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Technologies Division**

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Introduction

The use of daylight to replace or supplement electric lighting in commercial buildings can result in significant energy and demand savings. High performance fenestration systems are a necessary, but not sufficient, element of any successful daylighting design that reduces lighting energy use. However, these savings may be reduced if the fenestration systems impose adverse thermal loads. New fenestration technologies have been developed over the last twenty years, aiming at controlling the intensity of the incoming solar radiation, its interior distribution and its spectral composition, as well as thermal losses and gains. Some of these have proven successful for specific or general building applications, while others are still under development and testing to understand limitations and potential benefits.

In this paper, we review the state of the art of several advanced fenestration systems which are designed to maximize the energy-saving potential of daylighting, while improving comfort and visual performance at an "affordable" cost. We first review the key performance issues that successful fenestration systems must address, and then review several classes of fenestration systems intended to meet those performance needs. The systems are reviewed in two categories: static and dynamic. Static systems include not only glazings, such as spectrally-selective and holographic glazings, but specialized designs of light-shelves and light-pipes, while dynamic systems cover automatically-operated Venetian blinds and electrochromic glazings.

We include a discussion of the research directions in this area, and how these efforts might lead to static and dynamic hardware and system solutions that fulfill the multiple roles that these systems must play in terms of energy efficiency, comfort, visual performance, health, and amenity in future buildings.

Performance Issues and Requirements

The general performance requirements of a fenestration system will vary with location and climate, orientation, building type, exterior obstructions and shading, and interior spatial design, as well as the needs determined by interior visual tasks and individual occupant desires. These often interrelate in complex ways and are strongly time dependent, given the variability of climate effects. The single greatest cause for failure in daylighting designs is a lack of systems perspective that accounts for, and provides an integrated solution to, these sets of performance issues. For most building types in most climates, portions of the work day occur before sunrise or after sunset. Thus daylight is viewed as a source that will be supplemented with electric light in most building applications to meet total lighting needs. To the extent that energy savings is a major goal of many daylighting designs, integration with electric lighting systems and impacts on HVAC systems become important issues as well. Within this broad range of requirements it is useful to outline several recurring themes. These include:

Desired illuminance and luminance levels. In most building applications today, the desired total illuminance will range from 200-1000 lux, with lower levels acceptable for ambient light if additional task illuminance is provided. There is growing interest in the ability to provide much higher light levels for short periods of time, particularly in northerly climates, for health related

reasons. By comparison, exterior illuminance levels range from 10,000 lux to 100,000 lux. Several of our daylighting design approaches evolved in Europe and emerged from a “codes and standards” perspective of meeting a minimum illuminance level under overcast skies, which were also a “typical” condition. In much of North America today, partly sunny and sunny skies are a dominant condition, and air-conditioned buildings are the norm, so the perspective on minimum and average sky conditions must be reconsidered. The admittance of daylight in spaces also has associated impacts on luminance values and ranges in the field of view and adjacent areas. The luminance of a sunlit window can be as high as 20,000 cd/m², enough to create discomfort glare and far above the level of typical interior luminances. As visual tasks become more computer-oriented, control of glare will continue to be a major challenge.

Total luminous flux. The total flux needed to provide the illuminance determined in step 1 can be estimated. The total admitted flux is the product of incident illumination, aperture area, glazing properties, and other light loss factors. In a simplistic, idealized analysis (approximated with a single-story, skylighted space) the total flux needed varies directly with the desired illuminance levels and the floor area. To provide this flux, the required lumped fenestration transmittance parameter, “effective aperture” (the product of area and transmittance), can be derived based on various space geometric and reflectance properties. Although average values can be readily determined, these can be misleading since the external illuminance at the aperture varies by a factor of ten between typical weather conditions, e.g., cloudy to clear.

Savings potentials. Extensive simulation and limited field measurements suggest that effective apertures of 0.02-0.03 for toplighted buildings and 0.2-0.3 for sidelighted perimeter zones are adequate to offset 50-70% of electric lighting needs. The toplighted space provides greater savings with smaller apertures for several reasons. Daylight availability at mid-latitudes provides more luminous flux on horizontal surfaces than vertical throughout much of the year. A diffusing skylight can utilize not only diffuse daylight but direct sun as well. Furthermore, in principle, the entire building floorplan can be daylighted for single-story spaces of virtually any height. The opportunities with side lighting are somewhat different. For a space with a single glazed wall, the interior illuminance decreases quickly with the depth of the space (although it is influenced by ceiling height and interior reflectance). Any attempt to increase the area of conventional glazings to admit more light deeper in the space will create very high light levels near the windows. A conventional vertical window requires some form of sun control to reduce the intensity of direct sunlight in the space. Typically this is accomplished by absorbing or reflecting the light, although it might be redirected deeper into the space. The depth of the daylighted zone will rarely exceed two times the height of the window. To substantially increase lighting energy savings requires very large increases in aperture which will quickly prove to have adverse thermal effects. Total daylighted area for conventional vertical glazed walls is thus dependent on the relative dimensions of the overall floor plan, favoring extended building envelopes that bring most interior space within 8-10 meters of the facade. An alternative to extend the depth of the daylighted zone involves using light transport systems that can efficiently transmit light over relatively long distances (> 15 meters). Such systems, while technically interesting, are outside the scope of this paper.

Thermal impacts. Modern multilayer glazings with low-E coatings and gas fills can reduce heat loss to very low levels. Conventional single and double glazings with $k = 4-6 \text{ W/m}^2\text{-}^\circ\text{K}$ have been superseded by new technology that can reduce thermal transfer to the range of $k = 1-2 \text{ W/m}^2\text{-}^\circ\text{K}$. The largest reductions in thermal loss are achieved with some sacrifice in light transmittance but not

so low that daylighting capability is compromised. These also provide interior glass surface temperatures that are close to interior air temperatures, thus improving thermal comfort in the vicinity of the window. In commercial buildings in most temperate climates, peak cooling load and seasonal cooling energy are the primary concerns associated with admitting daylight and sunlight. Exterior and interior shading, both fixed and operable, may be used to provide dynamic control in addition to specifying glazing properties. The postwar era saw the development of tinted, heat-absorbing glass and later highly reflective glass as a vehicle to reduce direct solar gain and glare. However, in order to reject 70-90% of total solar gain, most of the daylight was rejected as well. The most significant breakthrough in the last decade has been the development of improved forms of spectrally-selective glazings, that reject the near-infrared portion of sunlight while still maintaining relatively high daylight transmittance. These glazings are now available from most manufacturers at relatively low cost and are quickly becoming a standard default glazing for commercial buildings.

Daylight efficacy and cooling loads. The use of daylight is often assumed to reduce cooling loads compared to conventional electric lighting systems. The reality is somewhat more complex. If the same windows are assumed to be used in a daylighted and non-daylighted building, then the building with dimmable electric lighting will almost certainly have lower cooling loads: both have the same solar gain. However, the comparison is not so clear if we compare a building with small, low transmission windows and no lighting controls to one with larger, higher transmission windows with daylighting controls. The confusion stems in part from the basis of the comparison. The assumption is that the system with the highest luminous efficacy will have the lowest associated cooling loads. Frequently the comparison one sees is a source efficacy comparison in lumens/Watt. Daylight efficacies range from 80 l/W (low sun) to 150 l/W for blue sky. The efficacy of fluorescent lights ranges from 60-90 l/W depending upon the lamp/ballast combination. Thus, it is claimed, daylight is more efficacious and will produce a lower cooling load. However, source efficacy comparisons can be highly misleading. The net system efficacy of electric lighting can be estimated by dividing the maintained illuminance levels by the lighting power density. A very good electric lighting system might therefore have an efficacy as high as 50 l/W (500 lux /10 W/m²) but more typically 20-30 l/W. The net system efficacy of a daylighting system will vary with the fenestration system, room geometry, and room optical parameters, and furthermore with the intensity and distribution of skylight and sunlight. Net system efficacy can range above or below typical electric lighting system values depending upon the specifics of daylighting system. Skylighted systems typically have much higher efficacies than sidelighted systems because the light distribution is more uniform.

Lighting controls. Many a good daylighting design has failed to achieve the expected energy savings performance because of failures in the lighting control systems. These include product design (sensors and electronics), architectural design (placement), installation, calibration, and operational problems. Not only must the system maintain the desired illuminance levels under a wide variety of daylight conditions, but the overall lighting design must create a visually appealing space as the illuminance levels from electric lighting are dimmed in response to daylight. As fenestration systems become more dynamic, e.g., use of electrochromic glazings, electric lighting controls must accommodate this added performance complexity. Increasingly, daylighting controls will be linked to whole building energy management systems as owners attempt to refine their control over energy management of the entire building.

Review of Advanced Fenestration Systems

Based on the analysis presented above, we believe that daylighting systems continue to have the potential, still largely unrealized, to provide substantial energy savings in conjunction with productive and appealing indoor work environments. Several themes emerge from this analysis in terms of required performance attributes for fenestration systems.

- Control spectrum of transmitted luminous flux to reduce cooling loads.
- Dynamic control of intensity and direction of transmitted luminous flux to reduce cooling loads, control glare, and improve light distribution.
- Design fenestration systems as part of an integrated building systems approach.
- Provide systems that support changing occupant needs and enhance satisfaction and performance, in addition to energy savings.
- Provide decision support tools that assist architects, engineers, and owners in evaluating options.

Over the last decade we have explored the development and use of several new daylighting strategies that are designed to address these performance needs. We summarize here the results of several specific efforts and comment on evolving needs in this area. Spectral control of luminous flux is largely a “solved” problem as noted below. We focus our discussion on new approaches for providing dynamic control of intensity and distribution within the context of an integrated system that meets occupant and owners needs in a building.

Spectrally selective glazings. Spectrally selective glazings preferentially transmit the visible portions of the solar spectrum. Approximately 50% of the energy in sunlight lies in the UV and near-infrared wavelengths and can thus be rejected without reducing visible transmittance or altering the perceived color of daylight. Even greater reductions can be achieved by reducing transmittance further at one or both ends of the photopic curve, although this will impart some color to the transmitted light. The fundamental technology to achieve this control utilizes either multilayer coatings to reflect near-infrared energy or selective absorbers to absorb near-infrared. The selective reflectors typically also have low-E surfaces (unless laminated between glass) providing some additional energy control. Overall visible transmittance can be varied with glass thickness and/or the addition of other coatings and glazing layers. Since these glazings are available commercially from several manufacturers and the costs are relatively low, they should normally be an element in any daylighting system for which cooling load control is an issue. (One application for which they would not be well suited is an aperture design that is intended to serve a solar heating function in winter; in this case a high solar transmittance glazing would be more appropriate.) We assume the use of these glazings as a standard component in most of our further explorations. Further information on the performance and availability of such products has been published [Windows and Daylighting Group 1994, Klems 1995, Lee 1998].

Dynamic control of intensity. The holy grail of the fenestration industry is a glazing that will dynamically and reversibly modulate transmittance properties (total solar and/or visible). After 15 years of serious R&D effort, there are several promising technologies moving from R&D labs toward the marketplace, each with pros and cons with respect to daylighting applications. These are discussed in more length elsewhere [Lampert 1995]. Of the emerging “smart glass” technologies, electrochromics appear to be the most promising in terms of meeting broad

daylighting needs. Other technologies, (e.g., photochromic and thermochromic) may be very well suited for specific niche building applications. Electrochromic coatings are multilayer thin films that are controlled via a low voltage signal, and switch reversibly and continuously from a clear, high transmission state to a dark, low transmission state. Visible transmittance dynamic ranges of 5% to 60% are achievable, with associated changes in solar heat gain coefficient of 10% to 45%. Such coatings may be designed to switch to even lower transmittance levels which may be desirable to improve privacy, but this is obtained with some sacrifice in other performance properties. Electrochromics have two related functions in a daylighting design strategy-switching over the entire solar spectrum to control total solar gain, and switching in the visible portion of the spectrum to control light levels and glare. The spectral switching properties of a specific coating depend upon the materials used, the overall coating design, and the complete glazing system, which may contain other glazing layers with coatings or absorptive properties [Reilly et al. 1989].

An important feature of such a coating as part of a daylighting strategy is the ability to link it to an automated lighting control system to provide desired interior illuminance over a wide range of exterior lighting conditions. A ceiling-mounted, daylight photosensor controls the interior electric lighting while additional sensors can be added to control the switching state of the electrochromic device. The control logic for such a switching system may include a complex set of parameters: glare control, maintaining desired illuminance, solar gain control, and view control, several of which may be contradictory. The switching time of the coatings to darken (typically 30-120 seconds) is more than adequate for thermal control but might create some short-lived visual discomfort if the coating alone must protect occupants from direct sun. But the primary advantage of the devices is the ability to integrate them with an automated control system to provide continuous control of the luminous environment. As noted below, it will be important to provide occupants with override capabilities and the ability to reset control levels, but much of the hour-to-hour adjustment is best left to a properly designed and calibrated automated system.

Coating developers can create electrochromic coatings with a wide range of performance capabilities. Using computer simulations of typical office buildings, we have simulated the effects of different coating properties as a function of window system size and design, orientation and climate [Sullivan et al. 1996]. As expected, there is a wide range of performance results, but the results are understandable in terms of the impact of the coating properties on both visible transmittance as well as solar heat gain. Depending upon the specific coating used, the overall window performance may be enhanced if additional static coatings are incorporated into the window units [Selkowitz et al. 1994]. We have also simulated the effects of these coatings on the visual appearance of the space using RADIANCE, a photorealistic ray-tracing tool that provides accurate simulations of interior light levels and appearances [Moeck et al. 1996, Ehrlich 1997]. These images have been assembled into a short movie to give a sense of the dynamic aspects of the switchable glazing in response to changing exterior light levels.

Glazing manufacturers are working hard to develop the fundamental coating technology that will survive moisture, UV, and elevated temperatures for 50,000 cycles or more over many years. We expect to see meter square prototypes in the next few years. Equally important are the control and systems integration issues for such devices. Since the electrochromic coatings are not yet available in large sizes for demonstration projects, we have conducted a series of tests with motorized venetian blinds as a surrogate for the coatings. The overall transmittance of the blinds varies from approximately 85% to 5% depending on slat angle, slat color, and incident solar angles. The

blinds present a more difficult control problem because of the added complexity of the interreflectance of the slats. Dynamic blind systems have been evaluated in two side-by-side test rooms in a large office building in Oakland, California (Figure 1). The "rooms within a room" are set up as typical offices and are also instrumented to measure cooling and lighting loads. The integrated control system worked very well, with the blind controls set to prevent direct sun penetration, permit view out when available, and actively manage incident daylight to provide 500 lux on the workplane whenever possible, topping off with electric light when needed. Sample performance over two typical days is shown in Figures 2 and 3. Energy and illuminance data have been collected for over a year and initial occupant response studies have been completed. Lighting energy savings range from 35% in winter to 40-50% in summer, when compared to a similar static blind system. If compared to a non-daylighted space, lighting energy savings ranged from 22%-86%. Summer daily cooling load reductions measured 5-25%; peak cooling load reductions were even larger. We are now testing a different type of blind that raise and lower as well as tilting slats. This provides higher interior illuminances under overcast conditions and better view.

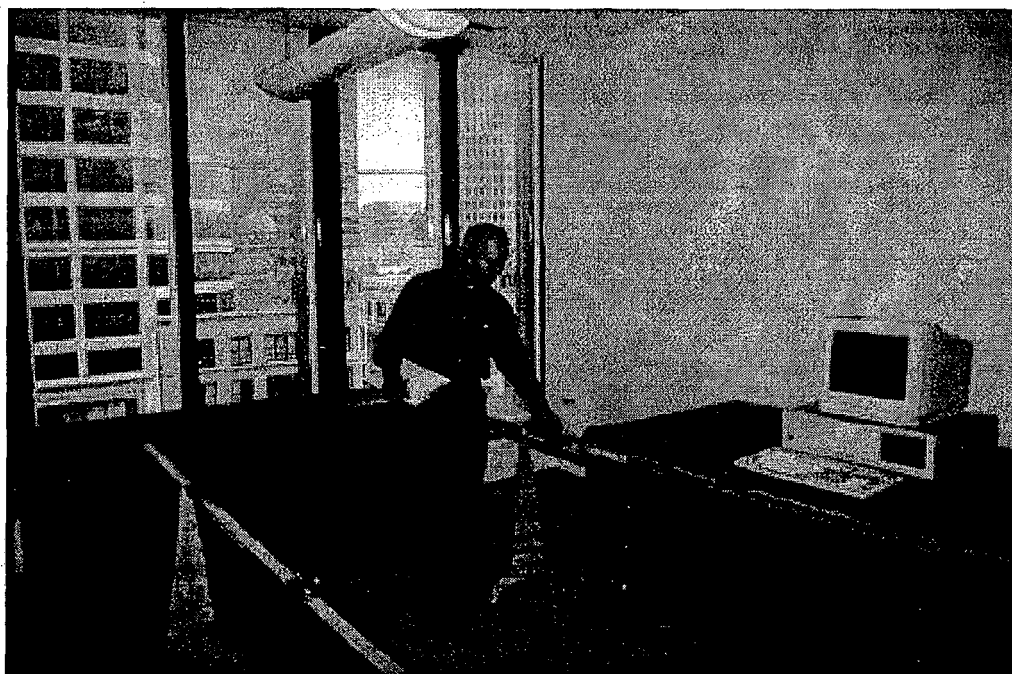


Figure 1. Interior view of the full-scale testbed office in Oakland, California.

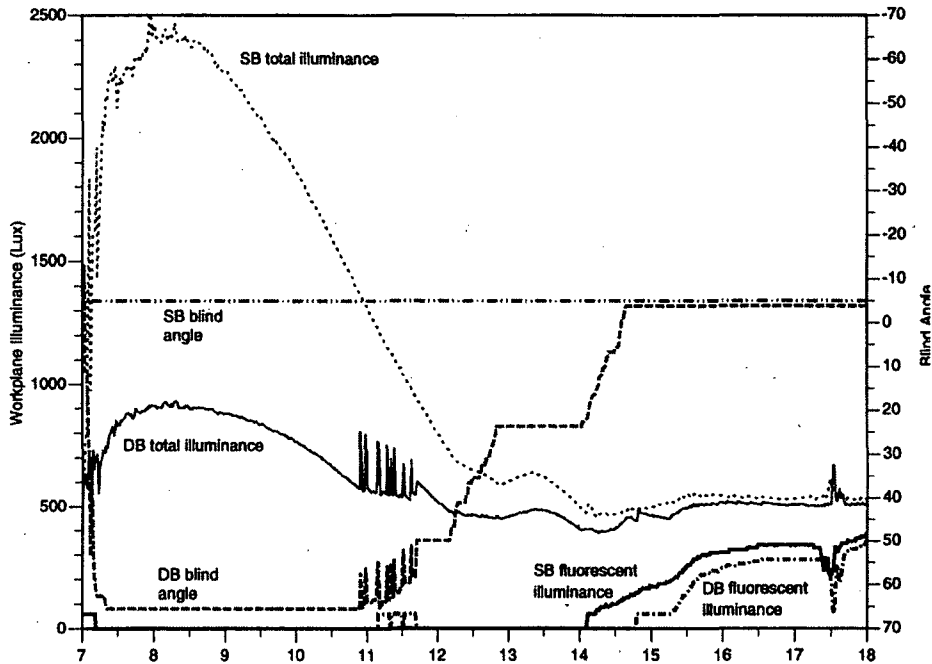


Figure 2. Dynamic blind vs. static horizontal blind: Monitored total workplane illuminance, fluorescent lighting illuminance, and blind angle for the static horizontal blind (SB) and the dynamic venetian blind (DB), both with daylighting controls. Daily cooling load savings were 21%. Peak demand savings were 13%. Daily lighting energy savings were 21%. Data are shown for southeast facing offices in Oakland, CA on a clear day, August 15, 1996.

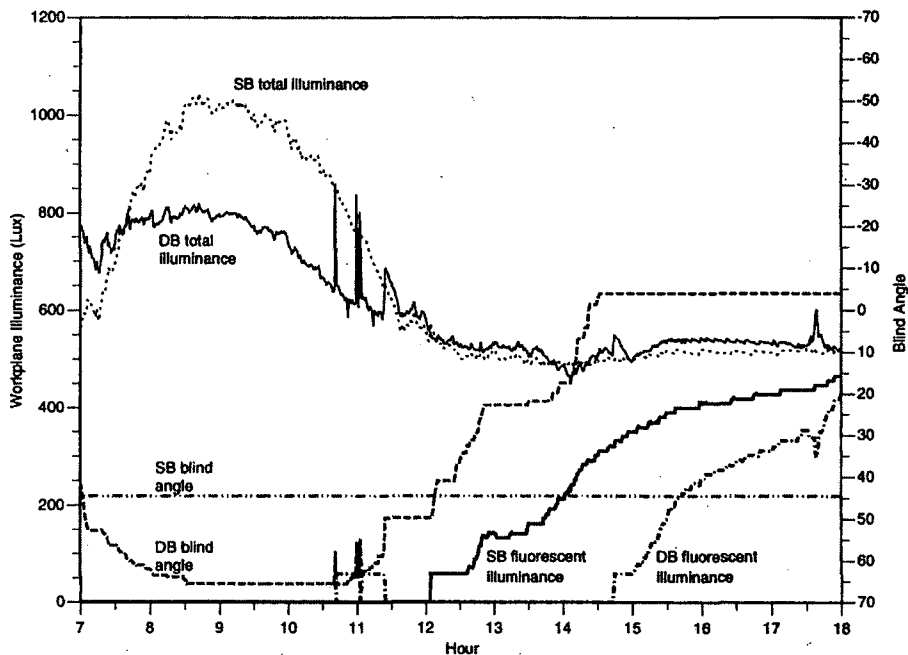


Figure 3. Dynamic blind vs. static 45° blind: Monitored total workplace illuminance, fluorescent lighting illuminance, and blind angle for the static 45° blind (SB) and the dynamic venetian blind (DB), both with daylighting controls. Daily cooling load reductions were 4%. Peak demand savings were 8%. Daily lighting energy savings were 46%. Data are shown for southeast facing offices in Oakland, CA on a clear day, August 18, 1996.

We conclude from these room scale tests and computer simulations that this class of dynamic device can provide large lighting savings and associated cooling energy savings as well. In addition, they will actively modulate glare and contrast ratios between a bright window perimeter and the interior of the room. One might argue that similar benefits can be achieved by a well-managed interior blind adjusted by occupants. However, field experience suggests that this potential is only rarely achieved in practice, as most office occupants have priorities other than continual adjustment of fenestration controls. Limited occupant testing suggests that it is important to provide control overrides and setpoint control for the occupants, even if they rarely use it. The need for an automated control system is also apparent if one attempts to reduce cooling system size with use of an automated fenestration system. Simulation studies suggest that it should be possible to downsize a cooling system in a building with automated control of smart windows. (Few professional engineers are likely to consider this if control is provided at the whim of the occupants.) We believe that with convincing demonstration projects and mature control and glazing technology, it should be possible to make such changes in future standard design practice. A critical issue is to design control systems (both hardware and operating logic) that seamlessly integrate the lighting and fenestration elements. This has been successfully accomplished in our demonstration project, although such systems are not yet commercially available [Lee et al. 1997].

Control of light distribution. A fenestration system is a daylighting luminaire and, like an electric luminaire, it must redirect flux from the source to create the desired interior luminous environment. This has both a quantitative element (the provision of adequate illuminance to meet the needs of typical visual tasks) and an equally important qualitative element (providing a pleasant and comfortable luminous environment, as perceived by the occupant). This is often a challenge in an electrically lighted space where the elements are static, but it becomes even more critical and challenging in a daylighted space with constantly changing daylighting conditions. The daylight source varies in two important ways (in addition to the variable intensity addressed in the previous section). Under diffuse conditions (sky, clouds, or external obstructions) the primary source extends across a large solid angle and has a variable luminance distribution. Under direct sun conditions, the collimated beam intercepts some or all of the aperture at a highly variable incident angle. With vertical glazed windows, diffuse light from the sky or clouds falls off rapidly as one moves away from the window, reaching a level of less than 1% of exterior horizontal illuminance at 3-5 meters from the window, assuming modest glazed areas. Illuminance in the area adjacent to the window may exceed 20% of exterior values, or twenty times higher than values at 5 m from the window. When direct sunlight penetrates the space, the gradients of interior illuminance across the space can be even higher. If one examines wall and ceiling luminance values, the differences can also be large, e.g., the luminance of a wall adjacent to the window versus the ceiling in the back of the room. These patterns are fundamental to the geometry of the spaces and the optical properties of typical glazing and room surface materials. They make it difficult to achieve adequate interior illuminance beyond a 3-4 meter depth (with typical ceiling heights) and create large luminance gradients that may be viewed as undesirable by many occupants. Furthermore, while the strongly directional and horizontal nature of the daylight in a sidelighted space may add interest to the modeling of three-dimensional objects, it may also create objectionable effects in terms of balance and contrast. If one desires to daylight a deeper perimeter zone (5-10 meters from the window), all of these problems are exacerbated. Finally, one must not lose sight of the fact that windows provide view and connection with the outdoors. Strategies that unnecessarily reduce desirable views in order to control daylight admittance should be avoided.

Glazing and fenestration systems that successfully address these problems can provide substantial benefits in a daylighted design. Most systems today that provide directional control over incident light do so by simple rejection and/or diffusion of incident light (various screens, louvers, fins, overhangs, etc.). They are primarily designed to control direct sunlight but not improve the issues of balance and contrast noted above, nor do they allow the daylighted zone to be extended. New technologies are needed that could increase the fraction of total floor area that can be daylighted, and improve the quality of the lighting design in both shallow and deeper perimeter systems. Few such systems exist today, making this a ripe area for further exploration. Fenestration systems might be designed for improved performance following several different pathways. The first is to provide view without excessive direct sunlight. Since the sun often penetrates the window at high angles of incidence whereas view is typically at low angles, an angle-selective glazing would provide benefits. Such an angle-selective glazing or coating might utilize the intrinsic microstructure of the glazing or coating to achieve such cutoffs or reductions on solar gain at specific angles. A better approach is to redirect the incident light to the ceiling where it can be diffusely redirected throughout the space. Silvered blinds, prismatic glazings, laser cut panels, and prototype holographic coatings have been developed for such purposes, but none meets the full range of desired performance requirements [Papamichael et al. 1994].

An extension of this approach is to construct a daylight collection system that collects and redirects light toward the ceiling in the back of the room. Anidolic collector designs have been developed for predominantly overcast skies. We have designed, built, and tested scale models of several variants of light shelves and light pipes that are intended to provide these functions in climates characterized by sunny and partly sunny conditions [Beltran et al. 1995]. The designs use both novel geometry and highly efficient reflective and refractive materials to achieve the desired light control without adjustments or moving parts. Average interior illuminance levels of 200 - 600 lux can be achieved at 8 meter depths in typical perimeter spaces for about six hours per day throughout much of the year with the light pipe systems, and similar performance levels with the light shelves. The light shelves control and redirect the light within the occupant's room volume and are susceptible to occasional glare conditions. The light pipes are placed in the ceiling plenum and are generally less obtrusive. Numerous variants are possible for both designs, and each must be optimized for climate and orientation, as well as for cost effectiveness. We believe these show promise for further development.

Conclusions

Fenestration systems are essential elements of all daylighting designs and are called upon to provide a wide range of performance attributes. In order for such systems to be successfully developed and utilized, it is advantageous to carefully and critically assess the desired performance attributes of "ideal" fenestration systems. In general, daylighting systems have not fulfilled their promise as a key energy efficiency strategy that also enhances occupant comfort and performance. Part of the problem can be traced to the lack of adequate, high performance fenestration systems. Low-cost spectrally-selective glazings can deliver daylight flux to a space with only half the associated cooling load of conventional glazings. But the wide range of performance needed from the "ideal" fenestration system is not readily available to specifiers today. Emerging technology for dynamic, smart glazings has the potential to provide an important new set of functionality that promises to address several critical shortcomings of existing technology. The topic of fenestration

systems that provide selective angular control as well as redirection and local transport of daylight is largely unexplored, but appears to offer future promise.

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