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DEVELOPING INTEGRATED ENVELOPE AND LIGHTING SYSTEMS FOR COMMERCIAL BUILDINGS

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ABSTRACT

Integrated envelope and lighting systems achieve significant energy, peak demand, and cost savings over typical component-by-component design practice by leveraging the interactive energy balance between electric lighting energy use and cooling due to lighting and solar radiation. We discuss how these savings can be achieved using conventional glazing and lighting components by taking an integrated systems design approach. We describe integrated dynamic envelope and lighting systems, currently under development, that actively achieve this energy balance through the use of intelligent control systems. We show how prototypical daylighting systems can be used to increase the efficacy and distribution of daylight throughout the space for the same or less glazing area as a typical window, while achieving greater energy savings with increased visual comfort. Energy performance simulations and field tests conducted to date illustrate significant energy savings, peak demand reductions, and potential practical implementation of these proposed systems.

1. INTRODUCTION

The optimum energy balance between the commercial building envelope and the electric lighting system varies widely with meteorological conditions and internal loads and, in basic terms, can be summarized as follows: Daylight admitted through the building envelope can be used to offset electric lighting requirements through the use of daylighting controls. This serves to reduce both lighting energy and cooling energy due to heat gains from lighting. On the other hand, the admission of daylight increases solar radiation heat gains, potentially increasing cooling energy requirements. Understanding this basic interaction between lighting and cooling energy use forms the basis for the development of integrated envelope and lighting systems. By designing a building with an integrated systems versus a component-by-component approach, one can leverage the interactive effects of energy use between envelope and lighting components to achieve lower energy use and peak demand, and greater cost savings.

A preliminary simulation assessment of how integrated envelope and lighting systems perform indicates potential whole building electricity use savings of 25% by 1995 and 48% by 2005, and peak demand reductions of 22% by 1995 and 40% by 2005 for typical commercial office buildings in California. If this concept is adopted by both new and retrofit commercial office buildings alone, we project a reduction in load growth of 20% in this California building sector or the equivalent of 500-800 MWh (1707-2732 MBtu) by the year 2005 [1].

We present a summary of work completed to date to develop integrated envelope and lighting systems. We describe an analytical method to weigh incremental energy savings when selecting conventional glazing and lighting systems. Two integrated envelope and lighting systems currently under development are discussed: (1) dynamic envelope technologies that actively modify daylighting and thermal properties to achieve, in combination with electric lighting/ daylighting control systems, an optimum energy balance in real time, and (2) daylighting envelope systems that, with a relatively small perimeter glazing area, extend the depth of daylighting penetration, and lighting energy savings, beyond the typical 4.6 m (15 ft) perimeter area defined by sidelight windows. We focus, in this paper, on our investigation to optimize the envelope/ lighting energy balance, with our efforts to address occupant comfort, market potential, demonstration, and commercialization of these systems described elsewhere [2].

2. CONVENTIONAL ENVELOPE/ LIGHTING SYSTEMS

Selecting conventional, commercially available glazing and lighting components that achieve an optimal energy balance requires a sufficient knowledge of the multiple complex building parameters that affect this balance and adequate analysis time. No method currently available allows the building designer to understand quickly and easily the incremental energy benefits of glazing and lighting choices. The selection is complicated by numerous building parameters: glazing shading coefficient, visible transmittance, and U-value, glazing area, orientation, shading device, lighting power density, daylighting control strategy, etc.

Using the DOE-2.1D building energy simulation program, we ran a large number of energy simulations varying both envelope and lighting parameters to develop a large database of performance data [3]. We developed simple algebraic expressions using multiple regression analysis to allow one to predict energy usage for any arbitrary envelope and lighting system configuration. The incremental energy use was then mapped in a series of surface contour plots as a function of solar aperture, a product of the glazing shading coefficient (SC) and glazing area, and daylighting aperture, a product of the glazing visible transmittance (Tv) and glazing area. In so doing, one is able to visualize how a choice in glass type, for example, can affect annual energy savings.

We illustrate this method for north and south perimeter zones of a prototypical office building module in Los Angeles (Fig. 1). The contours represent lines of equal incremental electricity consumption (0+ MWh is equal to an opaque insulated wall). Five glazing types for the window to exterior (floor-to-floor) wall area ratio (WWR) of 0.50 are superimposed on the contours. For the south zone, glazings C and E yield approximately the same annual electricity consumption. However, the choice of glazing E, representative of a double-pane reflective glazing (Tv=0.10, SC=0.20), will probably result in a gloomy interior environment compared to the more transparent glazing C, representative of a double-pane tinted glazing (Tv=0.53, SC=0.41). Glazing D, a spectrally selective low-E glazing (Tv=0.60, SC=0.30), performs the best by minimizing energy use without noticeably altering the visual appearance of the outdoors. For the north zone, the difference in energy savings between all five glazing types is small, due to the lower amount of incident solar radiation at this orientation. The difference in electricity consumption savings between glass type A and D, for example, is at most 1 MWh or 7.21 kWh/m^2-floor area (0.67 kWh/ft^2) for north zones, compared to 5 MWh or 35.8 kWh/m^2 (3.33 kWh/ft^2) for south zones. Peak demand and electricity cost can be plotted in a similar manner.

This method allows the designer to visualize easily the energy-savings relationship of various glazing/ lighting choices, to decide which envelope parameters have a significant effect on energy savings, and to assess by the slope of the contour surface the degree of change from one choice to another. Simple design tools, like this, are needed to assist the designer to make quick informed choices between conventional glazing and lighting systems, and attain high energy savings.

3. DYNAMIC ENVELOPE/ LIGHTING SYSTEMS

By coupling the operation of a dynamic envelope system to an electric lighting system with daylighting controls, the cooling and lighting energy balance can be accomplished by an intelligent control system on a real time basis. This active level of control can result in a more uniform cooling load due to solar radiation from hour-to-hour, giving this system the distinct capability to control peak demand. In addition, the lighting and thermal environment may be more consistent and more comfortable for occupants adjacent to the window wall.

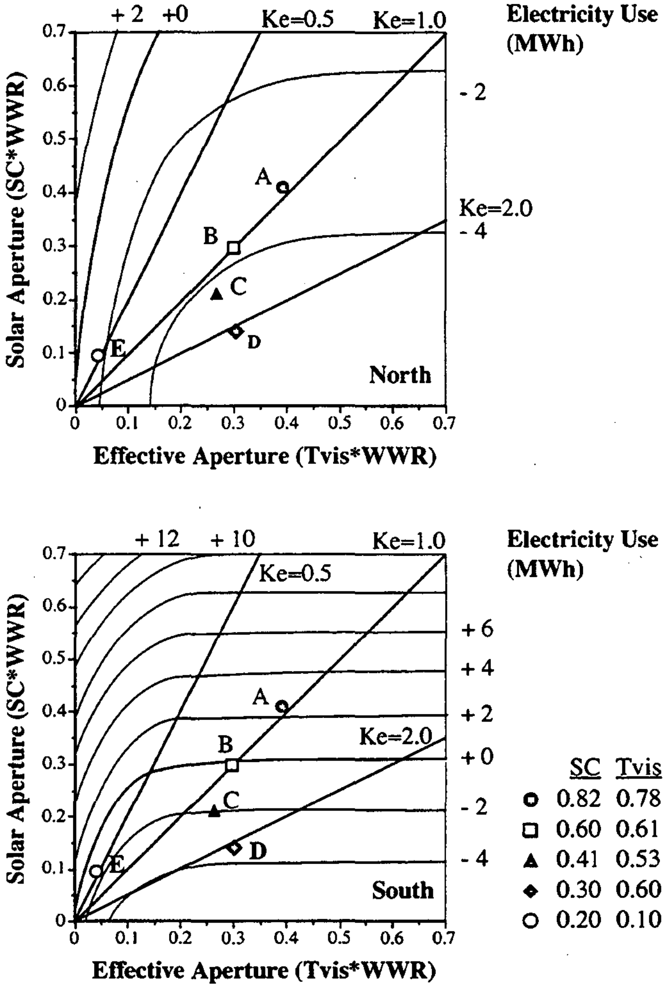


Fig. 1. Contours of incremental annual electricity (MWh) for a 139.4 m^2 (1500 ft^2) perimeter zone.

We categorize an envelope system as "dynamic" by its capability to modify its solar-optical properties to mitigate heat gains from solar radiation (solar) and modulate transmitted daylight (optical). The venetian blind meets this criteria, although typically manually operated, and is widely used with commercial buildings. In the long term, we view the electrochromic glazing system, an electro-chemical multi-layered glazing under development that can actively alter its solar-optical properties from a clear to dark tinted appearance with a small applied voltage, as probably the most elegant solution for dynamic control, due to its unobtrusive application in buildings.

The focus of this research centered on the evaluation of operational control algorithms. While there has been some research to investigate dynamic envelope systems over the years, there has been less research to investigate the optimal control and integration of envelope and lighting components to achieve the optimal energy balance described above.

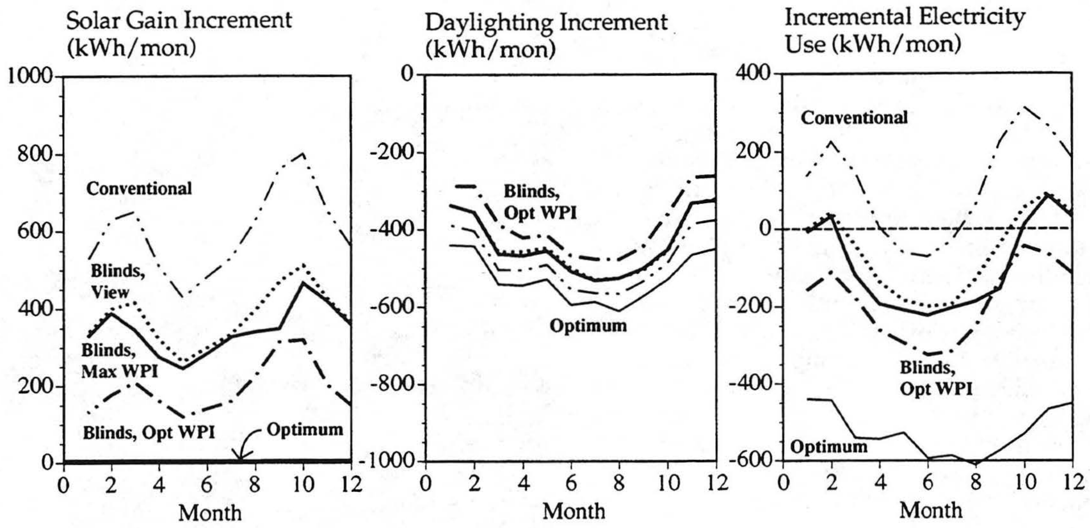


Fig. 2. The venetian blind control algorithm, block direct sun and optimize workplane illuminance (Opt WPI), is able to obtain near optimum energy performance (right) by minimizing the penalties due to solar gains (left), while achieving nearly the same daylighting performance as the other control algorithms (center).

3.1 DOE-2 Building Energy Simulations

We performed DOE-2.1D building energy simulations to compare the performance of various control strategies and to evaluate the resultant energy and peak demand performance [4]. These results indicate that the automated venetian blind can achieve significant annual energy consumption and peak demand savings over a spectrally selective low-E glazing (Tv=0.61, SC=0.41) with daylighting controls and no interior shading for south, east, and west-facing orientations of an office building module in Los Angeles (Table 1). The idealized broad-band electrochromic, which switches from transmitting to absorbing over the entire solar radiation spectrum (Tv=0.09-0.70, SC=0.26-0.84), performed slightly better than the venetian blind system. The idealized narrow-band electrochromic, which 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 (Tv=0.09-0.71, SC=0.11-0.50), achieved near optimal performance due to its superior solar-optical range. Both the automated venetian blind system and the electochromic systems were operated to meet the design workplane illuminance level of 538 lux (50 fc).

We found that the dynamic solar-optical properties of the envelope system had the greatest influence on the energy and peak demand savings for the same control strategy. Similar in principal to the superiority of spectrally selective glazing over heat-absorbing tinted glass, the narrow-band electrochromic provides better rejection of the near infrared solar radiation and thus lower solar heat gain for a given daylight level compared to the broad-band electrochromic, thus achieving higher energy savings.

Defining the solar gain increment as the detrimental cooling energy due to solar radiation, and the daylighting increment as the beneficial lighting energy and cooling due to lighting savings, we found that between three venetian blind/ lighting control strategies, "optimize workplane illuminance" provided the best solar control throughout the year with a marginal effect on daylighting savings (Fig. 2). If the control strategies were based on an optimization of predicted loads or predicted energy use, the performance of the automated venetian blind may have been further improved. Predictive control algorithms, however, are very difficult to implement in building simulation programs since the calculation of building loads is typically separated from the calculation of building energy use. Instead, we defined the lower bound of performance with a hypothetical optimum system to determine the incremental savings before pursuing this more complex solution.

TABLE 1. DOE-2.1D ENERGY PERFORMANCE DATA

	North	East	South	West
Electricity Use (kWh/ft^2·yr)				
Low-E IG, No S, No DLC	9.87	18.04	21.02	19.22
Low-E IG, S, No DLC	9.90	13.69	14.99	14.50
Low-E IG, S, DLC	5.33	6.43	7.05	6.57
Blinds, DLC	5.52	6.66	7.08	7.15
Broad-band EC, DLC	5.25	6.24	6.70	6.57
Narrow-band EC, DLC	4.83	5.02	5.06	5.01
Optimum	4.32	4.31	4.38	4.27
Peak Demand (W/ft^2)				
Low-E IG, No S, No DLC	5.40	11.08	12.46	11.09
Low-E IG, S, No DLC	4.47	5.50	5.70	5.71
Low-E IG, S, DLC	4.07	5.06	5.16	3.90
Blinds, DLC	3.78	4.97	5.02	5.24
Broad-band EC, DLC	4.15	4.89	5.06	5.13
Narrow-band EC, DLC	3.78	3.95	4.00	4.04

N: No, S: Shades, DLC: Daylighting Controls
EC: Electrochromic, IG: Insulated Glazing

3.2 MoWiTT Field Test

Outdoor calorimetric measurements of the dynamic system were conducted to understand better the diurnal variation in heat gains and their effect on cooling peak demand [5]. Due to the complex optical properties, geometry, and dynamic operation of the venetian blinds, the hour-by-hour mathematical models used in DOE-2 cannot accurately estimate the time-dependent heat transfer through this complex window system under realistic conditions. This is critical to the load shape and peak demand concerns of California utilities. Therefore, using the LBL Mobile Window Thermal Test (MoWiTT) facility (Fig. 3), we compared the heat flow through two systems, the automated interior venetian blind/ electric lighting system with daylighting controls, and a conventional tinted glazing system with daylighting controls, typical of commercial construction today. Measurements were taken in Reno, Nevada for a six week period from November through December.

Results for typical clear days (Days 18, 19, 20 and 23) indicate that the peak envelope *and* electric lighting heat flow of the base case sample is about two times that of the dynamic venetian blind/ lighting system (Fig. 4). The differences between the heat flows due to envelope only and the heat flows due to envelope + electric lighting heat flows were small. This was due to the early over saturation of daylight within the blind and base case model space, leading to nearly the same electric lighting power reduction and hence electric lighting heat gains in both chambers. Therefore, the dynamic system was twice as effective at reducing solar heat gain, while providing approximately the same level of useful daylight. These findings underscore the importance of solar heat gain control during peak cooling conditions.

These findings also point to a propitious if not self-evident result: the optimum balance point between lighting and cooling energy use varies widely with daylight availability for envelope/ lighting systems when daylight saturation does not occur. For example, in early morning hours when daylight availability is sufficiently low, a control strategy designed to meet the design lighting level with daylight will result in the largest energy savings, since lighting demand is the predominant end use for these hours. For peak cooling conditions in the afternoon, a control strategy designed to minimize solar radiation may result in the largest energy savings, since cooling due to solar radiation is the predominant load.

If daylight saturation does occur (as it would with large glazing areas), however, we must look at how the envelope/ lighting system can be designed to satisfy an occupant's desire for view and contact to the outdoors, since a dynamic system designed to minimize peak demand may result in the envelope positioned in its most "protected" state for the majority of the summer season. For electrochromic systems, this may not be an issue because even at its darkest colored state, transparency is maintained – even though the gloomy lighting environment may be detracting to the occupant. For venetian blind systems, however, complete closure of the blinds to minimize peak demand may be overridden by the occupant.

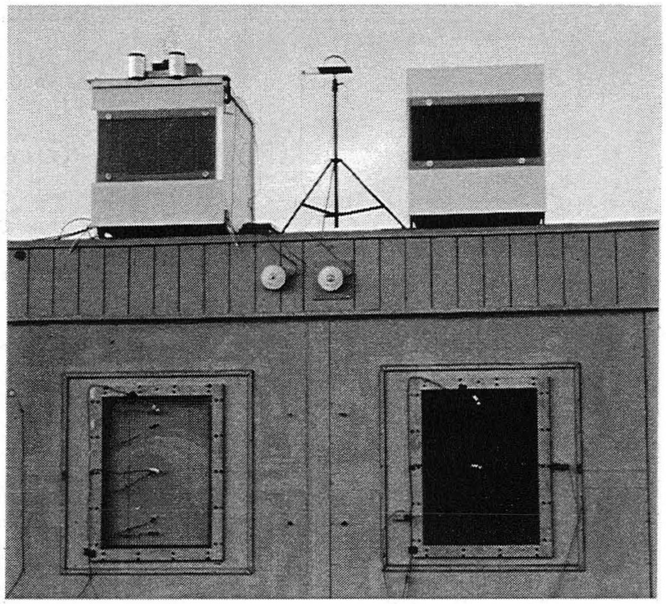
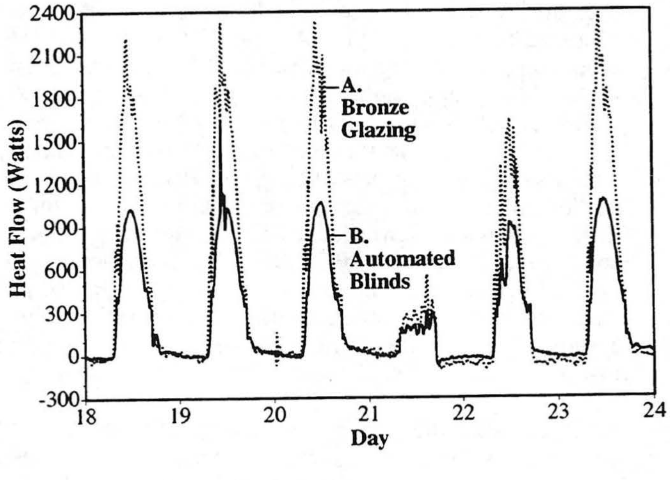


Fig. 3. The MoWiTT facility was designed to measure the heat flow in the lower calorimeter chambers and workplane illuminance in the upper, office-like modules.



A. *The base case sample was a 6 mm uncoated single-pane bronze glazing (Tv=0.53, SC=0.71, U-value=6.17 W/m^2·C (1.09 W/h·ft^2·°F)).*

B. *The automated interior venetian blind system was combined with a selective IG glazing (Tv=0.72, SC=0.46, U-value=1.36 W/m^2·C (0.24 W/h·ft^2·°F)), and operated to block direct sun and maximize view.*

Fig. 4. Heat flow due to fenestration and electrical lighting for a prototype office space between 8 AM and 5 PM for a design workplane illuminance level of 538.2 lux (50 fc).

3.3 Implementation

In a separate field test to determine the feasibility of implementing dynamic systems [6], we designed, built, and tested the automated venetian blind/ lighting system to determine if the system could be accomplished practically with a minimum number of sensors (Fig. 5). We investigated hardware issues such as how precisely the venetian blind angle could be positioned with standard motors typically installed in commercially available systems, how to detect sun angle position and the presence of direct sun using simple local sensors, and how to design an appropriate closed-loop ceiling mounted photosensor to measure workplane illuminance. We also examined software issues such as how often to actuate the system under rapidly changing clear/ cloudy sky conditions in order to satisfy the control strategy objectives.

Results from outdoor scale model tests indicate that the venetian blind system can satisfy defined control strategy goals in real-time under variable sun and sky conditions. The blind angle was found to correctly track the solar position throughout the day to exclude direct sun. The workplane illuminance level from daylight and electric lighting remained relatively constant throughout the day. The electric lighting power reduction followed the daylight levels in inverse proportion as expected. Data from partly cloudy days (hazy, still sunny conditions) had slightly larger deviations from the design illuminance setpoint, but in all other respects, performed comparably to sunny test conditions (Fig. 6).

Implementation of the system, however, proved to be difficult due to the inadequacy of off-the-shelf components to meet our needs. The final venetian blind motor and electronic circuitry, completely redesigned to meet our movement criteria, could be incorporated in the existing blind housing. Sensors designed to detect sun angle position and workplane illuminance will require further work before commercialization. Finally, we reviewed manufacturer products to understand the building-wide issues of local (space by space) and global (whole building) control with an appropriate building control networking system that would be both flexible, easily reconfigurable, and cost-effective. At this point, we were able to identify one U.S. manufacturer that held claims to an open-protocol networking system capable of operating on multiple media (twisted pair, radio frequency, etc.). Although, the hardware cost (microprocessor cost per point) is prohibitively expensive at this time, costs may fall substantially – we will revisit possible use of the system in future work. In the short term, localized space by space control will probably be the most cost-effective route.

4. DEEP PERIMETER DAYLIGHTING SYSTEMS

There are two major advantages to daylighting a deeper perimeter area from the window wall: (1) the solar heat gains introduced by the perimeter building envelope are offset by a lighting energy and cooling load reduction over a larger floor area, and (2) if the daylight is distributed well, the visual comfort within the space can be greatly enhanced. The inadequacy of sidelight windows to meet our visual needs throughout the space is evidenced by occupants sharing an office,

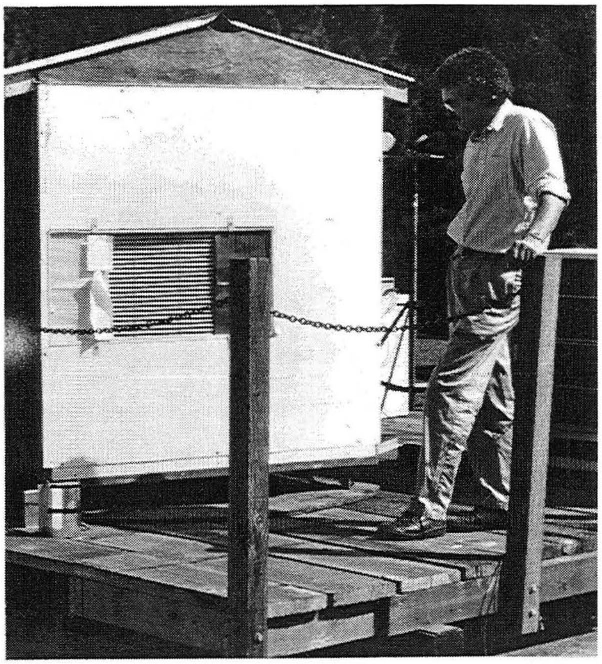


Fig. 5. Daylighting field test set-up with automated venetian blinds/ lighting system.

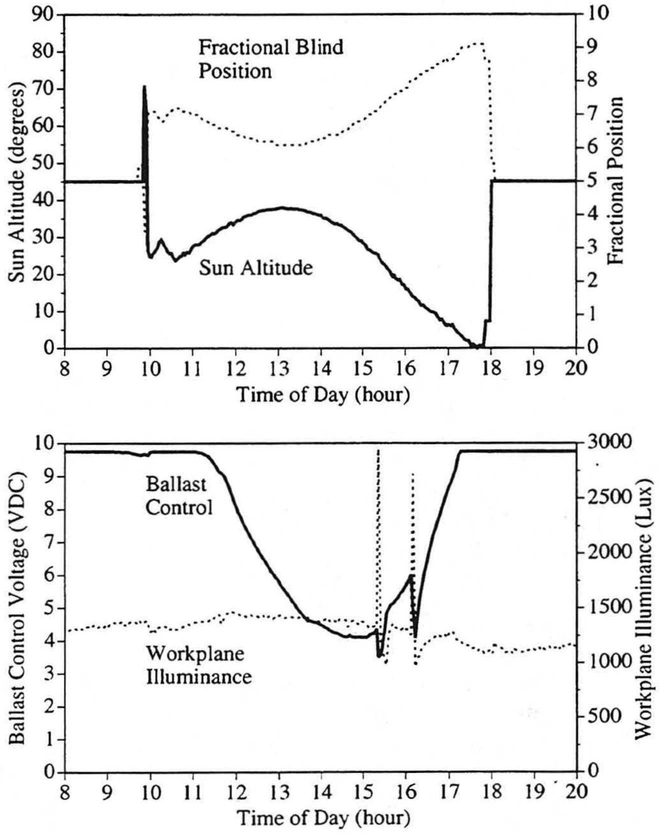


Fig. 6. Performance of the automated venetian blind with dimmable electric lighting for a clear day with the model oriented southwest.

where the occupant working adjacent to the window will draw the blinds to control glare, while the other working further back in the room will turn on a task light to increase the lighting level.

We have developed several designs in which the building envelope is divided into an upper daylighting window aperture and a lower view aperture. The lower view aperture has been designed to control glare, direct sun, and view for those occupants adjacent to the window. The upper daylighting aperture employs the prototype daylighting technology to redirect or transport daylight to 4.57-9.15 m (5-10 ft) deep perimeter areas of the building. Through an iterative series of design and redesign, employing laser visualization tests, computer ray tracing, outdoor physical model tests, and detailed experimental/ mathematical measurements, we developed three daylighting prototypes: a light shelf, light pipe, and skylight [7].

Measured results indicate that the daylighting contribution from a relatively small inlet aperture is significant at the workplane at a distance of 8.38 m (27.5 ft) for the south orientation. However, for oblique solar surface azimuth angles, the daylighting performance declined due to the inefficient redirection of daylight to the center of the room. We found the distribution of daylight within the space to be significantly better than conventional sidelit conditions, and expect visual comfort to be improved by these systems. In a collaborative building demonstration effort with Southern California Edison, we further developed the geometry of the reflector system to increase light redirection of off-azimuth angles in a skylight prototype for the Palm Springs Chamber of Commerce. In addition, the building was designed to showcase the concept of the whole building integrated systems approach through the use of state-of-the-art mechanical system, curtain wall glazing, and electric lighting components.

5. CONCLUSIONS

Through the integration of envelope and lighting technologies, we demonstrate that significant energy and peak demand savings can be attained with conventional, available technologies if a proper lighting and cooling energy balance is attained. In future work, we will further develop these systems in a testbed facility under occupied conditions to better understand practical issues with full-scale applications and the impacts on comfort and productivity. Demonstrations in real-world buildings will also continue.

6. ACKNOWLEDGMENTS

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