

To be presented at the ACEEE 1994 Summer Study on Energy Efficiency in Buildings, Building Tomorrow: The Path to Energy Efficiency, August 28—September 3, 1994, Asilomar Conference Center, Pacific Grove, CA, and to be published in the Proceedings.

A Comprehensive Approach to Integrated Envelope and Lighting Systems for New Commercial Buildings

Eleanor S. Lee, Stephen E. Selkowitz, Francis M. Rubinstein,
Joseph H. Klems, Liliana O. Beltrán, Dennis L. DiBartolomeo

Building Technologies Program
Energy and Environment Division
Lawrence Berkeley Laboratory
University of California
Berkeley, CA 94720

May 1994

This research was funded by the California Institute for Energy Efficiency (CIEE), a research unit of the University of California. Additional related support was provided by the Assistant Secretary for Energy Efficiency and Renewable Energy, Office of Building Technologies, Building Systems and Materials Division of the U.S. Department of Energy under Contract No. DE-AC03-76SF00098.

A Comprehensive Approach to Integrated Envelope and Lighting Systems for New Commercial Buildings

Eleanor S. Lee, Stephen E. Selkowitz, Francis M. Rubinstein,
Joseph H. Klems, Liliana O. Beltrán, Dennis L. DiBartolomeo
Building Technologies Program
Energy and Environment Division
Lawrence Berkeley Laboratory
Berkeley, CA

ABSTRACT

We define a comprehensive approach to integrated envelope and lighting systems design as one that balances energy efficiency with an equal regard to the resultant environmental quality. By integrating envelope components (glazing, shading, and daylighting), lighting components (fixtures and controls) and building HVAC/ energy management control systems, we create building systems that have the potential to achieve significant decreases in electricity consumption and peak demand while satisfying occupant physiological and psychological concerns.

This paper presents results on the development, implementation, and demonstration of two specific integrated envelope and lighting systems: (1) A system emphasizing dynamic envelope components and responsive electric lighting systems, that offer the potential to achieve energy efficiency goals and a near optimum comfort environment throughout the year by adapting to meteorological conditions and occupant preferences in real time, and (2) perimeter daylighting systems that increase the depth of daylight penetration from sidelight windows and improves visual comfort with the use of a small inlet aperture. The energy performance of the systems was estimated using the DOE-2 building energy simulation program. Field tests with reduced scale models were conducted to determine daylighting and thermal performance in real time under actual weather conditions. Demonstrations of these integrated systems are being planned or are in progress in collaboration with utility programs to resolve real-world implementation issues under complex site, building, and cost constraints. Results indicate that integrated systems offer solutions that not only achieve significant peak demand reductions but also realize consistent energy savings with added occupant comfort and satisfaction.

INTRODUCTION

In a survey of existing large office buildings in California using utility bill data, on-site surveys, and end-use metered data, 43-49% of the total annual electricity consumption was

estimated to be due to electric lighting, while 15-19% was due to mechanical cooling (Akbari et al. 1989). Commercial office building floor area is projected to represent 26% of the total California commercial floor area stock by the year 2005 (CEC 1991), with a total projected electric demand of 6.0 GW. We believe it is possible to reduce this projected demand by 20% to 4.8 GW if all new and 10-30% of existing commercial office buildings are retrofit with advanced building envelope and electric lighting technologies by the year 2005 (Sullivan et al. 1992). Achieving these market impacts will require not only these potential technological advances to save energy but new high performance building systems that improve the overall quality of the resultant indoor environment.

In the narrowest sense, the goal of incorporating window and lighting systems in commercial buildings is to provide occupants with an adequate level of daylight or electric lighting to perform visual tasks in a productive manner. Occupant surveys reveal some of the shortcomings of conventional design practice and broaden the definition of an acceptable office environment. In a study of office workers in the Pacific Northwest region (generally an overcast and cool climate), slightly over 40% of the occupants said they experienced the sun as too bright at least sometimes, and 60% of the occupants said that the window was a primary source of glare and interfered with their work. In addition, 55-60% of occupants along the east, west, and south walls said it was too warm at least sometimes despite the provision of space conditioning (Energy Edge 1991). Yet while visual and thermal discomfort frequently occur at perimeter office zones, over 50% of the occupants in several high-rise office buildings in Tokyo preferred to have seats nearer the window, citing advantages of brightness, outside view, wide visual range, and open feeling – with only 6-8% preferring seats further away (Inoue et al. 1988).

By taking a systems approach to combining disparate envelope and lighting components, higher energy savings can be attained with improved occupant comfort over conventional design practice. This integrated systems concept is based on

two approaches: (1) The large variation in solar radiation due to diurnal and seasonal changes of sun position, daylight availability, and cloud cover conditions is a major cause of both high energy use and occupant discomfort. However, there is an optimum cooling and lighting energy balance between the envelope and lighting system that can be used to advantage to reduce this large variation. Dynamic systems that meet this balance on an active basis can substantially reduce energy usage and peak demand, while increasing occupant comfort. (2) Direct sun and the poor distribution of daylight resulting from sidelight windows are a major source of glare discomfort and eye fatigue. When occupants adjacent to the window control interior shades to increase visual comfort, potential electric lighting savings from daylighting controls is reduced throughout the entire perimeter space. By redirecting the daylight to the ceiling plane, surrounding wall surfaces, and core areas, as opposed to the floor area immediately adjacent to the window, the lighting quantity and quality in the space can be improved while increasing lighting energy savings. This is now particularly relevant since most work environments make extensive use of partitioned workstations without direct access to windows, view, and daylight.

We present current findings from two related parallel efforts to develop integrated envelope and lighting systems: (1) dynamic envelope/ lighting systems that actively modify both daylighting and thermal characteristics of the building envelope to balance lighting and cooling energy use; and (2) daylighting envelope/ lighting systems that extend the depth of daylighting penetration and increase the uniformity of its distribution throughout a 9.14 m (30 ft) deep perimeter space. We briefly describe the methods used to develop these designs from concept to full realization in buildings. We present estimates of electricity consumption and peak demand savings resulting from these systems compared to conventional systems. In our evaluation, we focus on how well the designs achieve both energy-efficiency and environmental quality. Finally, we discuss practical considerations and our plans for future development of this concept.

DYNAMIC ENVELOPE AND LIGHTING SYSTEMS: ACTIVE CONTROL OF INCIDENT DAYLIGHT AND SOLAR HEAT GAIN

Dynamic systems offer the potential to achieve a near optimum physiological and psychological environment throughout the year by responding to meteorological conditions and occupant preferences in real time. Dynamic envelope components, such as automated venetian blinds or electrochromic glazings, are operated in synchronization with the electric lighting and daylighting controls system via an intelligent control system. The solar-optical properties of the envelope system, or related thermal and daylighting properties, are first used by the control system to predetermine the position of the envelope system that best fits the design criteria, then the electric lighting is dimmed in response to the resultant

available daylight. By working as a system, tradeoffs can be made between decreases in electric lighting energy use and cooling due to electric lighting heat gains versus increases in cooling due to solar radiation through the building envelope. In addition, the control system can be designed to accommodate occupant preferences for view, glare control, and task lighting levels.

In California climates and for cooling-dominated commercial buildings, daylight variability is the predominant meteorological variable requiring control at the window. In the Los Angeles climate, for example, the clear sky horizontal exterior illuminance levels from sun and sky vary from 10,000 to 90,000 lux (1,000 to 9,000 fc) from morning to noon hours at the equinox, and 110,000 to 15,000 lux (11,000 to 1,500 fc) from summer to winter at noon, with only moderate changes in outdoor average air temperature from 20° to 12°C (68° to 54°F) throughout the year. The dynamic range of the solar-optical properties of the building envelope system is therefore critical to achieving control over both the variability of daylight levels within the space and the heat gains introduced by solar radiation that contribute to occupant discomfort.

The automated venetian blind, for example, is one such envelope system that meets both energy and occupant criteria. The system has the ability to control daylight levels and, to some degree, its distribution within a large range through the choice of surface reflectance and the tilt angle of the individual louvers. By achieving a more uniform daylight level throughout the day, eye fatigue and discomfort glare caused by excessive luminance contrasts or the brightness of the window plane can be decreased. View and privacy can also be controlled by the degree of louver openness or by full retraction of the blind during periods of low daylight availability and night-time occupancy. The blind is also capable of variable thermal control to reflect and block direct solar radiation, which causes thermal discomfort through radiant asymmetry. If the blind is placed between two panes of glazing, the absorbed and inward flowing fraction of solar radiation heat gains can also be minimized. Airflow windows, where return air is circulated between the panes of glass, can be used to further reduce the thermal load, as can exterior blind systems.

Other envelope systems can be used to provide similar control. Of particular note, the electrochromic glazing provides an elegant and unobtrusive solution. Laboratory prototypes already possess excellent solar-optical properties which will hopefully be commercially available within the next three to five years. The electrochromic glazing is a multi-layer coating that can be applied as a thin film to a glass or plastic substrate. It uses an electrochromic layer and counter-electrode separated by an ion-conducting electrolyte. A small applied voltage moves ions from one layer to the other, inducing a reversible color change. This chemical reaction changes the appearance, and solar-optical properties, of the glazing from a clear to darkly colored state – typically blue or

bronze (Lampert and Ma 1992). This envelope system has the distinct practical advantage over many systems commercially available today, in that it has no moving parts, although the long term durability of an electrically active coating remains a research challenge.

The control system design is critical to the proper satisfaction of energy and comfort criteria. The central focus of the research conducted in this project was to investigate operational control algorithms and to evaluate the resultant energy performance against conventional static systems. Anticipatory or predictive control algorithms can be used to determine the optimal energy balance between envelope and lighting components prior to actuation of the system. However, this is very difficult to accomplish in both building energy simulation programs and in real-world implementation due to the complex relationship between instantaneous heat loads, characterization of the cooling and air distribution system, and the thermal lag introduced by the building mass. Most research has concentrated on control strategies designed to minimize instantaneous and measurable loads such as workplane illuminance (Warner et al. 1992), room air temperature (Rheault and Bilgen 1987), or transmitted direct solar radiation (Inoue et al. 1988). We have made a preliminary investigation into the incremental energy benefit of using predictive control algorithms (Lee and Selkowitz 1994A).

Likewise, development of control strategies based on physiological and psychological criteria such as discomfort glare, view, and privacy defy simple solutions. Visual and thermal comfort indices combine a number of occupant-based parameters, such as occupant view position, task being performed, activity and clothing level, that would be very difficult to measure with conventional sensors and to hard-code into a control algorithm. In our study, an accommodation of occupant comfort is thus an indirect product of meeting energy performance criteria. Similar to the provision of a thermostat, we propose a system that ensures energy savings through active control, yet offers the occupant the option to override the system should unexpected conditions occur.

In the growing demand for intelligent building systems (Geissler 1989), we see the potential to tie envelope and lighting components in on a whole building scale; e.g., integrating with mechanical system operation and utility real-time pricing schedules, or working with centralized energy management control systems for environmental, security, and life safety control.

INTEGRATED DAYLIGHTING AND LIGHTING SYSTEMS: EXTENDING DAYLIGHTING TO DEEP PERIMETER ZONES WITH LIGHT SHELVES AND LIGHT PIPES

Daylighting technologies can extend the area daylit by conventional sidelight windows by redirecting sunlight further from the window wall. This serves to reduce electric lighting

energy within a larger floor area and to reduce cooling due to lighting, without increasing solar heat gains, if properly designed. What constitutes an acceptable perimeter lighting environment? Standards for electric lighting set minimum task lighting levels, define the acceptable contrast gradient between the task surface, surrounding surfaces, and the background, and give guidelines to limit sources of glare from windows and electric lighting. Temporal changes in daylight levels are desirable from the perspective of psychological relief and maintaining some tangible contact with the outdoors. Under certain conditions, direct sun is viewed favorably, provided there is no glare. In the Pacific Northwest, 86% of the occupants liked direct sun in their workplace somewhat or very much – possibly due to the predominant overcast conditions (Energy Edge 1991).

The challenge of successful daylighting design is caused by the large variation in meteorological conditions, i.e., solar position and daylight availability. Optimally, the design for office task lighting, including computer usage, would (1) redirect daylight to a fixed location as the sun moves in its diurnal and seasonal cycle, (2) distribute the daylight flux uniformly throughout the ceiling and wall surfaces of the room, (3) maintain a relatively narrow range of interior daylight levels as the exterior daylight levels fluctuate with season, and (4) prevent the penetration of direct sunlight and direct source glare on or around the visual task location. With actively tracking heliostats coupled to an efficient distribution and light level control system, these design objectives can be fulfilled subject only to daylight availability. One such system uses rooftop active-tracking Fresnel lenses to collect sunlight and fiberoptic cables to transport the daylight to any location within the building. While these systems can provide daylighting to core areas of buildings, the few that have been built to date are very expensive and may require special skills to maintain. Another approach is to use static systems, such as prismatic glazings, reflective louvers, and light shelves, to passively redirect daylight from the window wall. Flat glazing technologies under development include holographic diffractive structures and laser cut light deflecting panels.

The system we propose consists of a south, east, or west-facing perimeter window wall divided into an upper daylighting aperture and a lower view aperture. The lower view aperture incorporates spectrally selective glazing with an operable shading device, perhaps the automated venetian blind system proposed above, to control glare, direct sun, heat gains, and view for those occupants adjacent to the window. The upper daylighting aperture incorporates the daylighting technology – a light shelf or light pipe – to efficiently redirect or transport direct beam sunlight to depths of 9.15 m (30 ft) from the window wall, with supplemental daylight contributed from a lower view window for the first 4.57 m (15 ft) from the window (Figure 1). The light shelf was constrained to fit within a 0.61-1.52 m (2-5 ft) deep articulated facade. The light pipe was designed to be used within a 0.61-0.92 m (2-3 ft) high ceiling plenum, with its input aperture placed

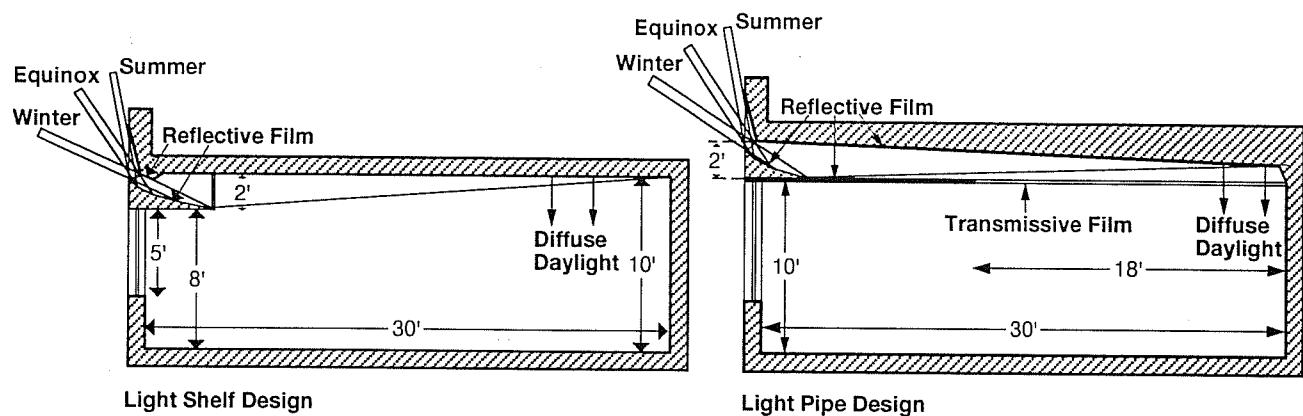


Figure 1. Ray Tracing Schematic of Sun Angles at Noon for Light Shelf and Light Pipe Designs

flush with the building spandrel and its overall dimensions constrained to accommodate other building subsystems within the plenum. In both cases, the ceiling height is 3.05 m (10 ft).

Each component of the design was carefully considered to meet our performance needs (Beltrán et al. 1994). The input aperture for both prototypes evolved into reflectors that block direct sun to prevent direct source glare and redirect sun according to the altitude angle of the sun throughout the year. The input aperture area was constrained to reduce solar heat gains. For the light shelf, highly reflective daylight films with selective angles of outgoing reflection were used to redirect incident flux to the ceiling plane 7.62-9.15 m (25-30 ft) from the window. Interreflections off the ceiling plane and walls distributed daylight to the workplane surface. For the light pipe, the same light shelf reflective daylight films and geometry were used to redirect daylight along the longitudinal axis of the pipe, minimizing interreflections and daylight losses. The transport section of the pipe was designed with an inclined ceiling plane and a combination of highly reflective films on all surfaces. The distribution section used a transmissive/ reflective film to redirect light downwards to the workplane surface.

METHOD

The development of both system designs required an iterative approach: starting from a general design concept using rough, quick evaluation methods to gain insight into the general performance, then progressing toward more accurate evaluation methods to fine-tune the design. Rough daylighting evaluation methods included scale model visualization using lasers, ray tracing calculations, and outdoor scale model testing. More accurate estimates of energy usage throughout the year were obtained by running DOE-2.1D (Simulation Research Group 1989) building energy simulations. Experimental measurements under laboratory conditions were combined with the daylighting algorithms (Papamichael and Beltrán 1993) in DOE-2 to more accurately predict the

daylighting performance of the optically complex window systems, i.e., the venetian blinds and the light shelf/ light pipe designs. The hour-by-hour mathematical models used in DOE-2 cannot accurately estimate the time-dependent heat transfer through the optically complex, dynamically operated venetian blind system. Therefore, we used the LBL Mobile Window Thermal Test (MoWiTT) facility to compare the heat gain of the dynamic system against a conventional static system and to characterize the differences in load shape and peak demand (Klems et al. 1994). The MoWiTT facility, consisting of accurate, twin room-sized calorimeters, is designed to simultaneously measure the time-dependent net heat flow through two fenestration systems of any complexity under realistic conditions. Lighting quality was investigated using the RADIANCE ray-tracing simulation software (Ward et al. 1986) and through direct observations of physical models.

The systems were further developed using reduced scale prototypes to resolve practical implementation issues, such as sensor design and placement or hardware/ software design of the control system, and to evaluate the system performance under realistic sun and sky conditions (Rubinstein et al. 1994). These systems will be further tested and developed in a full-scale testbed facility to make the transition from reduced-scale field tests to whole building applications. To better understand the market potential and barriers associated with these concepts, we conducted meetings with manufacturers and design firms to introduce the general concept of systems integration and to discuss the viability of specific prototype systems.

Demonstrations in real-world buildings were also pursued throughout the duration of the project with the objective to promote the concept of integrated systems in commercial buildings, and to field-validate their performance. Demonstrations with comprehensive end-use metering and user feedback can be invaluable to convince the risk-averse building industry to adopt new demand-side management (DSM) measures and to satisfy utility savings verification needs. We worked with several utility demonstration projects, providing in some cases a general level of design assistance while

promoting our concept, or in-depth full design and evaluation analysis for the cases when we were offered an opportunity to build and test our specific prototype systems (Lee and Selkowitz 1994B).

PERFORMANCE EVALUATION

Dynamic Envelope and Lighting Systems: Smart Coatings and Automated Blinds

Building energy simulations using DOE-2 confirmed substantial annual electricity consumption savings and peak demand reductions over conventional design practice. Figure 2 shows the incremental electricity consumption savings over an insulated wall for a conventional spectrally selective low-e insulating glazing (IG) glazing with and without shades, a hypothetical broad-band electrochromic, and a hypothetical selective narrow-band electrochromic.¹ The automated venetian blind system was operated to block direct sun and not exceed the design workplane illuminance level. The electrochromic glazing transmittance was modulated to meet the design workplane illuminance level. The operation of the shade was designed to emulate manual operation; operating from fully open to fully closed if the threshold for glare (glare index < 20) and/or direct solar radiation (< 94.5 W/m² (30 Btu/h-ft²)) was exceeded for that hour. Electric lighting control was based on the available daylight illuminance level at a distance of 3.05 m (10 ft) from the window wall and at a workplane height of 0.76 m (2.5 ft) above the floor. The design workplane illuminance level was set at 538 lux (50 fc). The prototypical commercial office space was 3.05 m wide by 4.57 m deep by 2.59 m high (10 x 15 x 8.5 ft). Results are presented for the inland Los Angeles climate.

Note that the solar-optical properties of the dynamic envelope system have a significant effect on energy savings. For the same control strategy, the narrow-band electrochromic (shading coefficient (SC) = 0.11-0.50, visible transmittance (Tv) = 0.09-0.71)² performed better than the broad-band electrochromic (SC=0.26-0.84; Tv=0.09-0.70) for all window orientations and range of glazing areas because it had a lower range of shading coefficient. Note also that the automated venetian blind provides a viable near term energy-efficient alternative to the electrochromic glazing, since the broad-band electrochromic, indicative of prototype systems

¹ Spectrally selective glazings are a relatively new class of commercially available products that admit a high proportion of visible daylight while excluding most of the heat gain arising from solar infrared radiation, with minimal loss of illumination and view. The hypothetical broad-band electrochromic coating switches from transmitting to absorbing over the entire solar radiation spectrum. The hypothetical narrow-band electrochromic switches from transmitting to reflecting in the visible portion of the solar spectrum only, with a minimum fixed transmittance and high reflectance in the infrared portion of the solar spectrum (Selkowitz et al. 1994). Electrochromic coatings will not be commercially available for three to five years.

that may become available in the next three to five years, performed only slightly better than the automated venetian blind.³ The performance of the venetian blind might also be improved to exceed the performance of the broad-band electrochromic. The venetian blind was modeled with discrete louver tilt angles at 15° increments and thus approximately met the design workplane illuminance level, whereas the electrochromic system was modeled with continuously variable transmittance and thus provided the exact design workplane illuminance level.

The conventional glazing system, a spectrally selective low-e IG glazing (SC=0.41, Tv=0.61) with manually operated diffusing shades, performed nearly the same as the broad-band electrochromic system for glazing areas less than 50% window-to-wall ratio,⁴ and worse for glazing areas greater than 50% due to its inability to control increases in cooling due to solar heat gains for all orientations. While in the ideal case an occupant will operate the shades to control direct sun and glare, it is unlikely that the occupants will operate the shade as modeled in DOE-2 on an hourly basis, if at all. This argument can be substantiated by observations of how occupants control shading devices. In a study investigating the frequency and nature of venetian blind operation by the occupant, it was found that about 60% of the blinds in several high-rise Tokyo office buildings were never used during the day (Inoue et al. 1988). In a separate study using data in part gathered from active badges monitoring occupant whereabouts, it was found that individuals typically spent 3.5 hours away from the office on excursions lasting 30 minutes or longer (Elrod et al. 1993). While these observations indicate that active shading systems may not substantially improve the comfort of an (absent) occupant, energy savings can be ensured over manually operated systems. For example, occupancy-based envelope and lighting control strategies may improve the projected energy savings by shutting off the lights and drawing the shades when the occupant is not in.

The diurnal and seasonal variations in peak demand are also presented for the dynamic and conventional systems for the west-facing orientation (Figure 3). Peak demand data for the venetian blinds are not given since the DOE-2 thermal model for this system is not accurate at the hourly level. Measured results of the venetian blind performance using the MoWiTT facility are presented below. Note again that because the

² Shading coefficient (SC) is a measure of total solar heat gain including both directly transmitted solar radiation and the indirect component of inward flowing heat due to absorption by the glazing. The visible transmittance (Tv) is defined as the percentage of visible light transmitted through the glazing.

³ Because of the time-consuming experimental methods used to define daylighting performance, we were able to measure only one glazing area, 50% window-to-wall ratio, for the venetian blind.

⁴ The glazing area, or window-to-wall area, is represented as a percentage of the floor-to-floor wall area, where the 70% window-to-wall value is equivalent to 100% floor-to-ceiling glazing area.

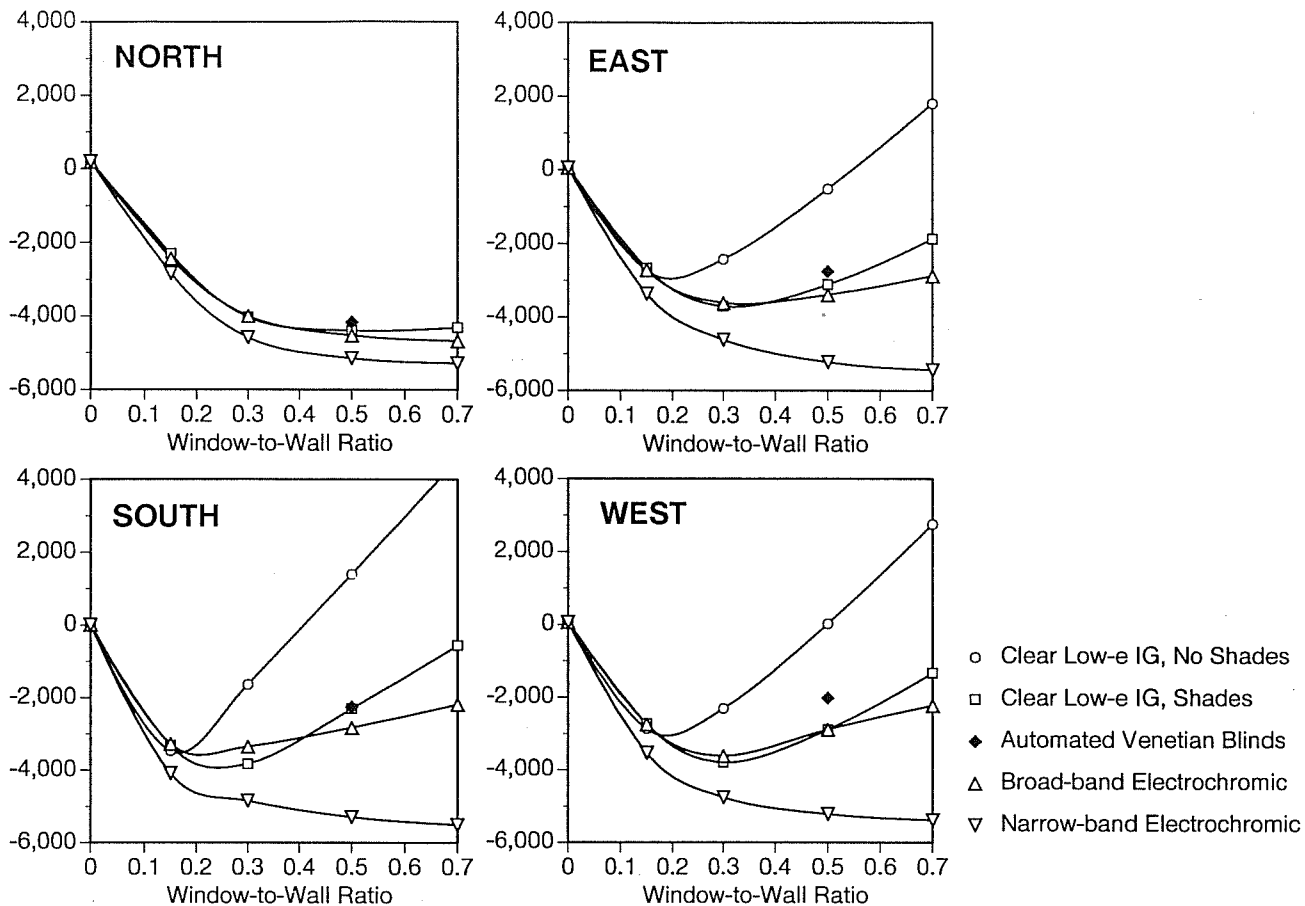


Figure 2. Incremental Electricity Consumption (kWh/yr) for a 139.4 m² (1500 ft²) Commercial Office Building Zone in Los Angeles

narrow-band electrochromic has a superior solar-optical range, the peak demand is nearly half that of all other active systems throughout the year. This decrease in the variation of electric demand and, necessarily heat loads within the space, may result in increased occupant thermal comfort. In an occupant survey of the effects of weather and the time of day on thermal comfort, researchers found that warm discomfort was more common when the sun was out, especially in late afternoon and in the summer, even though the space was air-conditioned (Energy Edge 1991). Other comments included, "In the summer, they turn on the air conditioner and it's too cold." While this may be an indication of a poor mechanical system design, if the perimeter space loads are decreased, thermal discomfort arising from either central control of the environment or inadequate control of individual zones may be decreased.

Due to the complex optical properties, geometry, and dynamic operation of the venetian blinds, we have not yet developed a venetian blind algorithm within the hour-by-hour mathematical models used in DOE-2 so, at present, we cannot accurately estimate the time-dependent heat transfer through this complex window system under realistic conditions. For the DOE-2 building energy simulations described

above, we used shading coefficient data calculated for a non-specular louver system between two glass panes for variable louver tilt angles and two average solar incident angles: summer and winter. There is, however, a significant dependence of heat transfer on solar incident angle as it varies throughout the day with both season and orientation. We used the MoWiTT facility to compare the heat gain of the automated venetian blind and dimming electric lighting system to a conventional static glazing and the same electric lighting system.

Results for a clear day indicate that the automatically controlled interior blind coupled with a selective glazing system was more than twice as effective at reducing solar heat gain as a commonly-used, single-pane tinted (bronze) glazing, while providing approximately the same level of useful daylight. The large differences in the heat flow between the two samples were driven principally by the admittance of direct sun into the base case chamber. Because the solar heat gains were so high, we conclude that the tinted glazing does not represent a satisfactory design for the space. The solar gains could be reduced to the level of the blind system if, for example, a lower shading coefficient tinted or reflective glazing is used. However, during periods of low daylight availability or cloudy conditions, the static glazing system would result in inadequate daylighting, resulting in higher electric lighting loads.

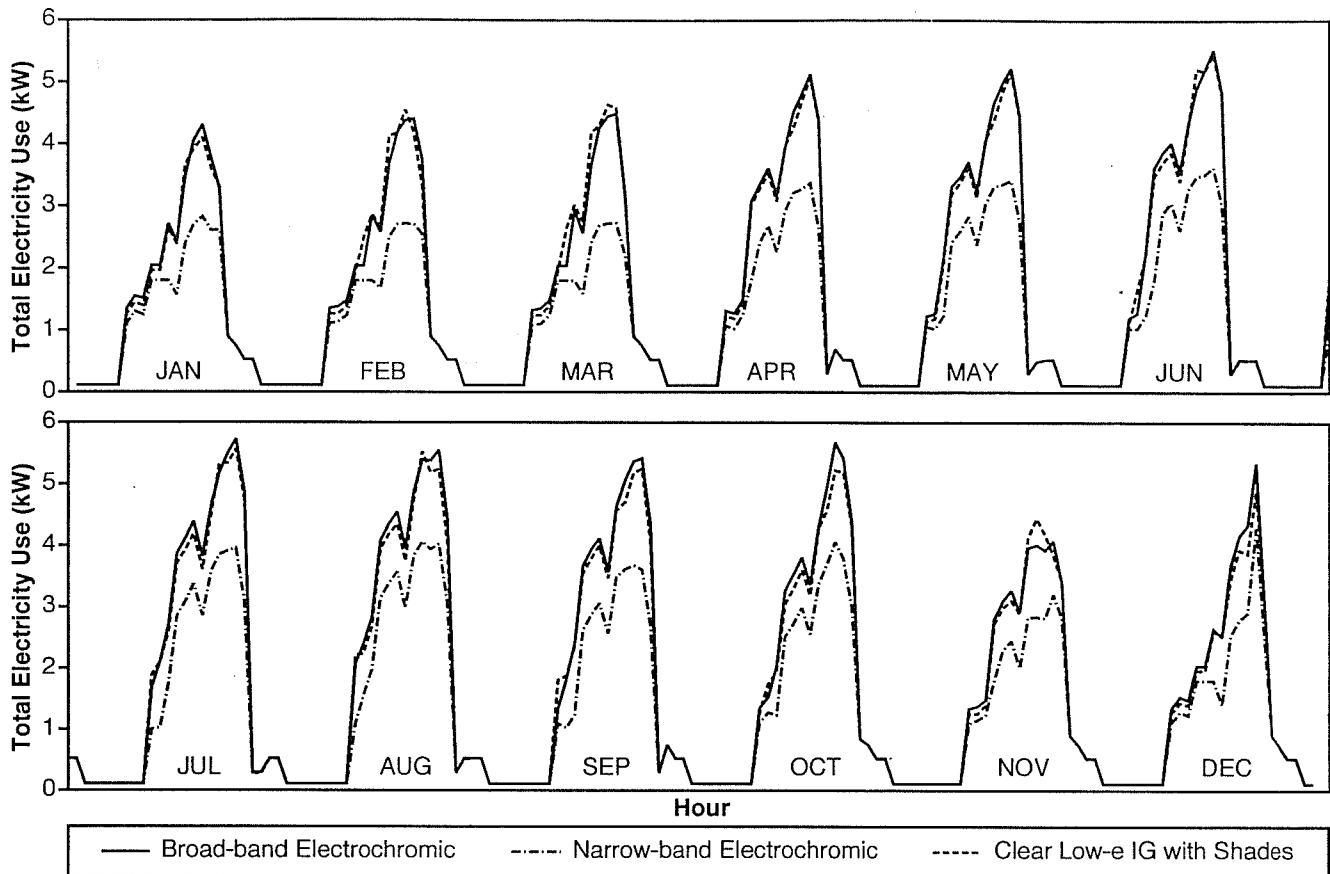


Figure 3. Total Electricity Demand for Typical Peak Days for a 139.4 m² (1500 ft²) Commercial Office West Zone in Los Angeles

Integrated Daylighting and Lighting Systems: Light Shelves and Light Pipes

Results given for Los Angeles indicate that for the south-facing light shelf prototype in a 6.10 m wide by 9.15 m deep by 3.05 m high (20 x 30 x 10 ft) workspace, the workplane illuminance level in the back of the room at a distance of 8.38 m (27.5 ft) from the window wall is over 300 lux (27.9 fc) throughout the year for surface solar azimuth⁵ angles, $\gamma < \pm 45^\circ$, and remains over 50 lux (4.6 fc) for $\pm 45^\circ \leq \gamma \leq \pm 90^\circ$. These daylight levels are given for the direct sun contribution only, since the clear sky contribution was relatively small: less than 24.6 lux (2.3 fc) throughout the year. For east or west-facing light shelf prototypes, the workplane illuminance level is over 400 lux (37.2 fc) throughout the year for $\gamma = 0^\circ$, and remains over 50 lux (4.6 fc) for $0^\circ < \gamma \leq \pm 90^\circ$. These daylight levels are achieved for an aperture that is only 0.18 m (0.6 ft) high across the width of the room, with a total input aperture area of 1.11 m² (12 ft²). These results were determined using experimental measurements and integrating mathematical algorithms (Papamichael and Beltrán 1993).

⁵ Surface solar azimuth is defined as the angle between the surface outward normal of the window and the solar azimuth angle.

The distribution of daylight in the 4.57-9.15 m (15-30 ft) workplane area from the window wall is fairly uniform under clear sky conditions. For the south-facing light shelf at noon, workplane illuminance levels are between 398-451 lux (37-42 fc) for the winter solstice, 212-245 lux (19.7-22.8 fc) for the summer solstice, and 430-894 lux (40-83 fc) for the equinox. Less uniformity occurs for sun angles that are not directly in front of the window since redirected sunlight falls on the upper side wall surfaces for very oblique sun angles. In open plan offices, where there are no side walls to obstruct redirected daylight, distribution will be more uniform for oblique sun angles. In individual offices, side wall reflectors at the light shelf may improve light output efficiency.

The light pipe designs performed less consistently throughout the year than the light shelf designs, primarily due to the smaller aperture area studied (0.15-0.37 m² (1.6-4.0 ft²)) and the square versus room-wide linear input aperture opening. Multiple light pipes or enlarged and redesigned collector apertures would improve this performance. For the south-facing light pipe prototype with an input aperture area of 0.15 m² (1.6 ft²), the workplane illuminance level at a distance of 8.38 m (27.5 ft) from the window wall is over 225 lux (20.9 fc) throughout the year for $\gamma < \pm 30^\circ$, and over 125 lux (11.6 fc) for $\gamma \leq \pm 50^\circ$. For $\gamma > \pm 60^\circ$, the workplane illuminance contribution from the light pipe was insignificant. The distribution of daylight in the workplane area 4.57-9.15 m (15-30 ft) from the window wall is not uniform over the full 6.1 m (20

ft) wide space due to narrow spread of daylight from the 0.61 m (2 ft) wide outlet aperture. The inefficiency of the light pipe for oblique sun angles is due to the increased number of interreflections within the transport section of the light pipe when the admitted daylight is not collimated along the longitudinal axis of the light pipe. To improve efficiency for oblique sun angles, the geometry of the light pipe side walls will need to be altered from the current design.

PRACTICAL CONSIDERATIONS

Dynamic Envelope and Lighting Systems: Automated Sensors and Controls

We built the dynamic envelope and lighting system to determine whether control of the venetian blind and electric lighting system could be practically implemented using a few simple sensors and controls. While dimming ballasts and control photosensors for electric lighting systems are commercially available (although currently expensive), control sensors that automatically adjust venetian blind tilt angles according to solar position or other criteria are not available off-the-shelf. In addition, control systems that optimally integrate operation of both the fenestration system and the lighting system are not available.

We used a computer-based data acquisition and control system to implement the control algorithms in software. Off-the-shelf motorized venetian blinds, lighting system, commercially-available photosensors, sun position sensor, and other sensor monitoring components were tested for suitability and extensively modified to meet the control criteria. We concentrated on achieving control at the local, office-by-office scale as opposed to the global whole building scale. At this time, our solution requires multiple sensors for proper control. Global control would increase the cost-effectiveness of our solution by spreading the cost of the sensors over a greater floor area, but may result in a loss of individual control. We will continue to investigate sensor designs that perform multiple functions.

We tested the system outdoors using a one-third reduced scale model to evaluate how well the venetian blind/ lighting system satisfied defined control strategy goals in real-time, under variable sun and sky conditions. Resolving issues, such as setting the appropriate time delay on the control system under rapidly changing cloudy sky conditions or how much precision is necessary to control the blind tilt angle ("hunting"), will impact daylight illuminance levels within the space, realized lighting energy savings, product costs, and an occupant's acceptance of the system. Field testing for a west-facing orientation indicated that the control system can successfully satisfy the control algorithm: block direct sun and maximize view. During consistently sunny conditions, we found that the system performed well. The blind angle was correctly tracking the solar position throughout the day to exclude direct sun, the workplane light level (daylight +

electric lighting) remained relatively constant throughout the day, and the electric lighting power reduction followed the daylight levels in inverse proportion as expected. Data from a hazy, still sunny day indicated that the workplane light level had slightly larger deviations from the design setpoint, but in all other respects, performed comparably to the sunny test conditions.

Through product research and discussions with manufacturers, architects/ engineers, and other research facilities, the interest and trend toward sophisticated intelligent dynamic systems was confirmed. Several utility DSM programs have specified or installed envelope systems with automated envelope/ lighting systems; e.g., the PG&E ACTT work with a dynamic skylight/ electric lighting system in a CSAA building in Antioch, CA;⁶ and the SCE Headquarters in San Dimas, CA with a motorized shade/ lighting system.⁷ A corporation outside of the building industry has developed and installed sophisticated occupant based lighting control systems in their commercial space, to be tied in eventually with envelope controls, with the expressed sole purpose to save energy in their buildings throughout the nation (Elrod et al. 1994). Numerous European manufacturers have created lighting management systems based on an advanced networking technology to facilitate distributed control and reconfiguration (Maniccia 1993). Further development of intelligent microprocessors and energy management control systems will continue to drive costs down in the future.

Integrated Daylighting and Lighting Systems: A Novel Skylight System

One specific building demonstration, the SCE Palm Springs Chamber of Commerce, gave us an excellent opportunity to prove the concept of integrated design and to test out the concepts developed for the daylighting technologies (Figure 4). We worked extensively with the architectural and engineering team to design and evaluate integrated envelope and lighting solutions for the entire building. Our work focused on developing a skylight system to daylight two windowless offices. Through an iterative series of ray-tracing calculations, outdoor physical model tests, and RADIANCE/ CADD modeling, we developed a single aperture skylight design that splits and redirects incoming daylight to the ceiling plane in two separate rooms. The design of this skylight system grew out of our experience, described earlier, with the light shelves and light pipes on vertical facades.

Our design was constrained by the building geometry, construction, and building code considerations. We found that while our design worked well to redirect daylight and improve its distribution, the design was perceived as rather

⁶ Personal communication with Grant Brohard, ACTT, Pacific Gas and Electric, San Ramon, CA, December 1993.

⁷ Personal communication with Gregg Ander, Southern California Edison, San Dimas, CA, January 1994.

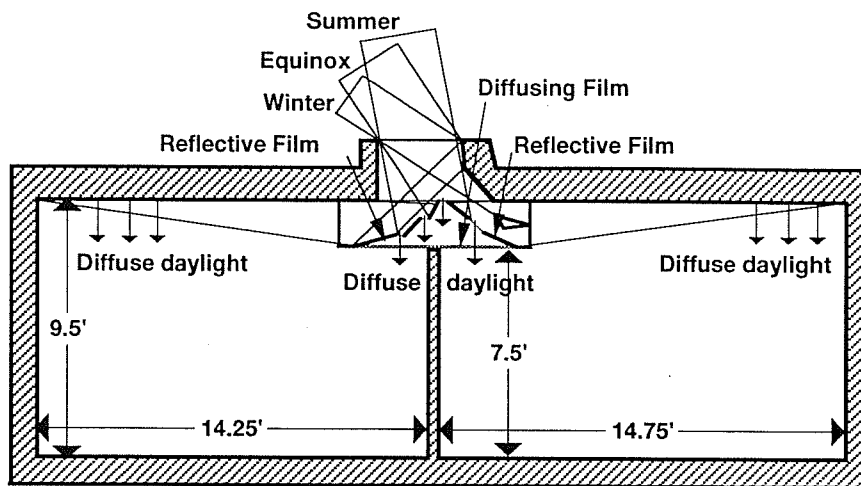


Figure 4. Schematic of the Palm Springs Chamber of Commerce Skylight Design

cumbersome and impractical by the architect for this particular retrofit application. Further work will be required to develop a robust mass-manufacturable system that can fit in with generic building types, such as new one-story commercial developments.

CONCLUSIONS

Significant reductions in energy use can be accomplished with possible increases in occupant comfort. To many occupants, energy-efficiency is secondary to environmental quality. Conventional building system designs that ignore this fact may find their energy-efficiency measures being overridden or dismantled. If economic value is placed on the potential increased comfort and productivity associated with an occupant's satisfaction with the visual and thermal environment, the drive toward more efficient, quality building environments can be further justified.

The approach we are developing requires a more involved design process. Simplistic approaches to increase energy-efficiency, such as swapping out components in exchange for more efficient components, must by necessity be replaced by a performance based approach. Integrated design requires a more sophisticated building designer, aware of the interactive effects of energy use and occupant comfort, and more powerful design tools that assist the building designer to make informed decisions on complex multi-variable problems (Papamichael and Protzen 1993). Utility programs, recognizing this as a market barrier, have set up design assistance programs emphasizing systems integration.

Our integrated approach will also require more forward thinking from manufacturers of envelope and lighting systems. Manufacturers will be required to expand the boundaries of their expertise from the component level to the whole building systems level when developing new product lines.

This again requires an understanding of how specific components play into whole building system energy-efficiency. For the specific integrated envelope and lighting systems proposed here, advances in control systems and additional developments in sensor technologies will be required before advanced dynamic control can be cost-effectively implemented. Close work with manufacturers will also be needed to develop a practical daylighting/ lighting technology.

In future work, we will continue to develop the integrated envelope and lighting systems with less emphasis on theoretical simulation models to verify performance and more emphasis on addressing the practical concerns of the manufacturer, designer, and user. We will set up a testbed facility to further develop and evaluate the systems in full scale and under occupied conditions. Demonstrations in real-world buildings will also continue.

ACKNOWLEDGMENTS

This has been a large multi-disciplinary project and we are indebted to our LBL colleagues, Konstantinos Papamichael, Robert Sullivan, Greg Ward, Guy Kelley, Mehry Yazdanian, Jonathon Slack, Michael Streczyn, Fred Winkelmann, and Fred Buhl for their assistance on this project. Thanks are also due to LBL student assistants Andrew Hamilton, Christopher Pawlowski, Werner Osterhaus, Paul Fritz, Ernie Ngo, Jessica Rothschild, Saba Rofchaei, and Jessica Sadlier, CIEE technical liaison, Karl Brown, and our CIEE Project Advisory Committee members.

This research was funded by the California Institute for Energy Efficiency (CIEE), a research unit of the University of California. CIEE is a consortium of the CPUC, the CEC, and California utilities including LADWP, SCE, SCG, SDG&E, SMUD, and PG&E. Publication of research results does not imply CIEE endorsement of or agreement with these findings, nor that of any CIEE sponsor. Industry in-kind support was provided by Cardinal IG and Levolor. Additional related support was provided by the Assistant Secre-

tary for Energy Efficiency and Renewable Energy, Office of Building Technologies, Building Systems and Materials Division of the U.S. Department of Energy under Contract No. DE-AC03-76SF00098.

REFERENCES

- Akbari, H., J. Eto, I. Turiel, K. Heinemeier, B. Lebot, B. Nordman, and L. Rainer. 1989. *Integrated Estimation of Commercial Sector End-Use Load Shape and Energy Use Intensities*. LBL Report 27512, Lawrence Berkeley Laboratory, Berkeley, CA.
- Beltrán, L.O., E.S. Lee, K.M. Papamichael, and S.E. Selkowitz. 1994. "The Design and Evaluation of Three Advanced Daylighting Systems: Light Shelves, Light Pipes, and Skylights." *Proceedings from the ASES 19th National Passive Solar Conference, June 25-30, 1994, San Jose, CA*.
- California Energy Commission (CEC). 1991. *California Energy Demand 1991 to 2011, Prepared for Consideration in the 1992 Electricity Report Proceedings, Vol. II: Electricity Demand Forecasting Methods, California Energy Commission, Sacramento, CA, P300-91-006*.
- Elrod, S., G. Hall, R. Costanza, M. Dixon, and J. Des Rivieres. 1993. *The Responsive Environment*. Xerox Corporation, Palo Alto Research Center, Palo Alto, CA 94304, CSL-93-5, June 1993.
- Energy Edge 1991. *Post-Occupancy Evaluation Project, Final Report (October 1991)*. University of Washington, Center for Planning and Design, College of Architecture and Urban Planning, Seattle, WA 98195.
- Geissler, R. "The Evolution of Building Intelligence." *Consulting/ Specifying Engineer, July 1989*.
- Inoue, T., T. Kawase, T. Ibamoto, S. Takakusa, and Y. Matsuo. 1988. "The Development of an Optimal Control System for Window Shading Devices Based on Investigations in Office Buildings." *ASHRAE Transactions, 94(2): 1034-1049*.
- Klems, J.H., M. Yazdanian, G. Kelley, D. DiBartolomeo, E.S. Lee, S. Selkowitz. 1994. *Heat Flow Measurements of an Integrated Venetian Blind and Electric Lighting System using the Mobile Window Thermal Test (MoWiTT) Facility*. Working information (January 14, 1994) for the multiyear project "Envelope and Lighting Technology to Reduce Electric Demand, Phase II," California Institute for Energy Efficiency (CIEE), Lawrence Berkeley Laboratory, Berkeley, CA.
- Lampert, C.M. and Y.P. Ma. 1992. *Fenestration 2000 Phase III: Advanced Glazing Materials Study*. Pilkington Glass, Energy Technology Support Unit, U.K. Department of Trade and Industry, Great Britain, ETSU S 12 15.
- Lee, E.S. and S.E. Selkowitz. 1994A. "The Design and Evaluation of Integrated Envelope and Lighting Control Strategies for Commercial Building." To be presented at the *ASHRAE 1995 Winter Meeting*, Chicago, IL, January 29 - February 1, 1995. LBL Report 34638, Lawrence Berkeley Laboratory, Berkeley, CA.
- Lee, E.S. and S.E. Selkowitz. 1994B. *Collaborative Demonstrations*. Working information (January 14, 1994) for the multiyear project "Envelope and Lighting Technology to Reduce Electric Demand, Phase II," California Institute for Energy Efficiency (CIEE), Lawrence Berkeley Laboratory, Berkeley, CA.
- Maniccia, D. 1993. *Lighting Controls Scoping Study, USA and European State-of-the-Art Lighting Controls Products (February 16, 1993)*. Lighting Research Center, Rensselaer Polytechnic Institute, Troy, NY 12180.
- Papamichael, K. and L. Beltrán. 1993. "Simulating the Daylight Performance of Fenestration Systems and Spaces of Arbitrary Complexity: The IDC Method." *Proceedings from the Third International Conference of the International Building Performance Simulation Association, Building Simulation '93*, August 16-18, 1993, Adelaide, Australia. LBL Report 33945, Lawrence Berkeley Laboratory, Berkeley, CA.
- Papamichael, K.M. and J.P. Protzen. 1993. "The Limits of Intelligence in Design." *Proceedings from the Focus Symposium on "Computer-Assisted Building Design Systems" of the Fourth International Symposium on Systems Research, Informatics and Cybernetics*, Baden-Baden, Germany, August 3-4, 1993. LBL Report 31742, Lawrence Berkeley Laboratory, Berkeley, CA.
- Rheault, S. and E. Bilgen. 1987. "Heat Transfer Optimization of an Automated Venetian Blind Window System." *Proceedings from the ASES 12th National Passive Solar Conference*, Portland, OR.
- Rubinstein, F., D. DiBartolomeo, A. Hamilton, E.S. Lee, and S. Selkowitz. 1994. *Implementation of a Dynamic Envelope and Lighting System*. Working information (January 14, 1994) for the multiyear project "Envelope and Lighting Technology to Reduce Electric Demand, Phase II," California Institute for Energy Efficiency (CIEE), Lawrence Berkeley Laboratory, Berkeley, CA.
- S.E. Selkowitz, M. Rubin, E.S. Lee, and R. Sullivan. 1994. "A Review of Electrochromic Window Performance Factors." *Proceedings from the SPIE International Symposium on Optical Materials Technology for Energy Efficiency and Solar Energy Conversion XIII*, April 18-

22, 1994, Friedrichsbau, Freiburg, Federal Republic of Germany. LBL Report 35486, Lawrence Berkeley Laboratory, Berkeley, CA.

Simulation Research Group. 1989. *DOE-2 Supplement, Version 2.1D*, LBL Report 8706, Rev. 5 Suppl., Lawrence Berkeley Laboratory, Berkeley, CA.

Sullivan, R., E.S. Lee, and S. Selkowitz. 1992. *Impact Assessment and Performance Targets for Lighting and Envelope Systems*. LBL Report 33075, Lawrence Berkeley Laboratory, Berkeley, CA.

Ward, G., F. Rubinstein, R. Clear. 1986. "A Ray Tracing Solution for Diffuse Interreflection." *Computer Graphics*, 22(4), August 1988. LBL Report 22789, Lawrence Berkeley Laboratory, Berkeley, CA.