Suggested Methodologies for Determining the SHGC of Complex Fenestration Systems for NFRC Ratings

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Original Publication

McCluney, Ross, " Suggested Methodologies for Determining the SHGC of Complex Fenestration Systems for NFRC Ratings ", For the National Fenestration Rating Council, February 27, 2002.

Publication Number

FSEC-PF-422-02

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NOTICE

ACKNOWLEDGMENT

This work is sponsored, in large part, by the U.S. Department of Energy, Office of Building Technology, State and Community Programs under cooperative agreement no. DE-FC36-99GO10478. This support does not constitute an endorsement by DOE of the views expressed in this report.

The author appreciates the encouragement and support from Samuel Taylor, program manager in Washington DC and Andy Trenka, project officer in Golden, CO.

Methodologies for Determining the *SHGC* of Complex Fenestration Systems

Ross McCluney
27 February 2002

For the National Fenestration Rating Council

Introduction

Simple fenestration systems, for the purpose of this paper, are those whose solar heat gain and visible transmittance performances can be accurately simulated using the Window 4 or 5 programs developed at Lawrence Berkeley National Laboratory (LBNL). Complex fenestrations are everything else, including obscure or "privacy" glazing, corrugated or otherwise complex patterned glazing, curved, bent, or domed glazing, fritted glazing, glass blocks, glass fiber reinforced plastic daylighting panels, and glazings with internal or attached shading systems of a variety of types. The latter include exterior awnings and overhangs, attached exterior shade screens and shutters (including roll-up shutters), between-the-panes shades, including miniblinds, and interior shades which are vertical planar, horizontal blinds and vertical blinds. Also included are flux-directing and light-piped daylighting systems such as tubular skylights.

As more building codes and governmental building requirements specify compliance with NFRC rules for rating, certification, and labeling of fenestration products for energy efficiency, and as these rules are extended to complex fenestration systems (CFS), the NFRC as well as manufacturers of these products are facing serious difficulties in getting such systems rated in the NFRC system. It is the complex nature of the optical performances of these systems which poses most of the problems.

The purpose of this paper is to describe the optical qualities of complex fenestration systems which prevent them from being simulated accurately using the methods of Window 4 or Window 5 (ISO standard 15099). It is also to survey a variety of measurement and calculational techniques which might be able to determine the solar heat gain coefficients (*SHGC*s) and visible transmittances (VTs) of these systems more simply than the most general of methodologies. To do this, a general calculational methodology thought to be applicable to any complex fenestration system will be described first. In many cases, this may be the only method available for cost-effectively approximating the solar heat gain and visible transmittance properties of such systems. A further purpose is to offer suggestions in some of the cases for simplifying the optical problems involved, sufficiently to permit relatively easy and practical methods for determining the needed values, through computation alone—or a combination of computation and minimal measurement.

Providing a detailed technical description of each different approach is beyond the scope of the present effort. Instead a general survey of some possible approaches is offered.

The Nature of the Problem

Window 4 and 5 are predicated upon the assumption that rays of radiation incident on the glazing systems modeled by these programs follow known paths through these systems using only the laws of specular reflection and transmission. This means that at every interface encountered by a ray there is no scattering—a ray bent entering a medium of different refractive index, quickly emerges from a parallel interface from that medium to another medium and thence through the last such medium into air again, having the same final direction that it had upon entering the glazing system. A second requirement of these computer programs is that the glazings simulated have plane parallel surfaces. A glazing which is corrugated, for example, does not obey this restriction and will redirect collimated (quasi-parallel) incident rays so that they emerge in a variety of directions.

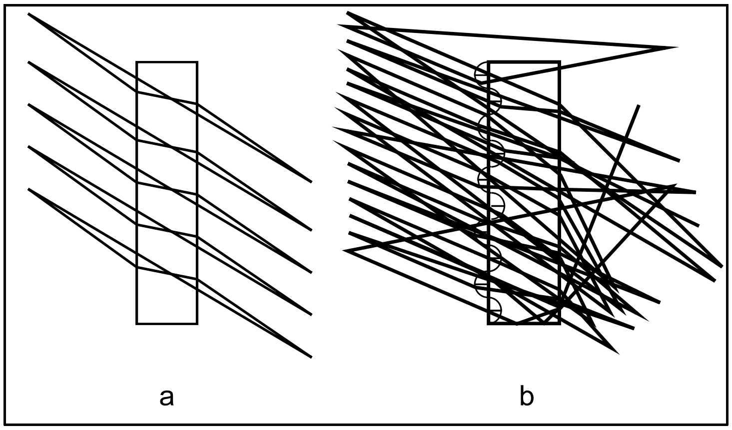

Figure 1. Illustration of ray propagation directions with planar (a) and corrugated (b) surfaces of a plate of glazing material.

The difference is illustrated in Fig. 1. Parallel rays incident upon a parallel plate of sheet glass (a) emerge parallel to their incident direction while those incident upon a plate of glass with corrugated front surface (b) emerge in a variety of directions.

The multiple reflections which take place within the glazing of Fig. 1 (a) follow well-defined and easily analyzed paths, making it easy to incorporate the effect of their presence on the property being determined, as illustrated in Fig. 2. The transmittances τ_1 and τ_2 and reflectances ρ_1 and ρ_2 of surfaces 1 and 2 are determined from well-known formulas attributed to Augustin Jean Fresnel (1788-1827). These depend upon the refractive index of the material. If the absorptance α along the slanted path and the thickness *w* of the material are known, then the sum of the transmitted components shown on the right side in Fig. 2 (an infinite sum of diminishing terms) is known precisely. In cases such as Fig. 1 (b), however, the emerging rays are not so easily calculated by simple analytical methods. (The Fresnel formulas still hold, but the divergence of the emerging rays is not treated.)

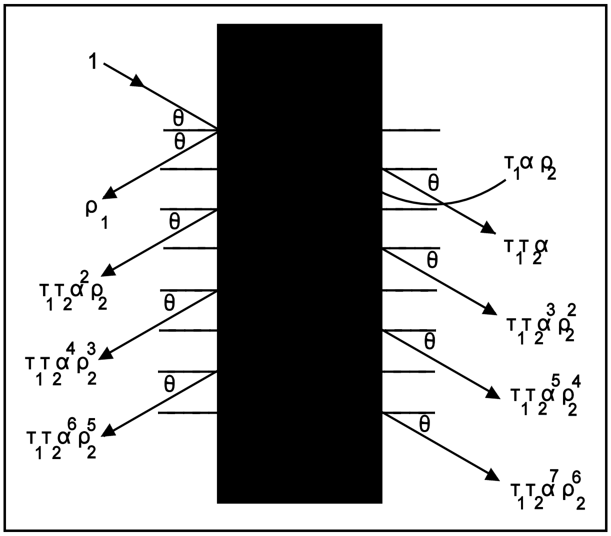

Figure 2. Multiple reflections within a parallel sheet of clear glazing.

A similar effect results if the irregularities in the surface are very small, or if the material of the glazing has many particles or other inhomogeneities imbedded in it which produce angular scattering effects, either in transmission or reflection. Propagation of such rays is not included in the optical modeling on which Window 4 and 5 are based.

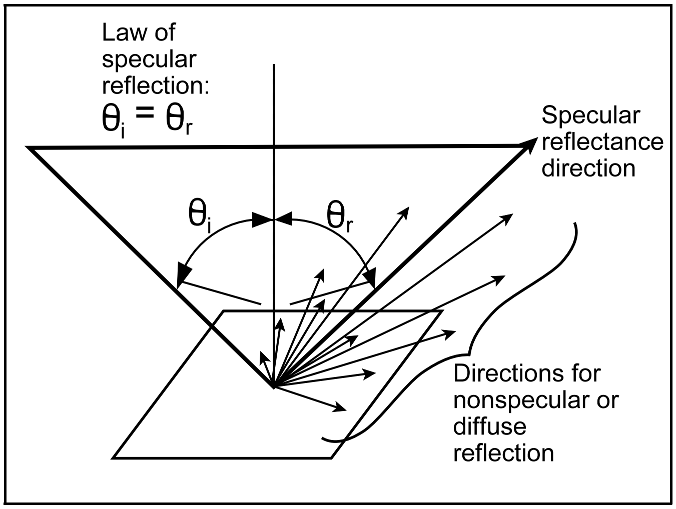

Figure 3. Illustration of specular and diffuse reflection from a planar surface.

As shown in Fig. 3, reflection can be described as having specular and diffuse components. For a specular surface, the diffuse reflectance or transmittance is effectively zero. For a diffuse surface, the diffuse reflectance or transmittance is large in comparison with the specular component. A totally diffuse surface is one in which the specular reflectance is almost nonexistent. (Some of the scattered rays will emerge from the surface in or very near to the specular direction, so there generally remains a small "specular" component to even the most diffuse surfaces.)

This problem is exacerbated when a glazing system contains not only diffusely scattering surfaces but non-coplanar shapes as well, as illustrated in Fig. 4 for a Venetian blind system.

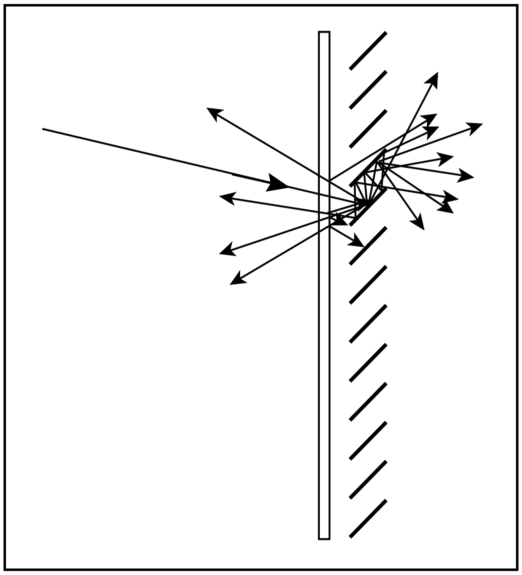

Figure 4. Illustration of multiple scattering within a Venetian blind attached to a window.

Effect of Complex Fenestration Systems on Solar Heat Gain Coefficient Determinations

The solar heat gain coefficient (*SHGC*) is defined to be the quotient of the total solar gain per unit area through a window to the interior of a building and the incident solar irradiance, also in terms of energy per unit area. Thus the *SHGC* is a dimensionless quantity, giving the fraction of incident irradiance which enters the building through the window. This fraction is composed of two parts. First is the direct solar transmittance T_s. This is the fraction of incident irradiance which is directly transmitted to the interior as radiation. Second is the inward flowing fraction N_i of the solar absorptance A_S. Combining these for single pane glazing, the total solar heat gain coefficient is given by

$$SHGC = T_S + N_i A_S \tag{1}$$

For multiple pane glazing systems, the inward flowing fraction term must be summed over all the quantity of such flux. (For daylighting studies, however, the biconical transmittance is essential for determining not only the total quantity of light flux admitted, but its directional distribution within the building space. This is needed to map the illumination distribution, and for determinations of the glare potential of the fenestration system.)

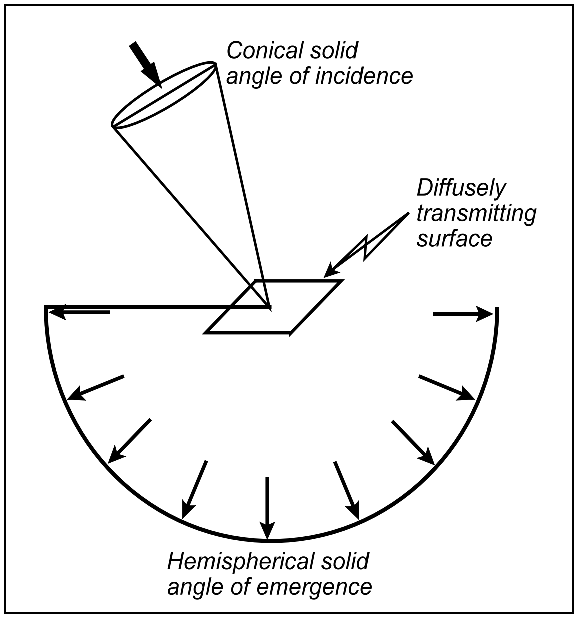

Figure 6. Illustration of solid angle definitions for the conical hemispherical transmittance.

The Generalized Optical Modeling Approach

A general calculational methodology has been suggested by Mike Rubin of LBNL and Ross McCluney of FSEC. With this approach, so-called "coupon samples" of each distinct optically important component within a CFS is prepared. This is a small (a few centimeters wide), planar sample of the material having exactly the same optical properties as the corresponding component of the CFS. The sample might be of a planar sheet of glazing material which is diffusely transmitting, or such a material given a curved shape in the fenestration product. Or it might be a small section of one of the slats of a Venetian blind. The only measurement needed with this approach is of the spectral bi-conical reflectances and transmittances of the sample. Everything else contributing to the solar heat gain is calculated.

A special spectral goniometric reflectometer and transmissometer intended for such measurements was built for LBNL by Optronic Laboratories of Orlando, FL. This instrument is a combined spectral gonioreflectometer and goniotransmissometer because it performs its measurements on a wavelength-by-wavelength basis and at a variety of combinations of incidence and emergence direction.

With this approach, the bi-conical spectral reflectances and transmittances of coupon samples of materials making up a CFS are measured and stored in an optical property database. The geometry of the CFS is then drawn in three-dimensions using a CAD type computer program. This is then imported into (or created in) any of several available optical ray tracing programs, and the measured optical properties of each component are assigned to that component by the program.

The ray-tracing program is then instructed to send a beam of rays simulating direct beam sunlight into the CFS entrance aperture in a chosen direction of incidence. The rays so launched are traced through the system as they multiply reflect, transmit, and are absorbed by various surfaces and media within the CFS. The program keeps track of the flux values associated with each ray as it is reflected, transmitted, or diffusely scattered by a surface. In the case of scattering, an incident ray is made to produce a number of child rays in varying directions and with varying flux values, matching the known angular optical property of the scattering surface, determined by the

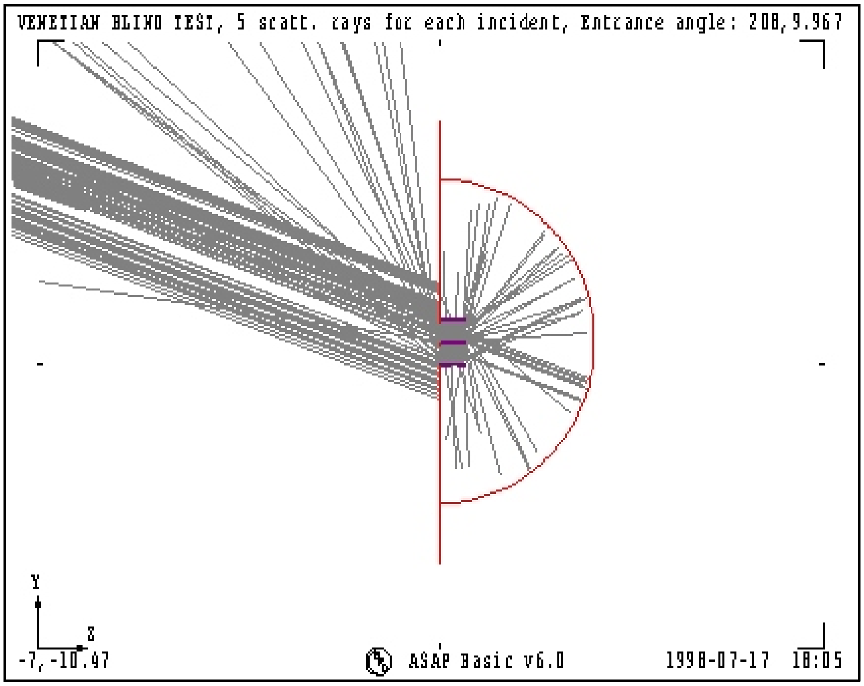

Figure 7. Result of a computerized ray trace of a three-slat Venetian blind. Collimated incident rays (from the sun) approach at an angle from the left, some pass through the beam delimiting aperture in the vertical plane and onto the blind slats, where they are subsequently multiply scattered between the slats and thence out of the blind system. Some scatter backwards out of the aperture while others scatter to the right, inside the building, and are captured for analysis by an artificial hemispherical surface used to intercept the emerging rays. The total ray flux of all the rays on the hemisphere is summed up and divided by the flux of the rays entering the aperture to obtain the conical-hemispherical transmittance of the Venetian blinds.

goniotransmissometer and gonioreflectometer. An example of such a ray trace analysis is illustrated in Fig. 7.

When the rays emerge from the system they are collected, and their fluxes evaluated and analyzed. If the process is used to determine the solar heat gain of the CFS, then the fluxes associated with all the rays filling a hemispherical solid angle of emergence from the exit aperture are added together and the result divided by the entering flux, to obtain an overall system conical-hemispherical transmittance for the direction of incidence used in the simulation. Then the incident direction is changed and the ray trace is repeated. The result is a table of conical-hemispherical transmittances of the total CFS. It takes two angles to specify a direction in space. For example, the angles (θ and ϕ) from and around a perpendicular to the entrance aperture, respectively. The resulting transmittance values can be arranged into a two-dimensional table, each entry giving the total system conical-hemispherical transmittance for the direction of incidence specified by the cell's values of θ and ϕ. If the CFS is spectrally selective, there will be a separate table of such transmittances for each wavelength simulated using the program.

The inward flowing fraction of absorbed radiation is not determined by the ray tracing program, since that involves more than just the radiant transfer of energy. The tracing program, however, is used to determine the quantity of flux absorbed by each component of the system. A separate analysis is required to determine how much of this absorbed flux from each component enters the space by means of conduction, convection, and re-radiation.

If it is the daylighting performance of the CFS that is desired, the ray trace program *is* used to determine the system transmittance over ranges of both incident and emerging directions. There are

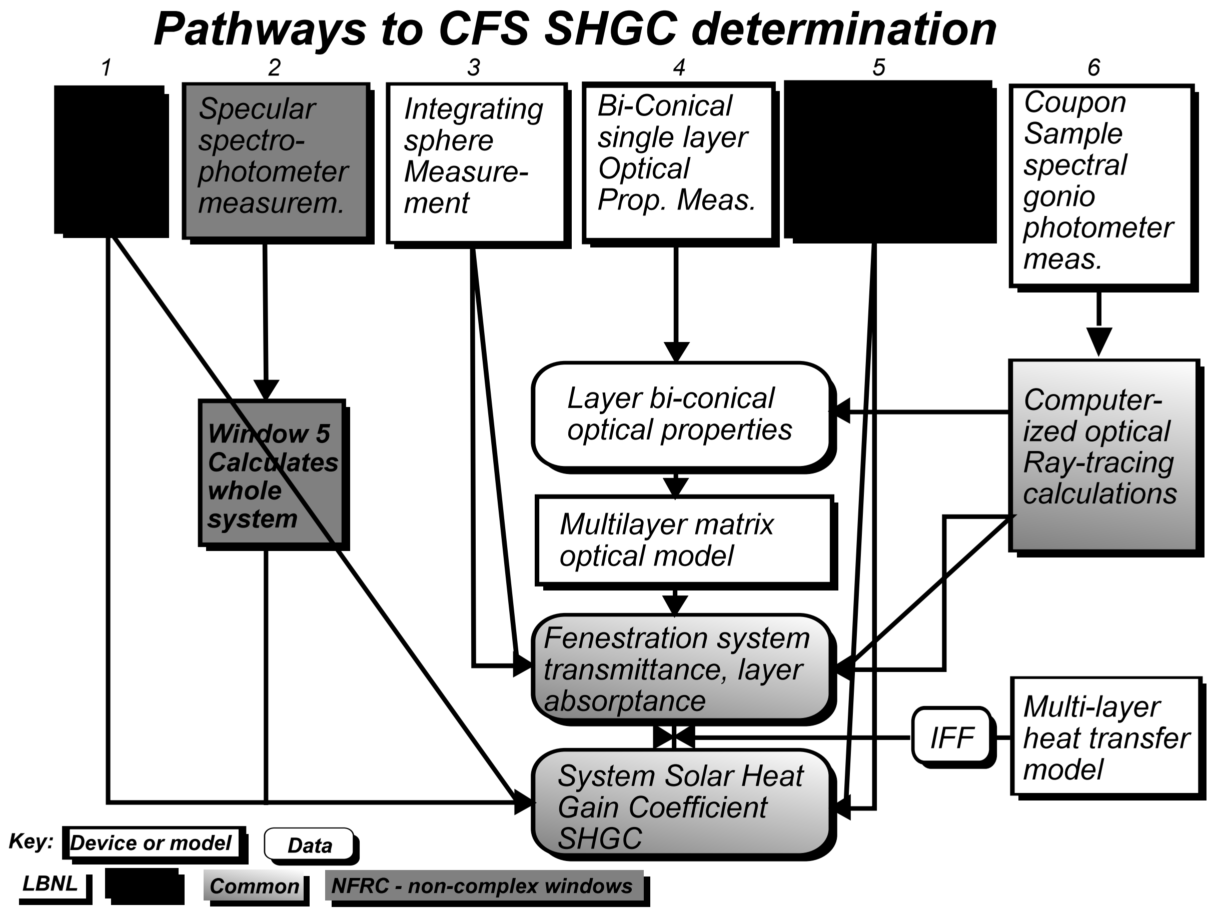

Figure 8. Measurement and calculation pathways to complex fenestration SHGC determination. Different pathways have been proposed and/or are being pursued by the three organizations listed in the key. Some are common to both FSEC and LBNL. The method NFRC uses for non-complex fenestrations is also shown. A "device" refers to an experimental measurement, a model to a calculational approach. For some pathways an independent multilayer heat transfer model is needed to determine the inward flowing fraction (IFF) of absorbed solar radiation, needed for final calculation of the solar heat gain coefficient.

therefore four angles involved in this measurement, the angles θ_1 and ϕ_1 of incidence and the angles θ_2 and ϕ_2 of emergence. I like to call the result for each incident direction a "flux map," since it describes the directional distribution of flux emerging from the system for one specific direction of incidence. The ray tracing program is used to determine flux maps for each of a number of different directions (θ_1 and ϕ_1) of incidence. The process is continued for each different incident direction until a full range of such angles has been covered. The result is a set of tables of transmittance values. Depending upon the number of incident and emergent directions of interest, the quantity of data in this set of tables can be relatively modest or large. Fortunately, currently available personal computers have more than adequate data storage capabilities, and the resulting data can be stored on a CD ROM for distribution, if this is desired.

In the case of spectrally selective CFSs, the process is somewhat more time consuming, but not unmanageable with the high speed personal computers now widely available. In this case, the flux map determination process is repeated for both changing incidence directions and changing wavelength. The quantity of data generated can in this case be quite large, but is easily handled by computer manipulation.

This approach is quite general, and can be used (at least in principle) to determine the solar transmittances of nearly any CFS one can imagine. Once the biconical data has been obtained, a simple integration (sum) of fluxes over the emerging directions will provide the conical-hemispherical transmittance data, if this is desired.

There is conceptually no limit on the type or complexity of fenestration system which can be modeled optically with this technique, as long as the geometry and optical properties of the system are known. Even holographic optical elements (HOEs) can be handled by some ray tracing programs.

Calorimetric Measurement

At the other extreme of the measure-versus-calculate range is the calorimetric approach, whereby the solar heat gain of the whole CFS is measured directly using a solar calorimeter. This is an insulated shell having an entrance aperture for holding specific CFS products and containing a means for collecting and measuring the ratio of solar radiant heat admitted to the chamber through the CFS to the solar radiant energy incident upon it. This ratio is the SHGC of the system. See Fig. 9.

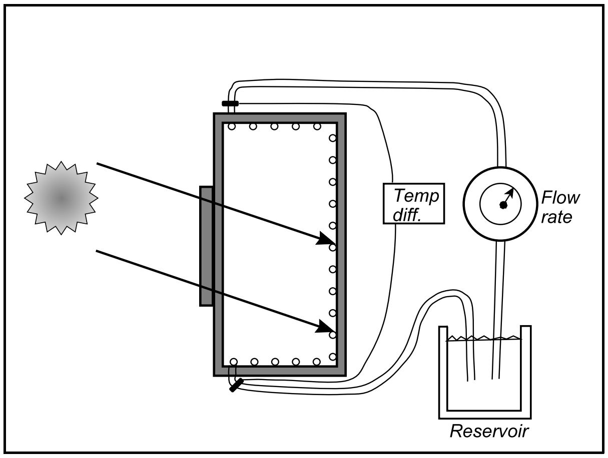

Figure 9. Schematic diagram of a box calorimeter. Solar radiation passes through the test article and into the calorimeter. The radiation is absorbed by black fins and tubes lining its insulated interior. Water flowing through the tubes at a known rate and temperature difference indicates is used to determine the solar heat gain of the cavity.

With this approach, every different model of CFS must be measured. For product lines containing only one or two models, calorimetry can be a cost-effective method for determining each model's SHGC. For product lines containing many different models and/or colors, however, calorimeter tests are time-consuming and expensive, making them impractical for large product lines.

The calorimetric approach has been pursued in some detail as part of the European research project ALTSET (Angular-dependent Light and Total Solar Energy Transmittance), coordinated by Werner Platzer of the Fraunhofer Institute for Solar Energy Systems in Freiburg. ("Total solar energy transmittance" is the name the Europeans use for our solar heat gain coefficient.) A 62 page 20 Feb 2000 report (ALTSET-3-00) offers a detailed draft standard practice for solar calorimetric measurements of the SHGC of complex fenestrations.

Intermediate Solar Heat Gain Determination Methods

Figure 8 illustrates a number of approaches to SHGC determination, ranging from the calorimetric method (number 1 in Fig. 8) to the generalized optical modeling method (number 6 in Fig. 8.) described above. First there is the calorimetric method. Second is the existing method used by the NFRC for simple fenestration systems. The last one on the right, number 6, is described above under the heading "The Generalized Optical Modeling Approach."

Method 3 in Fig. 8 is based on a measurement of the conical-hemispherical solar transmittance of whole complex fenestration systems using a large integrating sphere. See Fig. 10. A measurement is first made with the entrance port empty as shown. Then the measurement is repeated with a fenestration test article over that port. The ratio of the two readings is the conical-hemispherical transmittance of the test article.

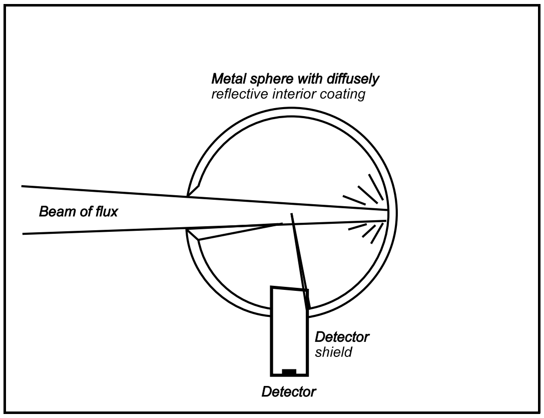

Figure 10. Integrating sphere detector. A fixed fraction of all radiation entering the entrance port reaches the detector at the end of the baffled tube. That fraction is the same regardless of the angular distribution of entering flux.

With this approach, the inwardly flowing fraction of the absorbed solar radiation must be determined by some other method in order to obtain the SHGC. In Fig. 8 the latter is assumed to come from a "multilayer heat transfer model." Once the inwardly flowing fraction (IFF) is known, it can be combined with the solar transmittance measured according to option 3, with an integrating sphere pyranometer to obtain the system SHGC. (The same multilayer heat transfer model can be used to determine the IFFs with method 6 and these can be combined with the calculated total system solar transmittance to produce the SHGC.) This approach was pioneered at LBNL many years ago and is now being considered seriously by several European investigators. For example, under the rubric of the ALTSET project, a number of investigators have prepared the 17 February 2000 report ALTSET-4-00 describing the process in some detail and assessing problems encountered and offering some recommendations for overcoming them.

Method 4, designated the "bi-conical single layer optical property measurement," was proposed and described by Joe Klems at Lawrence Berkeley National Laboratory nearly ten years ago. [Klems, J. H. (1994A). "A New Method for Predicting the Solar Heat Gain of Complex Fenestration Systems: I. Overview and Derivation of the Matrix Layer Calculation." ASHRAE Trans. 100(pt. 1): 1065-1072. Klems, J. H. (1994B). "A New Method for Predicting the Solar Heat Gain of Complex Fenestration Systems: II. Detailed Description of the Matrix Layer Calculation." ASHRAE Trans. 100(pt.1): 1073-1086.]

With this approach, a solar simulating source illuminates a single "layer" of a set of parallel layers of a complex fenestration system and the flux emerging at a number of fixed directions on the other side is measured using a goniometric method. The direction of incidence is changed and the emerging flux map is measured again. A matrix multiplication method developed by Dr. Klems is then used to determine the bi-conical solar transmittance of the overall system of multiple layers, from knowledge of the bi-conical transmittances and reflectances of each separate layer. The system could, for example, be composed of multiple panes of glass and an interior Venetian blind with the slats set at a specific angle.

This approach could also determine the solar gain properties of a multiple pane window with an exterior shade and an interior blind. A bi-conical transmissometer and reflectometer was developed at LBNL and used to prove the methodology.

The fifth approach diagramed in Fig. 8 is the primary subject of this paper. The basic idea is to use simplifying assumptions for each different CFS to simplify the problem—such that the SHGC can be calculated approximately using basic principles of optics and heat transfer. The desired result is equations or formulas for SHGC that work without the need for difficult or expensive calorimeter measurements or for ray tracing of the whole system.

In an example of this approach, Laney Mills and I developed a method for planar vertical interior shades attached to single or multiple pane windows of known SHGC and optical properties. [“Awning Shading Algorithm Update,” ASHRAE Transactions, Vol. 96, Pt. 1, 1990.] The resulting formula produced combined system SHGC values which matched quite well the results of a few calorimetric measurements of system solar gain. The experimental data was not collected by us and was minimal, so we cannot claim the approach to be universally valid for this type of complex fenestration system. The results were promising, however, and encourage further work in this area.

In the present paper complex fenestration systems are divided into a number of categories, and means for determining the solar heat gain coefficient of each is suggested, using the simplest, easiest, and least expensive combination of the strategies shown in Fig. 8.

“Short-cut” Methods for Complex Fenestration Systems

Most complex fenestrations can be categorized by type. A suggested categorization follows. Each different CFS affects incident solar radiation differently. In each section to follow, possible “short-cut” approaches to solar heat gain determination, specific to each separate category, will be presented. Where possible, they rely on the use of “simplifying assumptions,” assumptions regarding the optical and thermal processes taking place which lead to a simplification of the optical and thermal problem, hopefully making it easier to construct a means of *calculating* the solar gain through CFSs in each category, with minimal needs for measurement of more than just basic material properties.

The use of simplifying assumptions brings with it some degree of incorrectness. If our modeling of the physical processes taking place is simplified too much, the calculation results can be far from how the actual CFS performs. The goal is to strike an acceptable balance between simplification and correctness.

In most cases, the degree of correctness can only be determined by the use of more complicated analyses (with fewer or no simplifying assumptions) or by direct measurement. Both can be used to assess the success or failure of a proposed “short-cut” method.

Angle-dependence of solar gain and visible transmittance. Before starting the following descriptions, some remarks are needed concerning angle-dependence. Most complex fenestration systems have strongly angle-dependent optical and solar gain properties. To avoid the complication of dealing with this variable for conventional windows, NFRC has standardized on a single angle of incidence. For most fenestrations that angle is zero—solar rays are incident perpendicularly on the glazings for rating purposes. Some simplification may result from this selection of incidence angle, but, as with all such simplifications, it comes with a price. The rated properties can be substantially different at other angles of incidence, and these other angles are more prevalent for real installed fenestrations. CFSs share this problem, perhaps more acutely. CFSs are generally more angle-selective.

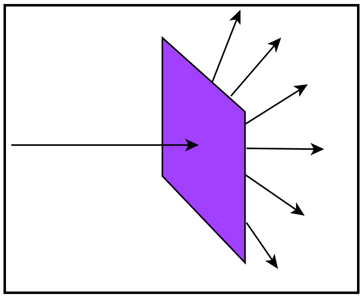

Figure 11. Single pane diffusing (obscure) glazing.

A. Obscure Lites (Diffusing Panes)

Single-pane. The SHGC and VT of single-pane windows with diffusing panes can be obtained with current NFRC procedures as follows. First the conical-hemispherical spectral transmittance of a sample of the pane is measured with an integrating-sphere spectrophotometer at normal incidence. Then the Window 5 computer program from LBNL is used to calculate the overall glass and window SHGC and VT. (Though the Window 5 program works only with specular optical properties, assuming no scattering in the system, for a single pane it does not matter whether the transmitted rays are scattered or remain specular., as long as the integrating sphere does its job properly. Either contributes the same to total solar gain.)

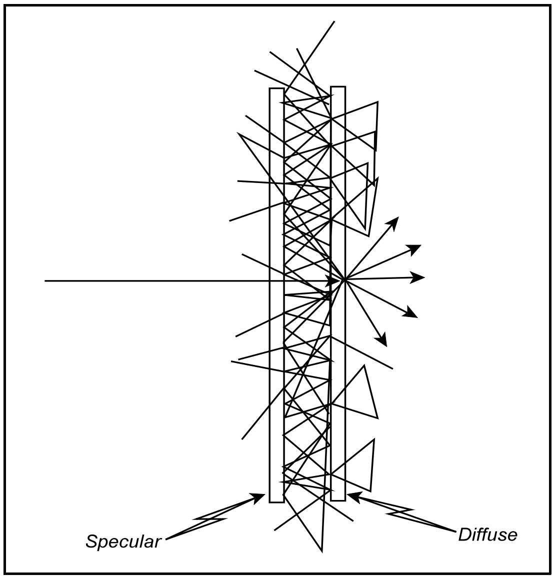

Figure 12. Double-pane obscure window with the diffusing pane being the second one, the one on the right in the illustration.

Double-pane. If a diffusing pane is part of a multiple pane glazing system, the above approach is not valid, and must be replaced with a different, somewhat more complex, procedure. The reason is that Window 5 models multiple reflections between the glazing layers as if both layer properties have no diffuse component. The presence of diffuse reflection by one or more of the glazings so alters the multiple reflections between layers that the predictions of the specular-only model are brought into question. To overcome this difficulty, two alternatives can be envisioned. First is to modify Window 5 to make it capable of modeling the effects of diffuse scattering. Diffuse scattering is in general angular dependent, so a consequence of this approach is to require a new kind of coupon sample optical property measurement, a goniometric one, which is not currently included in any NFRC standard practice. A possible approach for this strategy would be to use the matrix methodology proposed by Joe Klems and cited previously. To do this will require some means for determining the bi-conical angular variations in the transmittance and reflectance of the diffusing glazing layer. Klems explored a goniometric measurement approach. Ray-tracing is another, if the angular scattering properties of the glazing are known.

The second alternative would be to make some simplifying assumptions regarding the nature of the multiple reflections between the two layers, assumptions making the problem somewhat simpler and easier to solve. For example, in the case of a double pane glazing with one diffuse and one specular pane, one could assume that the effect of diffuse scattering by one of the layers is *a priori* inconsequential, so that the specular interreflection model can be used.

Such an assumption might be based on the fact that the angular reflectance of a non-diffuse pane of glass is fairly constant for angles of incidence from 0 degrees to 40 or 50 degrees, so that rays scattered from the second (diffuse) layer within this range will be reflected almost as strongly as those at normal incidence. The reflectance at normal incidence of a single sheet of clear glass is relatively low, so the contribution of the inter-reflection component to the overall solar heat gain will not be great.

Furthermore, the spacing between the panes is much smaller than the shortest lateral dimension of the glazing, so that edge effects have much less influence as well. (Rays scattered out of the normally incident beam will be reflected back and forth between the two panes many times before reaching the edge where they can escape, so the edge losses will be minimal.)

Accepting these assumptions, double pane glazings with one pane diffuse should have approximately the same solar heat gain coefficient and visible transmittance as a double pane glazing with no diffuse scattering, as long as the conical-hemispherical optical properties of the two glazings are the same. Such an assumption should not be accepted without experimental or other assessment of the errors it produces.

One way to verify these assumptions would be to measure the solar heat gain coefficient and VT of two double-pane or triple-pane glazings with identical conical-hemispherical optical properties but with one pane of each differing in the specular-diffuse ratio. Both would be multiple pane glazing systems, but one would have two specular glazings and the other would have one specular and one glazing diffuse, or otherwise nonspecularly reflecting and transmitting optical properties. Such a test, under the same conditions of irradiation, should reveal the magnitude of the error produced by the above simplifying assumptions. If that error is small, then perhaps this simplified approach to rating such systems will be acceptable.

Another approach would be to compare measured SHGC and VT values for the diffuse pane case with their modeled specular values obtained from Window 5. In this case, the diffuse pane system should be illuminated at normal incidence with collimated radiation and have the same spectral distribution as that used by Window 5 for spectral weighting and integrating.

A third approach would be to calculate the solar transmittance and VT of both specular and diffuse glazing systems with a sophisticated optical ray tracing program and use the results both to evaluate the magnitudes of the errors introduced by the simplifying assumptions and to posit improvements in the simplified model.

B. Exterior Shade Screens, Dark

If an exterior planar shade screen, such as an insect screen, a sheet of perforated plastic, or other, is dark (low reflectance) on its window side, then rays passing through the screen and redirected by the glazing back onto the inside of the screen will reflect only minimally back again to the glazing. Thus there will be little multiple reflection or multiple scattering between the screen and the glazing. A simplifying assumption can be postulated in this case. We assume that little of the screen-absorbed radiation propagating from the screen to the glazing (as long-wavelength infrared radiation) is transmitted through the glazing to the interior. Thus the inward flowing fraction (IFF) of the screen's absorbed radiation will effectively be zero and we can model the effect of the screen simply as an obscuration of a portion of the glazing, as illustrated in the drawing in Fig. 13.

Let A_{hi} be the area of the i^{th} hole in the screen and N be the number of such holes over the whole screen. The total open area of the screen A_h will be given by
If A_s is the total shade area, the fraction of open area will be given by A_h/A_s and the solar heat gain coefficient $SHGC_{total}$ of the shade plus window, in terms of that $SHGC_w$ of the window alone, will be approximated by

$$SHGC_{total} = \frac{A_h}{A_s} SHGC_w \qquad (4)$$

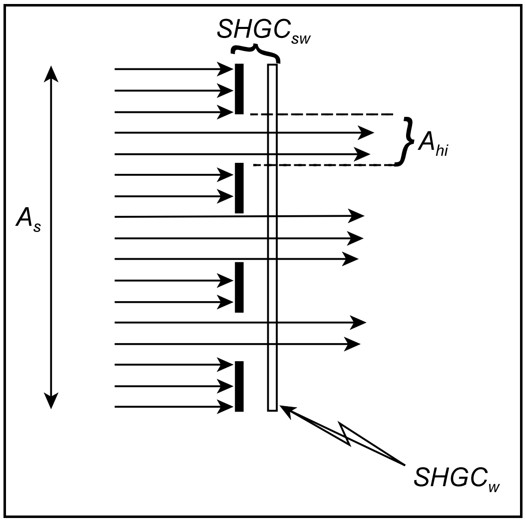

Figure 13. Illustration of solar rays incident on an exterior shade screen having both opaque and open areas.

Before accepting this simplified approach to determining shade screen and window solar heat gain coefficient, independent assessments of the validity of the assumptions must be made. As before, these could be by calorimetric measurement or by ray trace calculation.

$$A_h = \sum_{i=1}^{N} A_{hi} \qquad (3)$$

If the back side of the screen is not dark, then significant diffuse multiple reflections can take place between the screen and the window glass and this simplification is no longer valid. In such a case, it is expected that only direct calorimetric measurement or full optical ray tracing will yield acceptably accurate results. On the other hand, if the reflectance of the glazing system facing the shade is low, there will be relatively little of the transmitted flux that is reflected back to the shade, especially at normal incidence. It may be possible to use the same formalism in this case as for the dark shade, but this should be tested with calorimetry before being accepted.

C. Curved and Bent Glazing

For “bent” glazing, composed mainly of planar specular glazing sheets joined by relatively small “bent” or curved sections, the glazing can be modeled as a set of planar sheets with known optical properties, the “bent” section being replaced for the purposes of calculation by one or more narrow strips of glazing at intermediate angles to the primary planar sheets. The correct angle of incidence must be used for each planar section. The total solar heat gain coefficient would be approximated as an area weighted average of the SHGC values of the individual sections.

Domed glazing can be modeled with the laws of propagation and reflection of optical radiation through homogeneous media with plane parallel surfaces—in this case curved in the shape of a sphere. It should not be difficult for an optical engineer or physicist to analyze the geometry and derive a closed-form equation providing the transmittance of such a dome, in terms of the thickness of the glazing layer, the inner and outer radii of curvature, the material absorptivity, and its refractive index. The Fresnel formulas for reflection at a dielectric interface provide accurate reflectivities for such interfaces. The remainder of the problem is one of determining the variation of the total system transmittance with angle of incidence and averaging this over the effective aperture of the dome. I developed such an analytical model for plastic skylight domes in the early 1980s for a private consulting project. It should not take much work to improve, adapt, and verify the derivation, perform some verification tests, and publish the results.

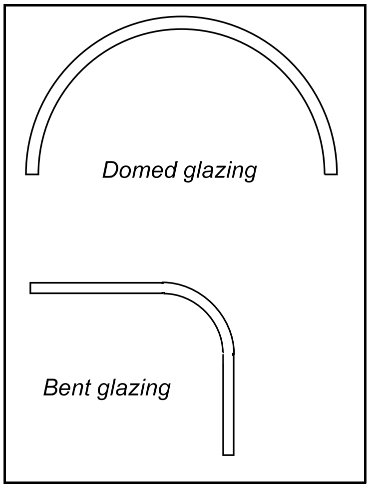

Figure 14. Illustration of cross-sections of bent and domed glazings.

D. Interior Planar Vertical Shades

In this category are interior planar shades hanging vertically, such as roller shades, Venetian blinds with the slats closed completely, vertical blinds with their “slats” closed completely, or a sheer curtain stretched to be flat and parallel to the window. See Fig. 15.

In “Effect of Interior Shade on Window Solar Gain” by R. McCluney and L. Mills, ASHRAE Transactions Vol. 99 Pt. 2, Symposium paper DE-93-4-2, published by ASHRAE in 1993, several simplifying assumptions were used to derive a simple model for the “center-of-glass” solar heat gain coefficient $SHGC_{\text{total}}$ of a combined window and shade where the solar transmittance T_w and solar heat gain coefficient $SHGC_w$ of the window are known, as are the back reflectance of the window R_w and the reflectance of the side of the shade facing the window R_s.

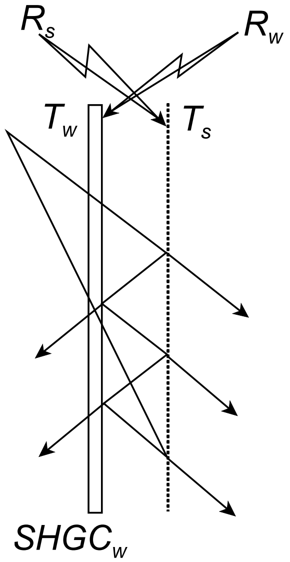

Figure 15. Illustration of vertical planar semi-transparent shade attached to a single-pane window.

Though the two sets of experimental results found in the literature to compare with this model's predictions indicated good agreement between experiment and theory, we concluded that "for neither set of measurements is it clear exactly how the measurements were performed, how accurate the shade reflectance values are, or how close the actual reference window systems used were to the SRG." The term "SRG" refers to the "standard reference glazing." The readers of that paper, as well as this one, are cautioned not to generalize these results without substantial additional comparison of theory with measurement, a task I hope to pursue later this year.

If new measurements indicate a degree of error in the previously published model, it should be possible to modify that model somewhat to achieve better agreement. The result could be a closed form, straightforward analytical method for calculating the effect on window solar heat gain coefficient of a planar interior blind parallel to the glazing system applicable over a wide range of shade reflectances and window glazing solar transmittances.

E. Awnings and Overhangs

The effects of awnings and overhangs on window solar gain are relatively easy to calculate using existing methods. However, this class of products are unlikely to be rated by the NFRC in the foreseeable future, so they are not further discussed here. Interested readers might wish to consult "Awning Shading Algorithm Update," by R. McCluney, ASHRAE Transactions Vol. 96, Part 1, 1990 and the references cited therein. The paper "Software for Window Solar Gain Analysis," Building Simulations '95, Fourth International Conference, International Building Performance Simulation Association, Madison, WI, 14-16 August 1995 describes a computer program (AWNSHADE) based upon the algorithm developed in the previous paper, and two additional programs for determining cloudless sky solar spectral (and broadband) irradiance (SUNSPEC) and the position of the sun in the sky for any date and time at any latitude and longitude (SUNPATH). All three programs are undergoing revision and updating.

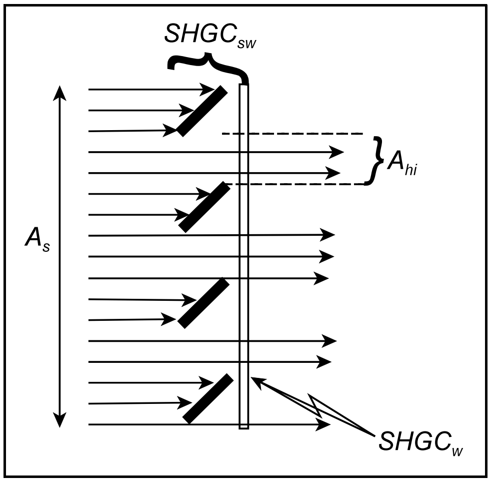

Figure 16. Illustration of dark exterior louvered blinds attached to a single-pane window and showing rays transmitted at normal incidence between the slats.

F. Exterior Louvered Blinds, Dark

Exterior louvered blinds are popular additions to many windows for greatly reducing solar heat gain while still permitting daylight entry and some visual connection with the outdoors. The possibility of multiple reflections between the slatted louvers and between the shade and the window makes these products difficult to rate without direct measurement using a calorimeter, or involved and time-consuming simulation with an optical ray-tracing program.

If the inward and lower surfaces of the slats are black, however, multiple reflections between them will be suppressed. The same is true of reflections between the glazing and the blind. Thus, in this particular case, the methods of case B above might prove acceptable, for rating purposes, at a single angle of incidence, such as normal to the fenestration aperture, as illustrated in Fig.16.

G. Patterned, Decorative, or Leaded, Multicolored Glass

For single-pane glazings with patterned, decorative, leaded, or otherwise multicolored glass in which well-defined homogeneous areas can be identified, the total *SHGC* and total *VT* could be defined as area-weighted sums of the individual area *SHGC* and *VT* values, respectively, as illustrated in Fig. 17. These values would be determined with Window 5 for cases that warrant it. For those that do not, an integrating sphere or calorimetric approach could be attempted.

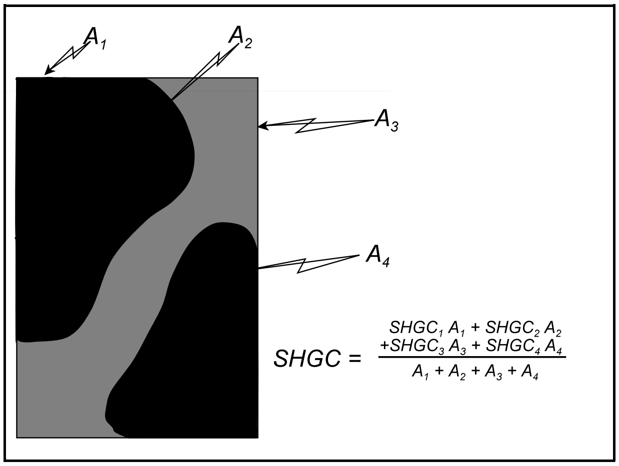

Figure 17. Illustration of patterned glass with four homogeneous areas, each with a different *SHGC*. If single-pane, one or more of the areas may have non-specular properties.

At an 11/3/2001 meeting of the Solar Gain Subcommittee of the NFRC in New Orleans I suggested that if the fenestration system being considered has well-defined, internally homogeneous, planar elements, then integrating sphere or calorimetric measurements could be made of each such area independently, such as areas 1 through 4 in Fig. 17, as long as the calorimeter aperture was smaller than each different area. The area-weighted glazing value would then be combined with the solar gain of the frame to achieve the total system *SHGC* value.

If the complex system contains irregularities which are regular and spatially periodic, such as corrugations or linear patterns, this approach could still work, as long as the calorimeter or integrating sphere aperture covers either one cycle of the period alone, or many cycles, thereby averaging the result over them. Only then could the results be safely extrapolated to the remainder of the glazing area.

If the areas are too small for a calorimeter or integrating sphere aperture, the *SHGC* of the i^{th} homogenous area could be determined by making a glazing system composed entirely of this i^{th} area's materials and measuring or calculating the *SHGC* of that larger system. This would be repeated for each different homogeneous area. Letting $SHGC_i$ be the *SHGC* value for the i^{th} area and A_i be the area of that region, the total glazing system *SHGC* value would be computed from the equation

$$SHGC = \frac{SHGC_1 A_1 + SHGC_2 A_2 + SHGC_3 A_3 + SHGC_4 A_4}{A_1 + A_2 + A_3 + A_4} \tag{5}$$

H. Exterior, Between the Panes, and Interior Slatted Shades

For slatted shading devices with significant (nonzero) reflectances, the multiple reflections between the slats and between the slats and the glazing system will be significant and there appears to be little alternative for determining solar heat gain but to measure whole systems with calorimetry or to simulate their performances with Monte-Carlo ray tracing calculations. The latter will yield only the overall system optical properties of solar and visible transmittance, and possibly the quantities of flux absorbed on the various surfaces and solids simulated. For the inward-flowing fraction of absorbed radiation, complex three-dimensional heat transfer calculations are likely to be necessary.

In the special case of slatted blinds on the interior of a window, the large integrating sphere approach could be used to determine system solar transmittance as a function of incidence angle (or at one particular angle for the purposes of certification and rating) without the need for ray tracing, but the inward-flowing fraction would still need to be found by some other means. This approach is being pursued by the Europeans in a project led by Werner Platzer.

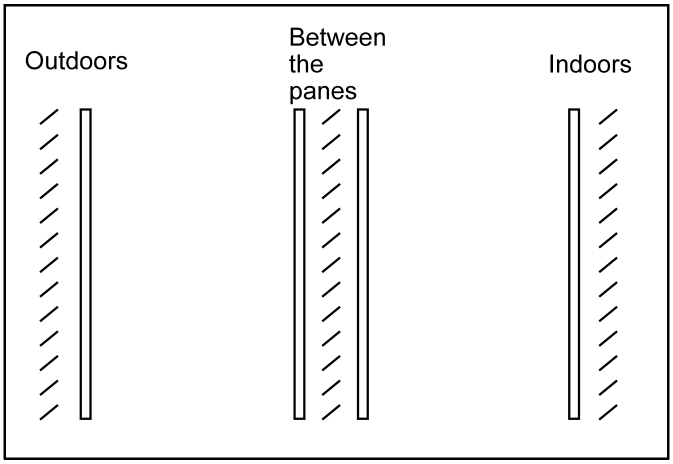

Figure 18. Illustration of exterior, between-the-panes, and interior horizontal slatted blinds.

Joe Klems of LBNL has proposed that the inward flowing fractions of a variety of common geometries be determined as a research project and the results published for use by anyone.

With this methodology, the solar transmittance and visible transmittance of any given slatted shade system would be measured using the large integrating sphere at several different angles of incidence and for several different slat tilt angles. The absorbed fraction of the incident radiation would be calculated analytically, knowing the absorption coefficient of the slat surfaces. The inward flowing fraction of this absorbed radiation would be determined by looking it up in the published table of values for the specific geometry used (slat length, width, and thickness, as well as spacing from the glazing and air speed adjacent to the slats).

I. Tubular Daylighting Devices

I wrote and submitted to NFRC on 24 December 2001 a white paper on this subject, titled "Test/Measurement Procedure Concept Paper for Tubular Daylighting Devices." The proposal calls for analytical optical modeling of a clear hemispherical top dome, plus a one-time ray trace determination of the transmittances of polished, specularly reflecting cylindrical light pipes of various reflectivities and aspect ratios. Finally,

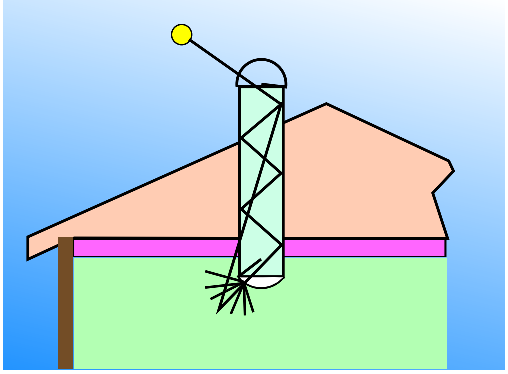

Figure 19. Illustration of the operating mechanism for tubular daylighting devices.

multiplication of the top dome transmittance by the cylinder transmittance and by the bottom diffuser transmittance is used to determine the solar and visible transmittances of the total system. For rating purposes, these values are determined for collimated beam solar radiation incident at a fixed angle from the vertical. In using this approach, it is assumed that the inward flowing fractions of radiation absorbed in the top dome and the reflective cylinder are both zero—that such absorbed radiation does not enter the conditioned space below the ceiling. It is further assumed that the inward flowing fraction of absorbed radiation for the bottom diffusing glazing is known independently, or may be assumed to be very small, and therefore ignored for rating purposes. This makes the system solar transmittance equal to the SHGC.

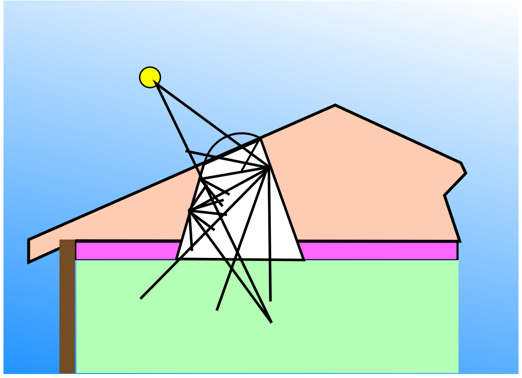

Figure 20. Illustration of the complex pathways followed by solar rays striking the walls of a conventional skylight's light shaft.

Some detailed optical work in support of this proposal is planned for the next few months, examining the validities of the various assumptions and deriving the top dome transmittance model. Subsequent to the publication of the 24 December paper, I found that nearly every commercially available tubular skylight now incorporates within the top dome, or just under it, a means for increasing the ability of the system to capture light from low in the sky, at zenith angles greater than about 40 to 50 degrees or so. The presence of these optical complexities threatens to undermine the simplifying assumptions on which the previous proposal was based. It is apparent, however, that for many of the available systems, a fixed zenith angle between, say, 25 and 40 degrees or so, minimizes the influence of the optically complex elements. This is another of the questions which needs to be evaluated by research in this area.

If the simplifying assumptions prove *not* to be viable, an alternative worthy of exploration would be to measure total system conical-hemispherical transmittance for the fixed angle of incidence, through the use of a solar simulator source and an integrating sphere broadband detector approximately seven to nine feet in diameter. By alternating between a flat-response pyranometer detector in the sphere and a photopically corrected one, both solar and visible transmittances can be measured, and from the first of these the approximate solar heat gain coefficient can be obtained. To avoid a need for the integrating sphere measurement, the needed properties of the whole system could be determined by ray tracing.

J. Conventional Skylights

Conventional skylights are also complex fenestration systems, by virtue of the curved top dome and diffuse reflectance from the walls of the light shaft or skylight well. Even if the top "dome" is really planar, as it is with most glass skylights, sometimes the glass is diffusely transmitting, a glare control measure. In this case, even if the glazing is specular, it is still difficult to determine the solar heat gain coefficient and total visible transmittance of the system because of the diffuse reflectance of surfaces below the top glazing.

Joe Klems has measured the solar heat gain coefficient of conventional skylights in a research setting. He found that thermal stratification of the air within the light shaft significantly alters the overall *SHGC* of the total system. Thus, even though the glazing system at the top of the well may be easily modeled with Window 5 (or Window 5 plus an analytical model to correct for glazing curvature), this is not the total story. The effect of the well on *SHGC*, and on *VT*, is significant, and not accounted for in Window 5.

The alternatives for determining these coefficients with this type of complex fenestration system are similar to those with tubular skylights, with the exception of the thermal stratification effects. The solar transmittance of the top dome or glazing system should be calculable using the optical methodology described previously.

The optical effect of rectangular skylight wells has been approximated by simple formulas for use in Illuminating Engineering Society procedures for calculating daylight illumination from skylights. The technique involves calculation of the "Well Cavity Ratio," given by the formula

$$WCR = 5h(w + l)/wl,$$

where w, h, and l are the width, height, and length of the well, respectively. Well efficiency is plotted versus the well cavity ratio for different well wall reflectances. The methodology is useful only for the diffuse component of skylight irradiation, however. The presence of the direct beam, critical for solar gain calculations, makes the problem much more complex.

Of the techniques shown in Fig. 8, solar calorimetry (with the calorimeter oriented to mimic the actual in-place installation of the skylight), the large integrating sphere measurement method, and ray tracing appear to be the best tools for determining performance. The last two of these, however, do not consider the inward flowing fraction of absorbed radiation. The fraction of well wall absorbed radiation admitted as heat gain to the space below depends on many variables. The varying geometries of different installations does not help the matter. Air flows within the well can have strong influence over the inward flowing fraction of absorbed radiation, by eliminating or reducing the stratification effect. It is not clear whether a reliable calculational method for determining solar heat gain through conventional skylights can be developed. It is likely that solar calorimetry will remain the mainstay for performance testing of these fenestration systems.

Conclusion

A variety of methodologies is available for rating the solar heat gain coefficient and visible transmittance of complex fenestration systems. In most cases a modest amount of work is needed to determine if simplified methods are possible, practical, and sufficiently correct to be accepted by the NFRC.