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Advanced Fenestration and Daylighting Systems

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Introduction

Advanced fenestration and daylighting systems form an interesting new class of devices and products for introducing natural lighting (daylight illumination) into buildings. They are split into two distinct classes. *Advanced fenestration systems* are new high-performance glazing and reflecting systems for otherwise conventional windows which offer specialized spectral and/or angular selectivity, intended for improved illumination quantity and quality while managing solar radiant heat gain to meet both human comfort and energy conservation objectives. These spectral and/or angular selectivities can be built into the glazings, incorporated into new objects placed between the panes, or they can be part of objects attached to the interior or exterior frames of the windows. The class includes a wide variety of fenestration attachment products, such as shades, blinds, screens, fixed and movable louvers, and even mirrored surfaces for re-directing the daylight entering fenestration apertures. This class also includes several novel new glazing types such as those containing electrochromic and holographic layers, still in the research stage.

The second class of systems, *advanced daylighting systems*, includes those manufactured by a new solar lighting industry, whose products are targeted for what has been called “core daylighting” because they are intended to introduce daylight into the core spaces of multistory buildings, spaces distant from the building envelope, or in other locations where more conventional daylighting apertures cannot be placed. Solar lighting systems include the widely available *tubular skylights* offered by many manufacturers in the U.S., Canada, and other countries around the world, and a variety of new systems just entering the market (or being prepared for future market entry). The distinction between solar lighting systems and more conventional daylighting systems is illustrated schematically in Fig. 1.

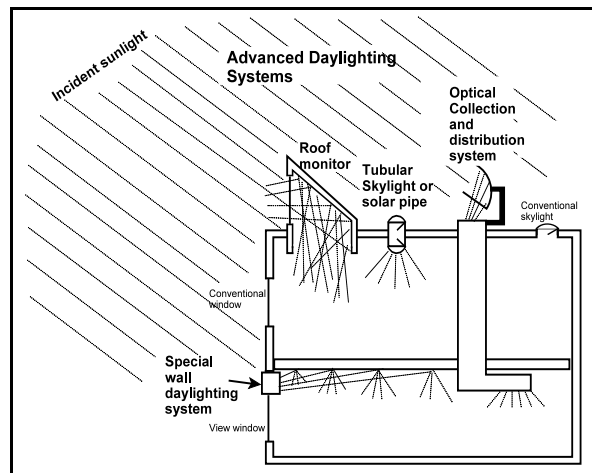


Figure 1. Distinguishing advanced daylighting systems from conventional windows and skylights.

Solar lighting systems are fairly recent innovations, and haven't yet experienced widespread use. Both categories include complex devices whose performances are difficult to predict and quantify for all locations and seasons. The difficulty of quantifying performance stems from the complex

nature of their angularly selective performances. The solar heat gain of spectrally selective clear glazing systems can readily be calculated with widely available computer programs. Spectrally selective materials which are also *non-specular* in transmission and reflection, however, pose difficulties. In order to understand the difficulties encountered, with all the systems described herein, and better to understand how some of the more elaborate systems work, a few concepts of optical physics and of radiometry need to be understood. These include the definitions of irradiance, radiant intensity, and radiance, as well as their photometric counterparts, illuminance, luminance, and luminous intensity.

An understanding of the fundamental optical properties of materials is also needed, including the biconical and conical-hemispherical transmittances and reflectances of sheet materials, both opaque, translucent, and completely clear. For comprehensive discussions of these quantities, the reader is directed to chapters 1,2, and 6 of a recent textbook on the subject¹.

Advanced Fenestration Systems

Figures 2 and 3 illustrate four examples of what is being called advanced, or complex, fenestration systems. They have strongly angle-dependent optical properties, and most of them include diffusely reflecting surfaces. Many additional geometries are used to control the admission of direct beam and diffuse sky light into a building, including vertical and horizontal fixed louvers, both inside and outside the building, exterior shading screens, and operable interior and exterior louvered shades, shutters, and awnings. The importance of including angular

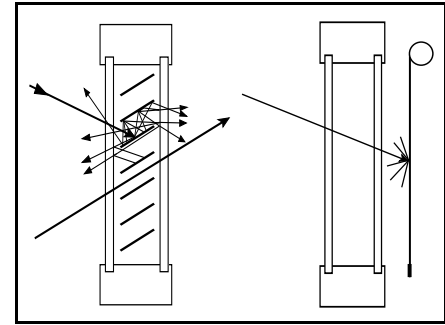


Figure 2. Between the panes and interior shades make for complex windows.

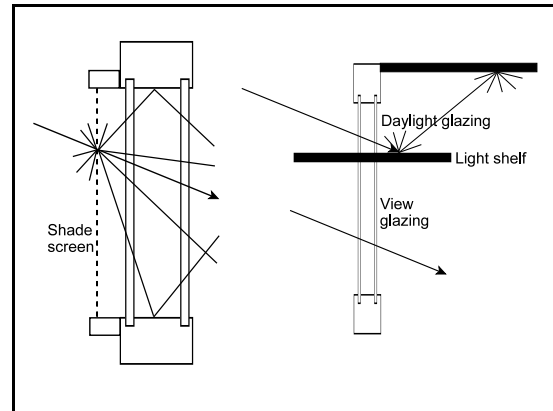


Figure 3. Exterior shade screen and light shelf advanced fenestration systems.

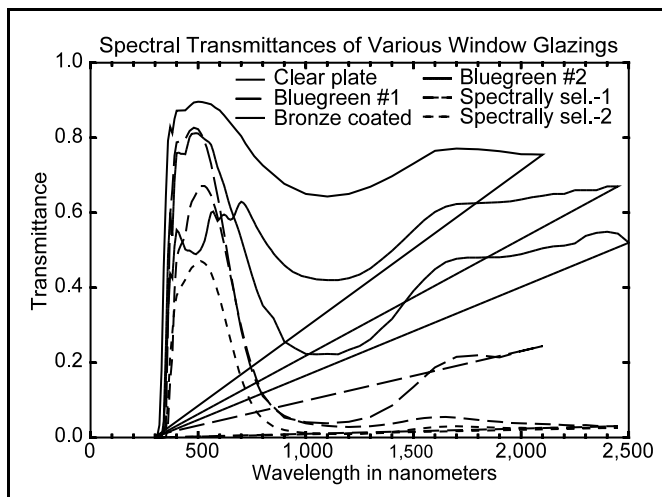


Figure 4. Comparison of commercially available conventional and spectrally selective glazings.

selectivity effects in conventional fenestration solar gain calculations was pointed out recently².

Glazing systems used in fenestrations can exhibit strong *spectral selectivities*, as illustrated in Fig. 4. The reason why this is important is illustrated in Fig. 5. The dashed cold climate transmittance spectrum is for ideal clear glass with a “low-e” coating applied to it. Only a limited portion of the solar spectrum contains visible light. All the rest, including

infrared and ultraviolet components, is invisible to the eye and hence not capable of producing illumination. All portions of the solar spectrum, however, produce heat when absorbed in a building's interior. A strongly spectrally selective glazing, such as the ones labelled "blue-green 2" and "spectrally selective 1 and 2" in Fig. 4, can produce adequate quantities of daylight illumination while rejecting much of the solar radiant heat gain. The influence of spectral selectivity on glazing system solar gain was discussed in two recent papers³.

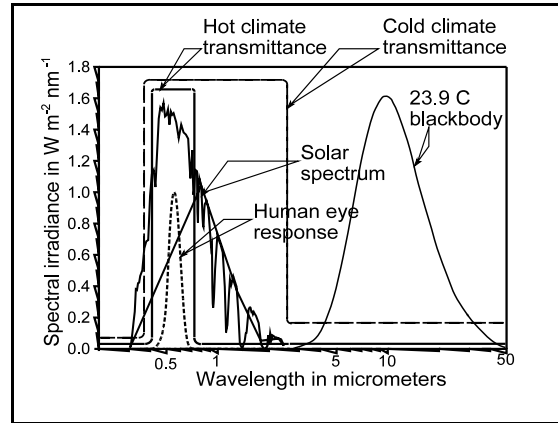


Figure 5. Ideal spectrally selective glazing transmittances compared with the solar spectrum, human eye response spectrum, and room temperature blackbody radiation.

With the exception of spectrally selective glazings, whose solar gain performances can be determined readily by existing, widely available methods, determining the solar heat gain performances of these systems is not currently a straightforward engineering process. Strategies for determining such performance are depicted in the flow chart in Fig. 6 below.

They range from a "measure everything" approach (solar calorimetry) on the left to a "measure as little as possible" approach. The latter involves theoretical calculation of the bi-conical optical properties of the entire fenestration system,

based on measurements of the bi-conical optical properties of small "coupon samples" of all materials of optical importance in the system. This latter approach, though potentially the most accurate and least expensive for fenestration manufacturers, is the most elaborate and involved of the possible strategies. It will be described in more detail in a later section. The chart shown above is described⁴ in more detail in Ref. 4.

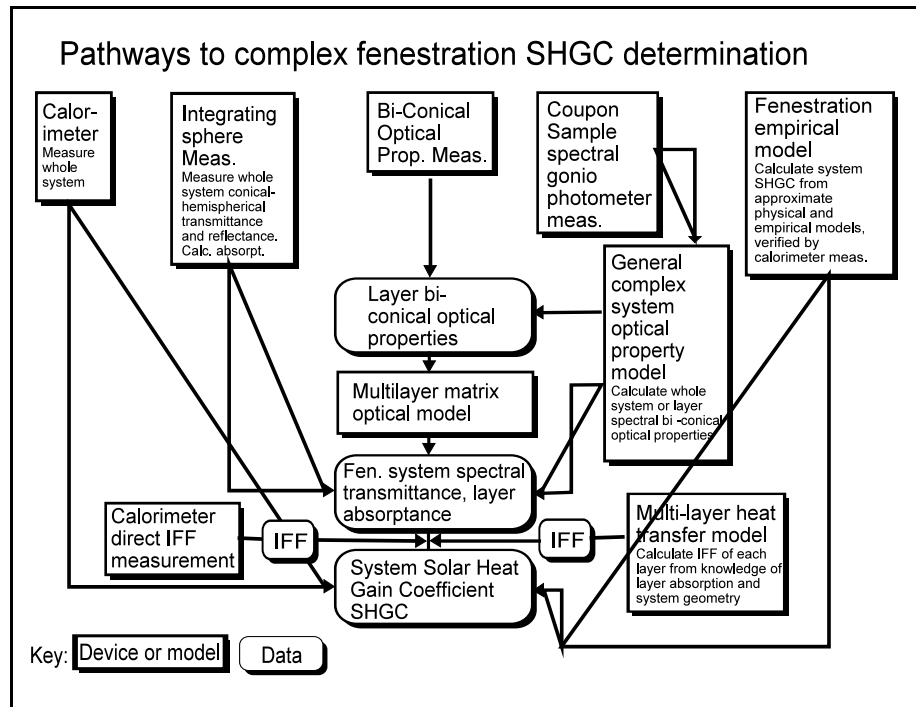


Figure 6. Various strategies for determining the SHGC of complex fenestration systems are shown schematically. "IFF" is the inward flowing fraction of absorbed radiation entering the space.

Advanced Daylighting Systems

Core daylighting systems are generally more complex, optically, than what I am calling advanced fenestration systems. They generally incorporate a solar tracking and concentration system, coupled with a light transport system of mirrors and/or light pipes, and one or more terminal solar luminaires, which serve the same purpose as light fixtures in electrical lighting systems, but in this case take light not from a self-contained lamp inside the fixture but the output from the light transport system and deliver it to the occupied space nearby. Not all core daylighting systems are either concentrating or tracking. Tubular skylights are a prominent example. *Nonimaging concentrators* form a relatively new class of optical elements, in which the degree of concentration is traded off with the angular acceptance or field of view of the concentrator. For low to modest concentration ratios, one can design a nonimaging concentrator with a reasonably large view of the sky, allowing direct beam sunlight to be collected without moving the concentrator for substantial periods of the daylight hours⁵. These optical components are also used (in reverse) in luminaires.

At their most complex, some daylighting systems can have sophisticated and potentially expensive aspherical collection and concentration mirrors, with one or more ingenious arrangements for directing the concentrated sunlight into the transport system. These can involve light pipes (with many multiple reflections inside them) or a complex array of mirrors inside light housings, for directing the light around corners and over significant distances to the luminaires inside the building. The goal of all luminaires is to deliver the maximum amount of flux from their source to the target area, according to a set of design goals for the spatial and angular distribution of the illumination in the illuminated space, and with a minimum of glare and occupant discomfort.

A number of papers has been published describing core daylighting systems and components. Some of these are cited here^{6,7,8,9,10,11,12,13,14,15,16,17,18}, covering the years from 1977 through 1996. In addition to these references, a number of relevant papers on both advanced fenestration systems and advanced daylighting systems can be found in the two-volume Proceedings of the 1986 International Daylighting Conference, held 4-7 November 1986 in Long Beach, CA¹⁹. Both volumes have separate sections of papers on Core Daylighting. Over the years there have been some very interesting developments in this field.

The phenomenon of *total internal reflection* has long been known to optical physicists. Modern fiber optics and other solid cylindrical light pipes rely on the capability of this phenomenon to reflect 100 percent of the radiation incident on the edges of the fiber, providing high throughputs, even if there are hundreds of thousands of reflections within the fiber. Absorption of energy from the rays passing through the solid material of the fiber, however, limits the distances over which significant quantities of solar illumination can be transported.

Lorne Whitehead, while a graduate student in physics at the University of British Columbia in Vancouver, invented and patented a unique new concept for the design of light pipes. His “prismatic” light pipes were meant to overcome the problem of absorption within solid pipes, by removing most of the solid material in the center of the light pipe, replacing it with a highly transmissive gas like air. The total internal reflection effect is retained in the Whitehead invention, but, in order to transfer the rays from the hollow air-filled pipe, the interior surface of his hollow

light guides is composed of triangular or sawtooth clear plastic or glass grooves running the length of the pipe, and behind this, a smooth cylindrical or rectangular interface between the plastic and the outside air, as illustrated in cross-section in Fig. 7.

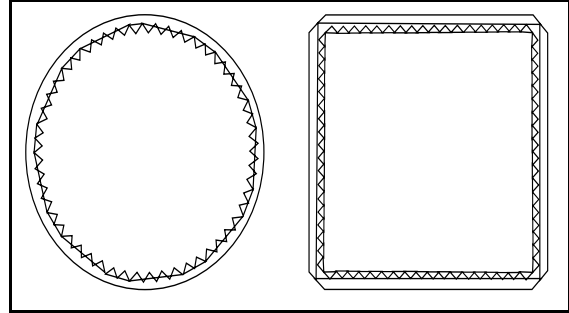


Figure 7. Cross-sections of two TIR light pipes.

It is at this outer interface that the total internal reflection takes place. There is reflection and refraction at the grooved surface of the light pipe, but the distance rays propagate within the solid plastic or glass material is much reduced, as are the absorption losses. As a result, these light pipes can carry substantial quantities of solar flux with only modest losses along the way.

The variety of possible strategies for introducing sunlight into the core spaces of multistory buildings is nearly unlimited. In the past their use has required a fairly comprehensive knowledge of optical physics, a discipline beyond the knowledge range of most architects. A goal of many companies is to design modularized daylighting system, systems for which the optical engineering has already been completed and the resulting systems can be introduced into new buildings with a minimum of complications and difficulties. Perhaps the best, and simplest example is the tubular skylight, depicted schematically in Fig. 8.

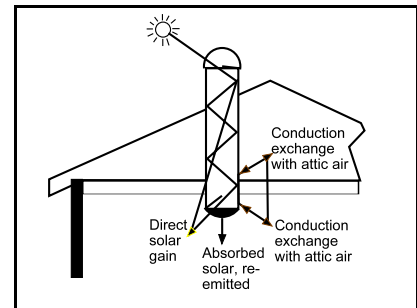


Figure 8. Energy flows in a tubular skylight.

Advanced Fenestration Energy and Illumination Performance

There is a problem common to both advanced fenestration systems containing non-specular components and nearly all advanced daylighting systems, as herein defined. It is that there are no existing, recognized procedures for predicting either the instantaneous or long-term energy and illumination performances of these systems. Available building energy simulation computer programs such as BLAST and DOE-2 have some ability to simulate these performances for buildings with conventional vertical windows whose solar optical properties are well-characterized. Currently the use of these programs is confined to windows containing clear or tinted glass with essentially no scattered radiation component.

With advanced systems, however, the optical processes are so complicated, or the systems contain such strongly non-specular components, that determining their overall system optical properties is not an easy or straightforward undertaking. Conceptually the problem is not a difficult one.

The directional distribution of luminous flux emerging from a fenestration or luminaire can be called the *intensity (or candlepower) distribution curve*. This is “a curve, often polar, that represents the variation of luminous intensity of a lamp or luminaire in a plane through the light center.”²⁰ This same terminology can be applied to fenestration and daylighting systems, with the exception that when it is the total solar radiation that is of interest, the map is of the solar *radiant* intensity. We

might also call this an *emerging flux map*.

Some lighting designers call it in informal speech the *photometrics* of a luminaire. The presumption is that whatever the photometrics of an electric luminaire, they are essentially constant. With solar lighting systems, however, the flux map becomes a continually varying entity, because the angular distribution of the flux incident on the entrance aperture varies continually, as the sun moves through the sky, cloud conditions change, and atmospheric scattering alters the quantity and directional distribution of the diffuse skylight component.

We can still characterize the performance of a fenestration system or a solar lighting system with a flux map, if we create a new flux map for each different direction of incidence on the entrance aperture, as indicated schematically in Fig. 9.

The characterization of fenestration or solar lighting system instantaneous performance in this way results in tables of data giving the directional distribution of flux emerging from the system for each of several (or many) directions of incident solar radiation. Illumination from the diffuse sky can be thought of as illumination from a large number of collimated beams from many directions over a full hemispherical solid angle of directions, so we can also determine the response of the solar lighting system to diffuse radiation.

The question thus arises as to how one might obtain these emerging flux maps. Will they be obtained by direct measurement or by calculation? The direct measurement approach is commonly used for electric lighting luminaires, where a device called a *goniophotometer* is used to perform the measurements. “Gonio-” means “angular” or “directional” and a photometer is used to measure radiant or luminous flux. A goniophotometer is a large device for positioning a lamp and luminaire, and rotating a mirror or a photometer on an arm around the luminaire, permitting flux measurements over a wide range of emerging directions. A *bi-directional* goniophotometer is needed to test a solar lighting system, one that not only positions the photometer over a wide range of directions but also repositions the source illuminating the test article over a wide range of *incident* directions, illustrated schematically in Fig. 10.

Any bi-directional goniophotometer for testing solar lighting systems needs to accommodate a wide variety of possible solar lighting system types, sizes, and geometries. To meet this requirement implies the design and construction of a large, complex, and expensive facility, something which only a national laboratory might be expected to afford, an unlikely event in times of severe budget

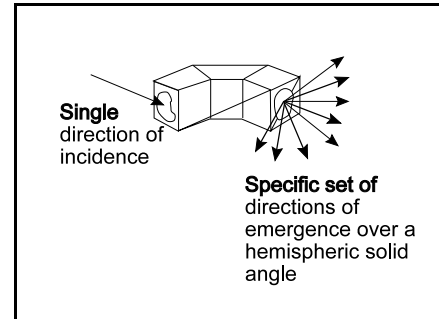


Figure 9. Generic diagram of an advanced fenestration system, or of a solar lighting system. The spatial distribution of intensity emerging from the exit aperture is herein called a “flux map.”

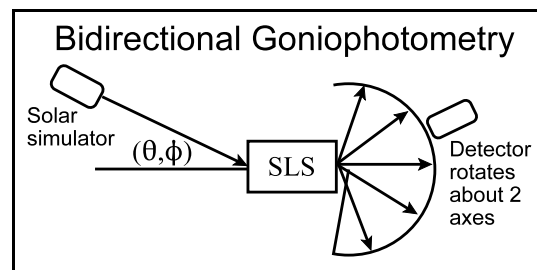


Figure 10. Schematic diagram of a bidirectional goniophotometer. Source illuminates solar lighting system (SLS) and detector measures emerging light over a hemispherical solid angle.

contractions. Even if the construction of the device were to be financed by the government, its use could entail rather large fees to the private businesses needing to use it to characterize their products, and this could put the federal government into competition with private testing laboratories.

A less expensive and more desirable alternative would be to *calculate* rather than measure the response of the fenestration or solar lighting system to flux incident from a variety of directions. Numerous optical ray tracing computer programs are available which can in principle perform the needed calculations.

Candidate software includes LightTools from Optical Research Associates, OSLO 6 from Sinclair Optics, TracePro and GUERAP V from Lambda Research Corporation, OptiCAD from Opticad Corporation (distributed by Focus Software, Inc.), ProMetric from Radiant Imaging, and ASAP from Breault Research Organization. One reason for the recent profusion of computerized ray-tracing programs is the rapid increase in speed, processing power, and disk space of personal computers. It is not uncommon to trace a million rays in a few minutes on a fast personal computer.

Figure 11 shows the results of an example ray trace of a hypothetical tubular skylight, performed by the author using ASAP. The parabolic mirror on the left, together with the emitting disk, make up a solar simulator, an optical system used to illuminate the top dome of the skylight with rays from an incandescent circular source having the same 0.5 deg angular diameter as the sun. Only a few rays are shown in this drawing, since the illustration would quickly turn black as more and more rays were traced through the system. An advantage of ASAP is that it can handle very complex geometries, can properly simulate rays from incoherent sources, and, most importantly, can accommodate nonspecular optical surfaces, surfaces which produce scattered light, containing significant diffuse components in their optical properties. It can even model holographic optical elements (HOEs).

Figure 12 shows the kind of flux map that can be generated by this program. It was generated by sending 7,000 rays into the system, resulting in over 67,000 emerging from the diffusing dome. The ray trace shown in Fig. 10 was then repeated for different directions of incidence, generating additional flux maps to characterize the system. If the system had contained significant spectral selectivity, these calculations would have been repeated for a number of different wavelengths, to generate a spectral version of the set of flux maps. ASAP can output flux map files in a standard IES

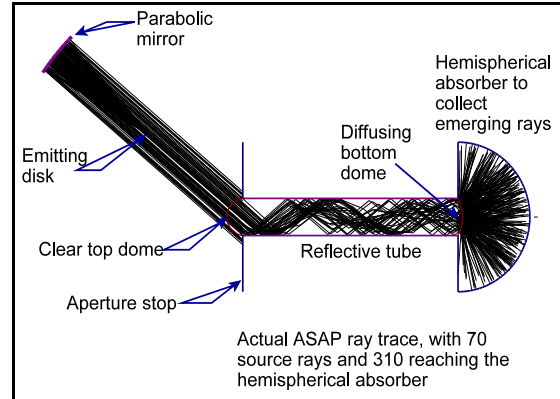


Figure 11. Ray trace of a tubular skylight, 40° angle of incidence.

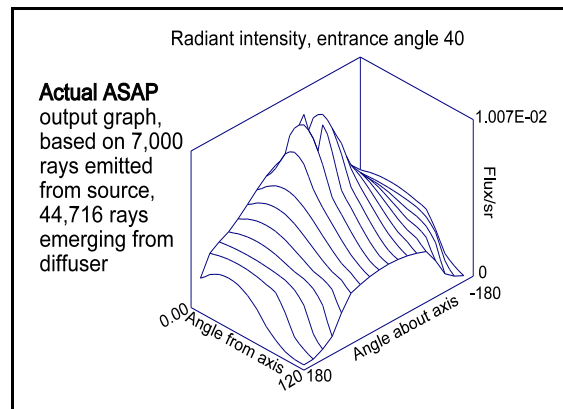


Figure 12. Tubular skylight ray trace sample output.

format.

This process generates a substantial quantity of data indicative of performance. Fortunately, however, with the costs of digital storage media declining, and the capacities of computers to handle large quantities of numbers increasing, this should pose no real obstacle to the standardization of this process for use by the fenestration and solar lighting industries.

Annual Energy and Illumination Performance Calculations

Whether the flux map characterization of advanced fenestration or solar lighting system instantaneous performance is done experimentally with a bidirectional goniophotometer, or numerically by ray tracing, the result can then be used to predict emerging flux maps for any combination of direct beam and diffuse sky light distribution incident on the entrance aperture. This provides a “picture” or “snapshot” of system performance at an instant of time, for one specific condition of incident radiation. This prediction can then be repeated for each daylight hour of a typical year, as sun position and sky conditions change. At the completion of the simulation, the statistical illumination and energy performances of the system over the year can be determined and summarized.

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