heat gain coefficient, but which has very poor view and daylight illumination performance. If this problem is bad enough, it can cause the turning on of electric lights indoors during the daytime, adding to the electric bill.

The light transmitting property of a window is called the visible *transmittance*, T_v. It is like the solar weighted solar transmittance, except that an additional weighting function is needed in this case, the spectral response of the human eye. This weighting function has been standardized by the *CIE*, the International Commission on Illumination. It is shown in Fig. 29 and is called the *human photopic spectral response function*. Since the symbol $V(\lambda)$ is used for this function, it is also called the *V-lambda* function.

Secondly, broadband methods of solar gain analysis are likely to produce errors when strongly spectrally selective glazing systems are involved, unless special techniques are used to account for these changes.

One possible method would be to define a number of specific solar spectral distributions, representing the range of possibilities of interest, and to determine a different shading coefficient or solar heat gain coefficient for each of these "standard" solar spectra. If this were to be adopted, window manufacturers would be forced to publish this variety of different values of either SC or SHGC for each window offered for sale, including not only spectral-dependent values but also angle-dependent values. This approach would seem to defeat the purpose of simplifying solar gain calculations, a simplification which the shading coefficient method was devised to provide.

Using the previously introduced notation and

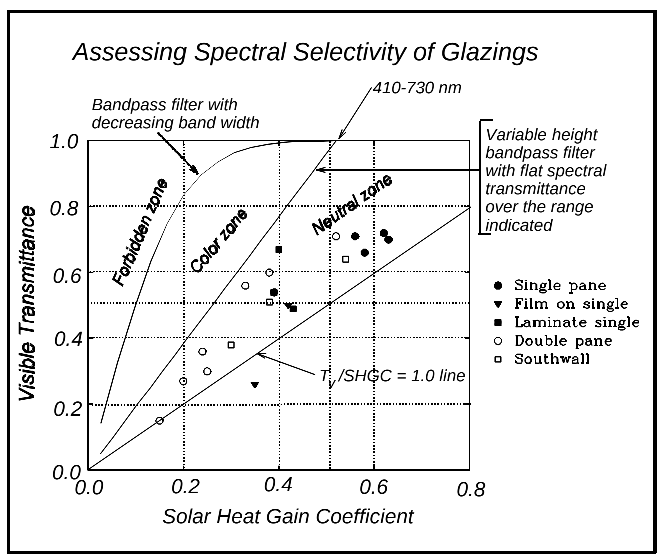

Figure 30. Plot showing the spectral selectivities of various commercially available glazing systems.

terminology, the visible transmittance T_v of a glazing system having spectral transmittance $T(\lambda)$ is given by

$$T_v = \frac{\int_{360}^{720} T(\lambda)\, E_\lambda\, V(\lambda)\, d\lambda}{\int_{360}^{720} E_\lambda\, V(\lambda)\, d\lambda} \qquad \textbf{(18)}$$

$$T_v \cong \frac{\sum_{i=1}^{N} T(\lambda_i) E_{\lambda_i}\, V(\lambda_i)\, \Delta\lambda}{\sum_{i=1}^{N} E_{\lambda_i}\, V(\lambda_i)\, \Delta\lambda} \qquad \textbf{(19)}$$

In most applications it is important to have a high visible transmittance. In northern climates a good solar heat gain is also good to have for offsetting wintertime heating costs. In southern climates a low solar heat gain is good for offsetting summertime cooling costs. Turning our attention to the latter situation, we find that it is difficult to have both a high visible transmittance and a low solar heat gain coefficient. Figure 30 shows a plot of visible transmittance versus SHGC for a number of glazing systems covering a range of spectral selectivities. The data is only for normal incidence and a single, ASTM standard solar spectral distribution.

Three different zones are delineated on the graph. 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 neutral zone. In the *color zone* one way to achieve higher visible transmittance for a given level of solar heat gain coefficient is by stripping some of the red and blue wavelengths at the edges of the V-lambda function off of the glazing transmittance spectrum, imparting color to it (or by otherwise altering the spectral transmittance and hence color over the visible portion of the spectrum). In the *forbidden zone*, no combination of visible transmittance and solar heat gain coefficient is possible that will place a point in this area on the chart, for normal incidence and for the solar spectral distribution used.

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*, and it was defined previously as

$$LSG = \frac{T_v}{SHGC} \qquad \textbf{(20)}$$

Since many glazing manufacturers have in the past given only SC values, a related index, called the *modified light-to-solar-gain* ratio, *LSG'* can be defined as T_v / SC. This definition should no longer be necessary for the following reason.

Every major window manufacturer in the U. S. has re-measured the optical properties of the glazings in their windows and have determined the corresponding SHGC values for each of their fenestration products in preparation for compliance with NFRC rating procedures. In consequence one can expect all new fenestration product literature to list SHGC values for the products listed. Some characteristic values for T_v, *SHGC*, and *LSG* are given in Table 2 for several different glazings, using the ASTM standard spectral distribution and normal incidence to calculate the values.

Table 2. Spectral Selectivity of Several Glazings

Glazing	T_v	*SHGC*	*LSG*
Refl. 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
Low-e sun + green	0.36	0.23	1.56
Low-e squared + clear	0.71	0.40	1.77
Low-e squared + green	0.60	0.30	2.00

The *LSG* can be useful in spotting errors in the calculation of 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.

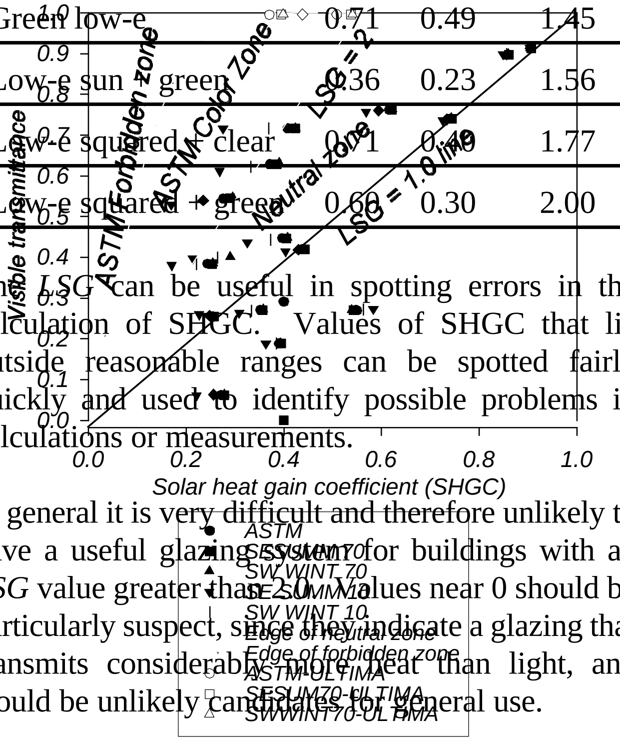

Figure 31. T_v versus SHGC for a number of glazing systems with varying spectral selectivities.

Figure 31 shows a plot of T_v versus SHGC for the glazings analyzed in Ref. 3. It can be seen that the glazings which transmit more solar radiant heat than light cluster on the lower portion of the plot. The ULTIMA hypothetical glazings for a 10- degree sun angle are not plotted, for a reason to be described.

Looking at the data plotted in Figs. 30 and 31, the transition boundary line between the neutral zone and the color zone is determined as follows. A hypothetical glazing with zero absorptance (meaning that the solar transmittance equals the solar heat gain coefficient) is made to have spectral transmittance of zero outside the visible wavelength region and 1.0 inside that region, much like the hypothetical glazings whose angular properties are plotted in Figs. 18 and 19. Then the transmittance inside the visible is decreased steadily from 1.0 to 0.0. The SHGC and T_v decline steadily from their initial values for the standard solar spectrum used, to 0.0. A plot of the resulting values of T_v versus SHGC yields the straight line transition curve illustrated in Fig. 30, as well as the LSG = 1.0 and 2.0 straight lines in Fig. 31.

The transition boundary line at the edge of the “forbidden zone” is obtained similarly, but in this case the spectral transmittance in the pass band is kept at 1.0 but the edges of this band are brought together, forcing the glazing to transmit only radiation from the center of the visible region, narrowing it constantly, and stripping off radiation at more and more colors, until all radiation is gone, and the SHGC and visible transmittance are zero. For the incident solar spectrum used in the calculation, there is no physical way for a glazing to be devised with a visible transmittance and SC or SHGC that place it to the left and above the “theoretical limit” and into this “forbidden zone”.

Fig. 32 shows a similar plot, for the greater variety of glazings studied in Ref. 3. In this case four different lines for the transition from the color zone to the forbidden zone are plotted, each with different edges to the passband used to generate the data. One can clearly see the effect of stripping off colors at the edges of the visible portion of the spectrum, in moving the transition line to the left on the plot. Since the three leftmost lines do strip off noticeable quantities of radiation in the red and blue portions of the spectrum, these are not acceptable boundaries for the neutral zone, but are shown here for comparison purposes only.

Three points, being for the hypothetical "ultima1" and "ultima2" glazings with the southeast summer 10° beam spectrum, are not plotted in Figs. 30 and 31, because they would fall to the left of the "theoretical limit" curve shown on those Figures.

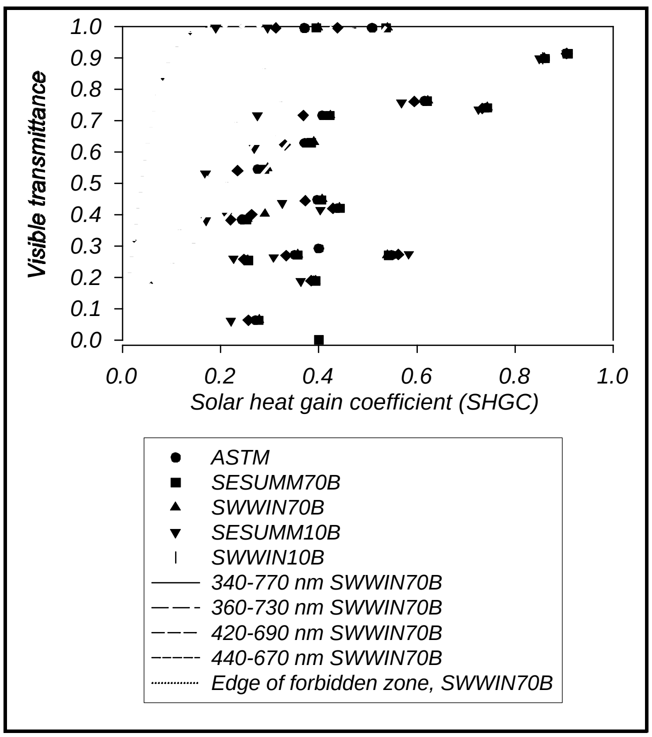

Figure 32. Visible transmittance versus SHGC for a variety of glazings. Changes in incident solar spectra generally affect the SHGC more than the visible transmittance. This is seen I the horizontal grouping of points for some glazings as the incident spectrum is changed.

To explore the cause of this, the plot was repeated, but in this case, the neutral-to-color transition line and the forbidden zone curve were replotted using not the ASTM standard spectrum but the southeast summer 10° one instead. The results are shown in Fig. 33.

Due to the shift of the low sun angle spectrum toward the red, the transition curves are accordingly shifted to smaller SHGC values, indicating the decreasing proportions of radiation in the visible portion of the spectrum relative to the infrared. Now the low sun "ultima" glazing points (shown as open triangles and a diamond) no longer fall to the left of the transition curve. Actually, since their optical properties are very close to those assumed when plotting the theoretical limit curve, these points actually fall on or very close to the curve, as expected.

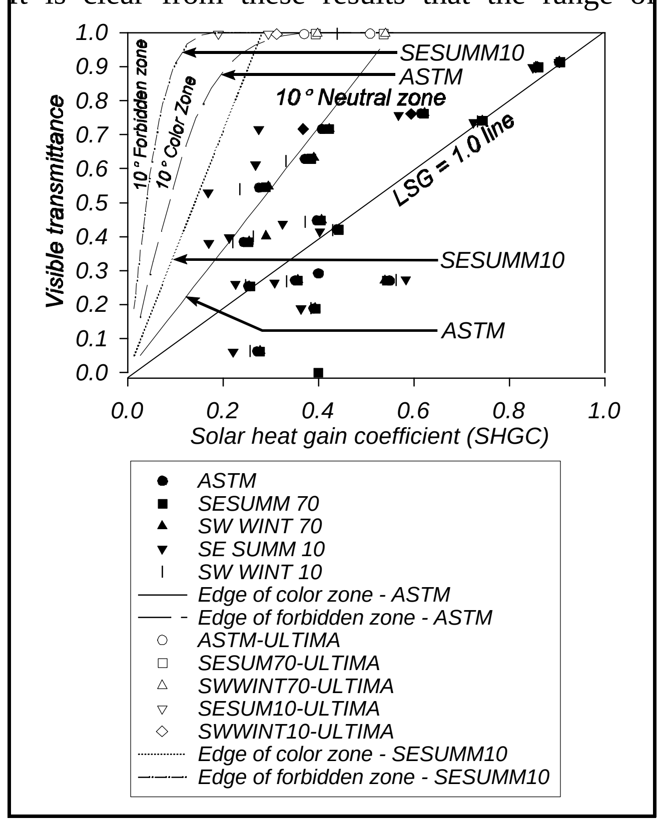

Figure 33. Visible transmittance versus SHGC plot, with zone transition curves plotted using both ASTM and SW Winter, 10° sun angle spectra.

It is clear from these results that the range of possible positions of points on a T_v versus SHGC plot can be extended by narrowing their visible transmittance pass band and by varying the shapes of the solar spectra used in calculating their solar gain and optical properties. Of course, a consequence can be that the color of radiation admitted by the window can be altered so much as to make the window objectionable from a human factors perspective.

Some of the consequences of stripping too much color out of a window to make it more energy efficient can be found on the Window 4 glazing system Optical Properties screen, in the window labeled “Color Properties.” The properties listed, for both transmittance and reflectance, are the dominant wavelength, color purity, and color coordinates L*, a*, and b* in the CIE 1976 L*a*b* color space[8], devised to facilitate color difference calculations[9]. It is expected that these color calculations will be retained in Window 5.

One way to see how much the solar spectrum is shifted by a given glazing system, is to first run Window 4 for the glazing STRPH_3.PPG whose spectral transmittance is essentially constant over the solar spectrum. The results for the transmittance of this “water white” clear single pane glass and for the default ASTM standard spectrum are:

Dominant Wave-length	**Color Purity**	**L***	**a***	**b***
545 nm	0.1%	96.5	-0.1	0.09

Departures from this, which can be considered essentially “white light”, will impart more or less color, depending upon the magnitude of the departures from these values.

Complex Fenestration Systems

Although most of the fenestration systems sold in the U. S. today are of the type described above whose solar gain properties can be determined through the use of a computational procedure such as the Window 4 program, there is a large class of additional

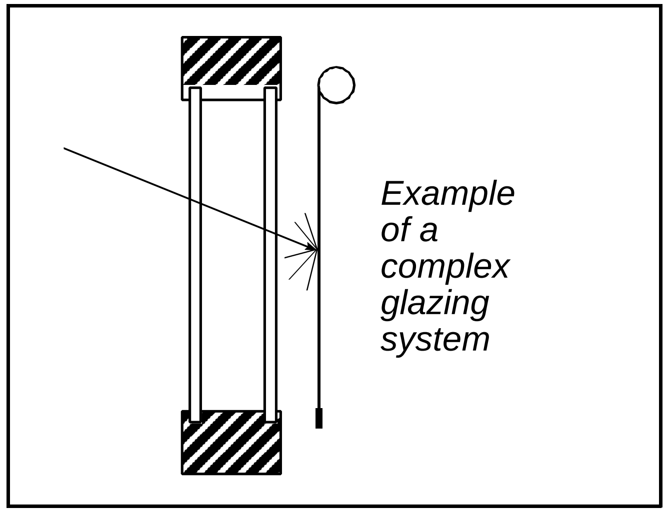

Figure 34. Illustration of a complex glazing system.

fenestration systems and attachment products that cannot be handled with these now conventional procedures. This class is termed “complex fenestration systems.” An example was depicted in Fig. 14. Another is shown in Fig. 34. Included in this class are fiber-reinforced-plastic translucent panels, windows with what are called “obscure lites,” glass with a patterened or textured surface, milk-white glass or plastic, and windows with any of a large assortment of shading devices such as screens, louvers, and shades added.

The solar heat gain properties of these complex fenestration systems simply cannot be handled by any of the existing approved measurement or calculation procedures. The NFRC is determined to include these products in its rating and certification program at the earliest possible time. A number of difficult technical problems, however, stand in the way of full and immediate implementation of any one approach.

The remainder of this publication is devoted to a discussion of the issues involved and the various technical pathways that are available for including complex fenestration systems in the NFRC energy rating program. Some thoughts concerning the costs to the government and to manufacturers of the different options are also expressed. These are the

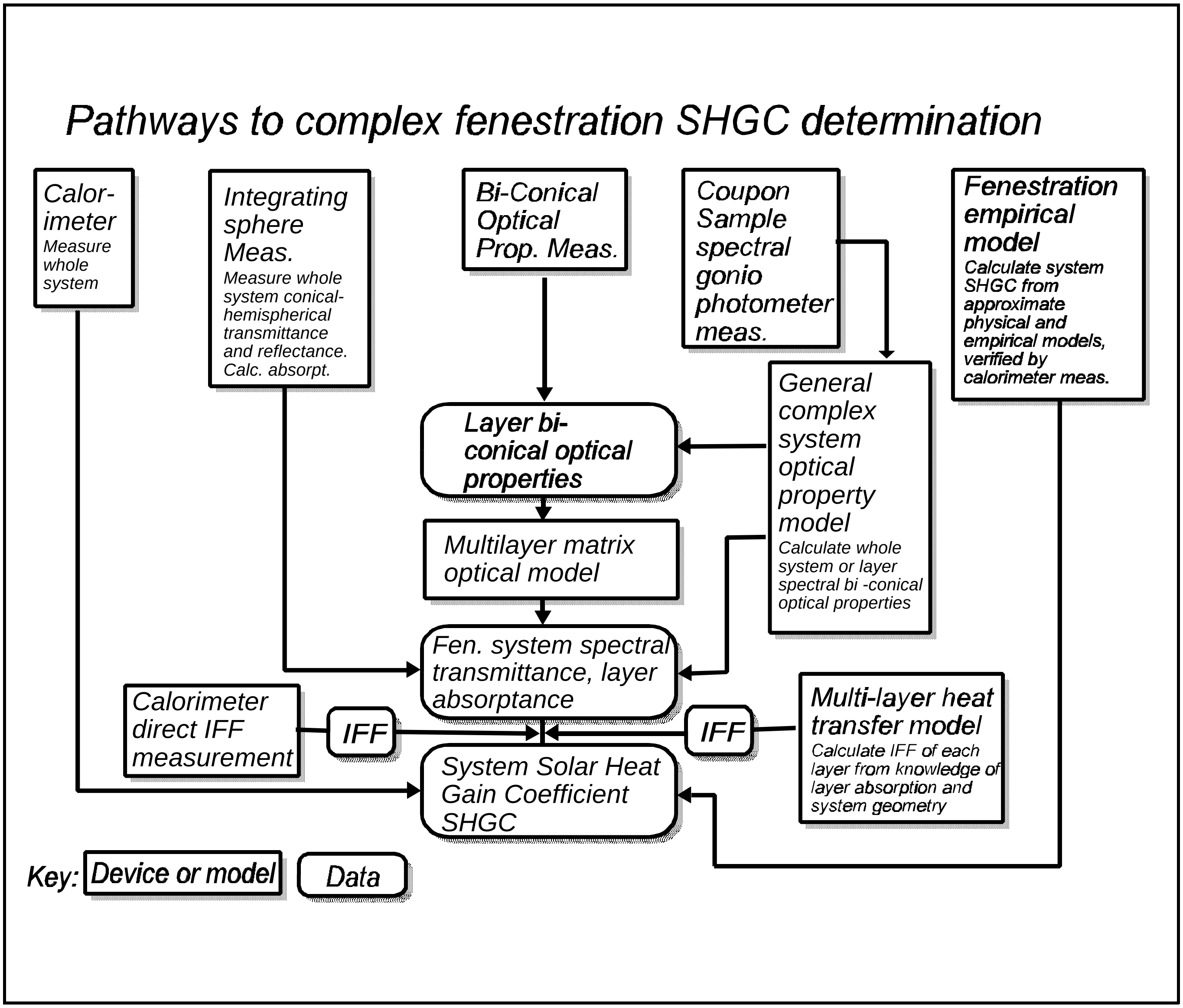

Figure 35. Technical options for determining SHGC of complex fenestration systems.

current views of the author and are not the views or policy of the NFRC, the Florida Solar Energy Center, or of the U. S. Government.

The options (shown in Fig. 35) range between two extremes. At one end is a "measure the whole fenestration" strategy. This is accomplished with a device called a solar calorimeter, an insulated chamber lined with heat absorbing and removing surfaces and having an entrance port into which a test article can be mounted. The fenestration is irradiated with a known quantity of real or simulated solar radiation and the amount entering the chamber and removed from it under steady-state conditions is measured.

The ratio of the heat removed to the incident solar flux is the solar heat gain coefficient of the test fenestration for the particular environmental conditions of the test. To perform this test, a complete fenestration system must be tested and the test takes some time to set up and perform. If determinations of the SHGC for different angles of incidence are desired, then the test takes even longer. If the measurements are made outdoors with real solar radiation, the conditions have to be just right to complete a test, meaning that the sky must be fairly clear and remain so during a test. In some areas of the country it may take quite a few days to achieve these conditions and they may persist for only a few hours.

The advantage of this approach is that it involves direct measurement and a minimum of computation. It is expected to be the first option to be made available to manufacturers. (Several laboratories already offer solar calorimeter measurement services, but no standard procedure currently exists. A task group of the NFRC's Solar Gain Subcommittee is working to draft such a standard procedure for adoption by the NFRC in the near future.) The calorimetric approach, however, could prove to be very expensive for manufacturers of a variety of products intended for application to a variety of different non-complex fenestration systems.

At the other end of the extreme on the scale is a "measure as little as possible and calculate everything else" strategy. This is the next-to-last option on the right of Fig. 35. (The rightmost option is described separately below.) In this case of calculating nearly everything, one breaks complex fenestration systems down into the parts that are non-complex, and can be properly characterized with existing calculational procedures, and the parts that are complex, that are non-specular.

The non-specular components are further broken down into their smallest optically and thermally significant pieces, and small, homogeneous samples of these are provided. They are called "coupon samples" because they are small portions of the materials used in making the complex portion of the fenestration system. The bi-directional and spectral optical properties of reflectance and transmittance are measured on each of these coupon samples. These are the only measurements performed using this extreme pathway (except possibly for measurements of the component material thermal conductances) and everything else is calculated.

The calculational process is formidable, and is described subsequently. The measurement of the coupon samples, though tedious and time consuming, need be done only once per sample and the process can be automated. The advantage of this approach for manufacturers is that computations are generally less expensive than measurments and this approach provides the maximum flexibility for "mixing and matching" different combinations of glazing systems, framing systems, shading systems, and other complex attachment products.

On the other hand, it will require substantial investment in developing the computational techniques as well as the spectral goniophotometric system needed to measure a large number of coupon samples of materials used by manufacturers of complex fenestration systems. A schematic illustration of a goniophotomter is depicted in Fig. 36.

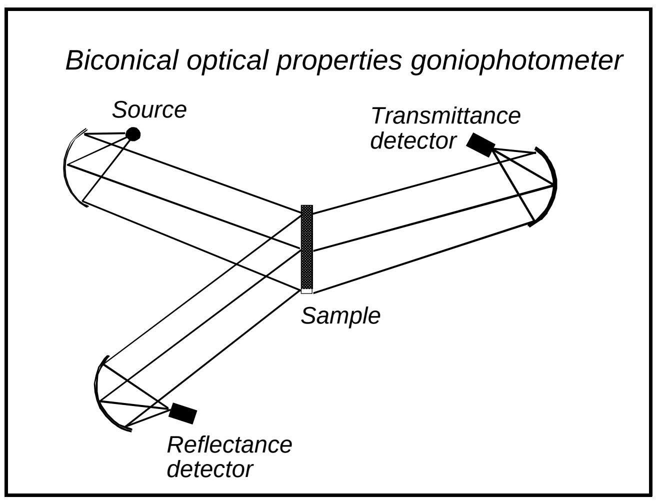

Figure 36. Schematic representation of a biconical goniophotometer for transmittance and reflectance measurements.

A spectral goniophotometer would have a monochromator in either the source or the detector component and would scan not only over directions of incidence and emergence but also over wavelength for each direction, thereby generating a large quantity of data for each coupon sample measured.

A beginning step toward developing this instrument has been taken by Lawrence Berkeley Laboratory, in partnership with Optronics Laboratories of Orlando. Much work on portions of the computational methods has been performed in the past, but much remains to be done, as is described subsequently.

In between these two extremes are various possible intermediate strategies involving combinations of measurement and calculation of complex fenestration systems and their component parts. The possibilities are diagrammed in Fig. 35.

The "Semi-Empirical Shade Model" approach shown in Fig. 35 and described in the next section could greatly reduce the costs of determining SHGC values for complex fenestration, but this possibility must be proven by additional research.

The NFRC and the U. S. Department of Energy are committed to research and analysis to determine which ones of the pathways shown in Fig. 35 are most appropriate for different complex fenestration products. The issues involved are not just technical, for a considerable amount of money will be required to develop one or more of the approaches and different approaches will have different costs to manufacturers for having their products rated and certified using them. Some of the paths shown in the Figure are currently more developed than others, and the lack of completed research and analysis makes it difficult to select amongst the options at the present time. In the following sections, each of the pathways depicted in Fig. 35 will be described and assessed.

Determining SHGC for Complex Systems -- Future Research

Solar Calorimetry. The solar calorimetry approach was described above. In spite of its historic availability, there are several important technical problems to be overcome in developing a standard test procedure that different laboratories can use in producing consistent results. One of the issues is that, as we have seen, the solar spectrum varies with atmospheric conditions and solar altitude angle. Another is that few solar simulators match any of these solar spectra very well, so that differences can be expected between tests of the same spectrally selective fenestration systems using two different sources.

Still another issue relates to whether the test can or should be made with the calorimeter fixed in position while the sun moves through the sky during the test, or with the calorimeter made to track the sun and maintain a relatively constant angle of incidence over the test period. Additional issues relate to the geometry and thermal mass of the calorimeter and methods of heat removal and measurement.

Another point of discussion is the effect of reflection of radiation admitted to the calorimeter chamber back out of the fenestration and of long-wavelength infrared radiation emitted from the chamber walls back toward the fenestration being tested. Should the interior of the calorimeter be large and have relatively bright reflecting walls, as if it were a room in a real building, or should efforts be made to prevent admitted and emitted radiation from escaping back out through the fenestration? The current draft of a planned NFRC solar calorimetry standard test procedure attempts to avoid making some of these decisions. Testing is permitted with either the room-like design or the "flat-plate-collector-like" design. Similarly, fixed or tracking tests are also permitted, as are tests with real solar radiation and with a solar simulator. The intent is to describe the proper way of making each of these tests, leaving it to the agency calling for the tests to specify the conditions of test.

Assuming that these and other issues are settled and a standard procedure is developed by the NFRC, there are still questions concerning the accuracy of results obtained with the procedure and the costs to manufacturers to have their products tested with this method. A single test can be expected to cost in the neighborhood of $500 to $1500 or more. Manufacturers with large product lines, interested in determining how they perform separately and in conjunction with other fenestration products, therefore can face substantial costs if this is the only method available to them for determining SHGC values for their products.

Inward Flowing Fraction Determination. All remaining pathways shown in Fig. 35, except the one on the far right hand side, involve optical measurements of various kinds, to determine the directly transmitted component of the solar heat gain coefficient. These methods therefore require some independent means for determining the inward flowing fraction of the radiation absorbed on various component parts of the fenestration system.

Two ways of providing this information are shown in Fig. 35. The first one is called "Calorimeter direct IFF measurement." Using this approach, a calorimeter is used, indoors or at night, to measure only the inward flowing fraction of heat supplied to the components of the fenestration system. This is a purely thermal measurement and the heat can be applied in a variety of ways, as long as this heat is generated only in the components of the fenestration.

Joe Klems of Lawrence Berkeley Laboratory has used this approach to determine the inward flowing fraction coefficient N_i of venetian type metallic horizontal blinds. By attaching electrical contacts to the ends of each metal slat and passing a electrical currents through them, Dr. Klems has been able to measure directly the quantity of heat applied to each slat, and from his calorimetric measurement deduce the fraction of that heat which entered the interior of the space as a heat gain.

Several other methods can be envisioned for applying known quantities of heat directly to the components of complex fenestration systems. These include the attachment of electrical heating elements to non-conductive component parts, irradiation with long-wavelength infrared radiation in such a way that none of this radiation reaches the calorimeter heat metering surfaces directly, and possibly focused microwave heating methods.

The other approach to determining IFF fractions for complex fenestrations, depicted in Fig. 35, and called the "multi-layer heat transfer model," involves purely theoretical calculations of the heat flows involved. Complex heat transfer computer programs are available for some material geometries and a considerable body of literature has been developed on heat transfer for a variety of other geometries. The idea here is to develop a large computer program, or modify as needed existing ones, capable of accurately calculating IFF values for the variety of geometries and materials found in complex glazing systems on the market today and in the foreseeable future. This is expected to require a considerable body of technical research and it remains to be seen how it will be funded and who will perform the needed work.

In the following sections, it will be presumed that one of the above methods is or will be available for determining inward flowing fractions once the optical portion of the problem has been solved.

Integrating Sphere Measurements. With this approach, whole glazing systems that might have been measured using a calorimeter are attached to a large-aperture integrating sphere and irradiated with real or simulated solar radiation, as depicted schematically in Fig. 37. The integrating sphere collects all the directly transmitted solar radiation and sends a fixed portion of it to a flat-response, broadband radiation detector, a solar radiometer.

The ratio of the transmitted to incident solar flux is the measured solar transmittance of the fenestration system. The measurement is repeated, but with the integrating sphere operating in reflectance mode, so that both the solar transmittance and reflectance of the test article can be determined. From this is determined the overall absorptance of the system. It is then a simple matter to multiply this absorptance by the separately-determined inward flowing fraction and add the product to the solar transmittance to obtain the total system solar heat gain coefficient, as expressed in Eq. 2.

The integrating sphere aproach has the enormous advantage of being an optical measurement, for which thermal effects are of minimal importance. The measurement of T_S with an integrating sphere is considerably more straightforward and therefore more rapid and less expensive than the calorimetric approach, if the source is real solar radiation, or an accurate simulation of same.

The integrating sphere approach works only for whole fenestration systems. It cannot be used for shading systems separately from glazing systems, because the test procedure tells us nothing about the directional distribution of the radiation reflecting back and forth between the fenestration system and the shading system.

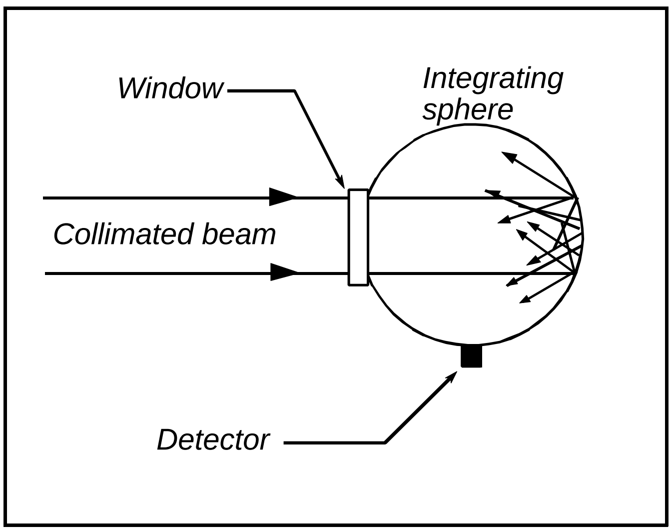

Figure 37. Schematic representation of an integrating sphere measurement of conical-hemispherical transmittance of a window.

Whenever one has two separate layers at least one of which is non-specular, the directional distribution of the radiation exchange between the two layers is important in determining the total solar transmittance. There is a class of fenestration systems, however, such as thick, glass fiber reinforced daylight illumination panels, which are amenable to this approach, if the inward flowing fraction of the absorbed radiation can be determined separately.

Bi-Conical Optical Properties Measurements. With this approach, complex fenestration systems are separated into one or more constituent layers and each is measured separately. A computational procedure is used to combine the measured optical properties of the separate layers into a set of optical properties for the sandwiched system. The separate layers are measured with a (broadband) bi-conical transmissometer/reflectometer. For the measurement to be valid, the incident radiant flux should have a spectral distribution close to that of beam solar radiation, especially (as we have seen) if the layer exhibits significant spectral selectivity. The geometry for defining bi-conical transmittance and reflecance is shown in Fig. 38. One possible embodiment of a device for measuring bi-conical optical properties was depicted schematically in Fig. 36.

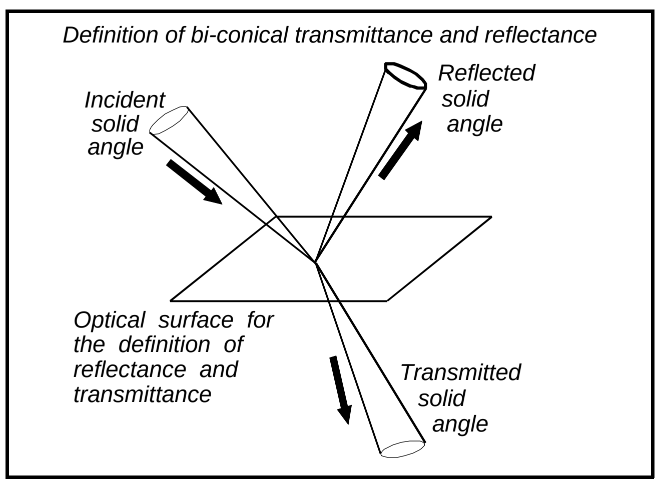

Figure 38. Geometry for the definition of bi-conical transmittance and reflectance.

This measurement is intended for whole window layers and for whole shading systems, so that their separate properties can be determined and then combined mathematically without having to measure every combination of sandwiched systems.

It is possible to use the approach to measure portions of a complete fenestration layer, but the portion measured must be large in relation to any inhomogeneities contained in the layer and the portion must be replicated by other portions of the layer, if the results are to be expanded to the whole system. The method is therefore applicable to generally large systems and is therefore somewhat expensive and time consuming to perform. Joe Klems and others at LBL have developed an apparatus for performing such a measurement on layers up to about a half a meter in each dimension. Measurements have been completed with this apparatus for venetian blinds and flat shades, among other samples.

The multilayer matrix optical model depicted in Fig. 35 for use with this approach has been developed and reported by Dr. Klems[10]. As with the integrating sphere methodology, this approach also requires independent determination of the inward flowing fraction of the absorbed radiation.

Coupon Sample Spectral Goniophotometer Method. This approach was described briefly previously. It involves separating the complex portions of complex fenestration systems, such as a Venetian blind system, into its smallest optically significant components. The spectral and directional transmittances and reflectances of coupon samples of portions of the smallest components are then measured on a spectral goniophotometer and the results used to compute the directional spectral absorptances as well.

The next step is to assemble the complex portions of the system into a complete configuration, using a mathematical, or geometrical, model of the system. This might be done, for example with a computer aided drafting program such as AutoCAD. Then the directional and spectral optical properties of the complete assembly are calculated. The method of calculation might employ ray-tracing techniques. They might use other means of following the histories of photons of different wavelengths and directions as they are "fired" into the system.

The end result of these calculations is the total layer or system directional spectral optical properties. These can then be used to calculate the transmitted solar flux for any direction of incidence and for any spectral distribution of radiation. Adding the inward flowing fraction of absorbed radiation from an independent model completes the calculation of solar gain for the specific conditions of irradiation involved.

The box labeled "General complex system optical property model" in Fig. 35 has not yet been developed but several possibilities for this important component of the approach are being explored by Michael Rubin of LBL and this author, working together. Commercially available software, as well as computational engines developed for other purposes at LBL, are being considered. The problems of converting one or more of these methods for use in this application, considering the variety of possible material geometries, are formidable. The "multi-layer heat transfer model" box also shown in Fig. 35 is another large challenge in pursuing this extreme approach to solar gain determination.

Although the computational portions of the coupon sample spectral goniophotometric approach are challenging, there are considerable advantages to this approach if it can be developed. The main one is the low cost to manufacturers in getting their complex products rated and certified in the NFRC program. Once the relevant coupon samples have been measured for their product, possibly by or at an NFRC or government subsidized laboratory, then running the computer programs is expected to be a relatively straightforward task, and one with modest associated costs.

Semi-Empirical Modeling. This is an additional methodology which I have proposed[11] that attempts to short-circuit the more generalized approaches described above. It is intended for fenestration systems amenable to approximate mathematical modeling from first principles (such as those that can be easily divided into a conventional glazing layer and a shading layer), with empirical corrections being made to the model using a limited set of direct calorimetric measurements. Without *a priori* knowledge of its success it is a sort of hit-or-miss proposition. It relies on the use of current techniques to determine the needed properties of the non-complex glazing systems portion of the fenestration. For example, Window 4 or Window 5 can be used to determine the SHGC and the back reflectance of a conventional multipane glazing system. Assumptions are then made concerning alterations in the directly transmitted and inward flowing fraction of absorbed radiation components of the solar gain that are caused by the complex portion of the fenestration, for example an interior pull-down shade, or a diffusing second glazing layer ("obscure lite"). Then the principles of radiometry are used to estimate the combined SHGC of the system, using the previously made assumptions regarding the physical processes involved.

The theoretical results are then compared with calorimetry results obtained with complete systems of the type being simulated. If there is good agreement, the model can be used for other complex fenestrations of the same basic design. If the agreement is not good, the model is revised in an attempt to account for the discrepancies between the model and the experimental tests. There is no certainty at the beginning of this approach that a given system geometry can be successfully modelled. However, if the approach is successful, it may result in a fairly simple or straightforward formula for determining the SHGC of a specific class of complex glazing systems.

For this approach to be successful, a fairly large number of solar calorimeter tests need to be performed on a variety of complex systems. Once the data from these tests is obtained, as well as knowledge of the solar optical properties of the component layers, the empirical models can be developed and tested. The results of two applications of this approach are encouraging,[10,12] but the experimental data available for those applications were quite limited and no generalization can be made from their apparent successes.

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