LBL-19734
EEB-W 85-12
BS-201

Presented at the Second Annual Symposium on Improving Building Energy Efficiency in Hot and Humid Climates, Texas A&M University, September 24-26, 1985.

COOLING ENERGY AND COST SAVINGS WITH DAYLIGHTING IN A HOT AND HUMID CLIMATE

D. Arasteh, R. Johnson, S. Selkowitz, and D. Connell

Applied Science Division
Lawrence Berkeley Laboratory
University of California
Berkeley, California 94720

July 1985

This work was supported by the Assistant Secretary for Conservation and Renewable Energy, Office of Building Energy Research and Development, Building Systems Division of the U.S. Department of Energy under Contract No. DE-AC03-76SF00098.

COOLING ENERGY AND COST SAVINGS WITH DAYLIGHTING IN A HOT AND HUMID CLIMATE

D. Arasteh, R. Johnson, S. Selkowitz, and D. Connell

Applied Science Division
Lawrence Berkeley Laboratory
University of California
Berkeley, California 94720

ABSTRACT

Fenestration performance in nonresidential buildings in hot climates is often a large cooling load liability. Proper fenestration design and the use of daylight-responsive dimming controls on electric lights can, in addition to drastically reducing lighting energy, lower cooling loads, peak electrical demand, operating costs, chiller sizes, and first costs. Using the building energy simulation programs DOE-2.1B and DOE-2.1C, we first discuss lighting energy savings from daylighting. The effects of fenestration parameters on cooling loads, total energy use, peak demand, chiller sizes, and initial and operating costs are also discussed. The impact of daylighting, as compared to electric lighting, on cooling requirements is discussed as a function of glazing characteristics, location, and shading systems.

INTRODUCTION

When possible, dimming electric lighting systems in response to varying daylight levels (termed "daylighting") can significantly lower electric lighting requirements in office buildings. Further energy and demand cost savings as well as increased occupant comfort can be realized by properly designing fenestration and shading systems that minimize radiant gains and glare while still providing good illumination.

In this paper the expected daylighting effects in a typical office building located in a hot-humid climate are discussed. The reduction in lighting energy and its implications on total energy requirements, peak demand, and chiller size are also mentioned. In hot climates, daylighting will reduce cooling loads relative to a nondaylighted case (with the same fenestration characteristics). Daylighting's impact on cooling loads (i.e., the "coolness" of daylight as compared to electric lights) is also discussed.

BACKGROUND

The material presented here is part of ongoing research to assess and understand the energy impacts of fenestration systems (windows, skylights, and shading systems). In this phase of our work we use detailed hour-by-hour DOE-2.1B energy analysis computer simulations (1). In later phases, we will experimentally validate these results using a specially constructed window field test facility and by monitoring suitable buildings. To date, our work has focused primarily on two typical office building modules, one with windows in four perimeter zones facing the four cardinal directions, the other with only flat skylights as the fenestration elements. We have simulated these buildings in over fifteen climates throughout the United States, varying important fenestration and lighting-related parameters. This paper focuses on the office module with vertical windows in a hot-humid climate, and compares it with the skylighted office module.

Figure 1 illustrates the final building modules. The window building module consists of four identical perimeter zones, each 15 ft. deep and 100 ft. wide, separated into 10 equal offices 10 ft. wide and surrounding a common core. The ceiling and floor are modeled as adiabatic surfaces. For the skylight module, the perimeter zones are dropped, the side walls become completely opaque and adiabatic, and skylights are evenly distributed over the (now non-adiabatic) roof. These and other characteristics of the final building modules were determined through a series of sensitivity studies. Details are given in Reference 2 for the window module and in Reference 3 for the skylight module. We note that in the design of these studies we were primarily interested in relative performance between alternative envelope designs, rather than absolute energy consumption.

Previous sensitivity studies also identified the important fenestration and lighting-related variables to be modeled parametrically. These include the glazing window-to-wall-area ratio (WWR) based on ceiling height, or the skylight-to-roof-area ratio (SRR), the glazing's shading coefficient (SC) and visible transmittance (T_v), lighting control strategy, window management strategies, lighting power density, and for skylights, the light well transmission factor (WF).

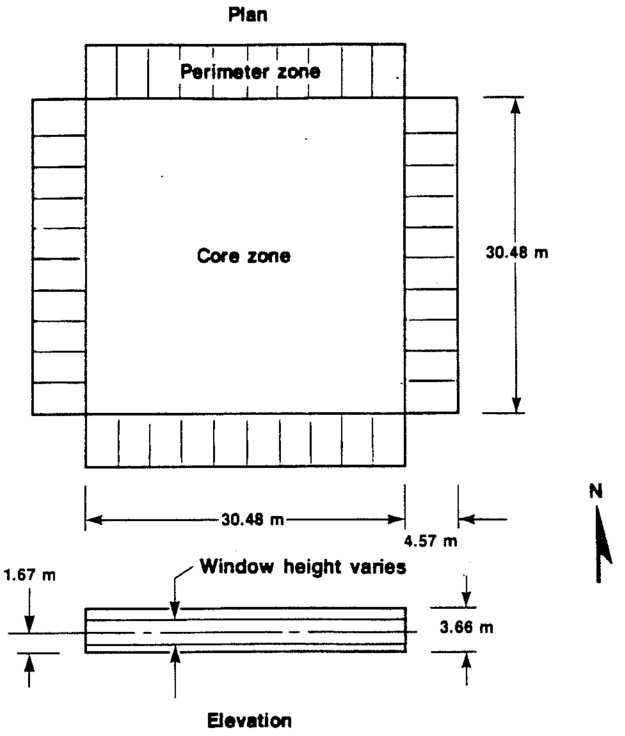

Fig. 1a. Diagram of building model for vertical fenestration simulations.

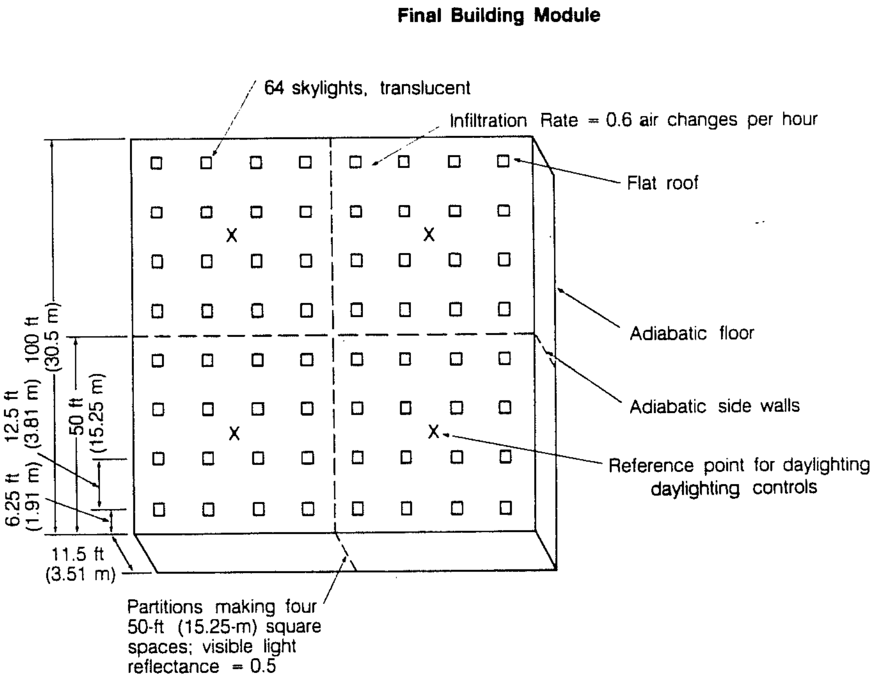

Fig. 1b. Diagram of building model for skylight simulations.

METHODOLOGY

To isolate fenestration effects, thermal transmission was limited to the fenestrated surface including its wall. The overall heat transfer coefficient, U_o of the wall or roof (including glazing) was held constant at values consistent with ASHRAE 90 standards. Since the thermal conductance of the glazing (single or double) exceeds the maximum U_o, as the glass area increases, the conductance of the opaque wall is reduced in order to maintain a constant U_o.

The installed lighting power was varied from 0.7 to 2.7 W/ft^2 based on a design illuminance of 50 fc. This range covers lighting power densities one would expect to find in offices today and in the near future. Since the design illuminance level is held constant, the varying lighting power densities reflect a variation in lighting system efficacy and can accommodate a wide range of luminaires, lamps, ballasts, and designs.

Two types of lighting controls are modeled. A continuous dimming system dims from 100% light output with 100% power to 0% light output with 10% residual power losses. This system continuously responds to variations in daylight levels and maximizes the benefits from low daylight levels. The second system type provides multi-level step switching with the number of steps depending on the installed lighting power density. Simple two-step or on/off systems reduce electric power only when daylight provides half or all required lighting respectively; at zero electric light output there is zero power consumption. Step-switching systems are most effective at high interior daylight levels where all the space's lighting requirements are met by daylighting; here their performance will exceed that of continuous dimming systems. At small effective apertures, step systems can be less effective or even useless depending on the number of steps, the control setpoint, and the interior daylight level. In this study, our analysis of the thermal effects of daylighting, daylighting's influence on annual energy consumption and costs, and peak demand are based on the use of continuous dimming systems.

To simplify our analysis of fenestration characteristics, a single parameter consisting of the product of the WWR (or SRR) and T_v (or T_v x WF for the case with skylights) was used. We call this new lumped parameter the <u>effective aperture</u> (A_e). Results in this paper are expressed as a function of effective aperture. Effects of mullions and other opaque elements can be accounted for in the WWR term and a dirt depreciation factor can be incorporated into T_v. A constant relationship between shading coefficient and visible transmittance is assumed for vertical tinted glazing where $T_v = 0.67$ x SC, which is typical of commonly available products. When considering skylight systems with light wells, we assume that a change in the light well will alter the light flux transmitted to the space but not change the solar gains. This simplification does not address the effect of light well heat stratification, an effect difficult to quantify.

We assume that the thermal and visual comfort of the occupants requires that simple interior shades or blinds be deployed for any hour in which transmitted direct solar radiation exceeds 20 Btu/hr-ft^2, or for any hour in which the glare level is no longer acceptable (i.e., a glare index of 20). The window management system used here reduces solar heat gain by 40% and visible transmittance by 65% and is considered representative of many conventional interior shading devices. Current work, using the results of detailed illuminance-calculating computer programs and experimental work, is aimed at a more complete assessment of the impact of both interior and exterior movable shades.

The DOE-2.1B and 2.1C building energy simulation programs were used to predict annual energy performance. We used ASHRAE WYEC (Weather-Year for Energy Calculations) tapes containing hourly weather data for Lake Charles, Louisiana. WYEC tapes do not represent a specific year but are rather a compilation of the most typical months and days based on weather data recorded between 1951 and 1980 (4). Lake Charles, with a climate very similar to Houston and New Orleans, was chosen to represent a hot-humid climate in the southern U.S. (Lake Charles: 67.1^{o}F average dry bulb temperature, 62.2^{o}F average wet bulb temperature, 1,632 CDD_{70}; Houston: 67.7^{o}F average dry bulb temperature, 62.2^{o}F average wet bulb temperature, 1,715 CDD_{70}.) For economic analysis, Houston utility rates are used. An analysis of other climates is presented in references 5 and 6.

The entire floor area modeled (16,000 ft^2) is served by one electric chiller and one gas-fired boiler. DOE-2 calculates total plant-level energy consumption for the entire five-zone floor. Equipment sizes are calculated for each run and are based on calculated peak loads. To examine the effects of orientation, we studied zone-level coil loads in which each of the zones has its own constant-volume, variable-temperature fan-coil system served by the central plant. These coil loads include the effects of thermostat setbacks, floating temperatures, and use of an economizer cycle. Where presented, these coil loads are factored by an annual COP of 3.0 to yield plant-level-comparable numbers. The annual average COP for the total building (all five zones) as calculated by DOE-2 was approximately 3.0.

RESULTS

LIGHTING ENERGY SAVINGS

Daylighting's primary effect on building energy consumption, for small to moderate effective apertures, is to reduce electric lighting requirements. As effective aperture increases from an opaque wall, electrical lighting energy consumption first drops sharply and then levels off. For a given effective aperture, the fractional savings (for all installed power densities) depend on the design illuminance level and the lighting control strategy. Figure 2 illustrates the fractional lighting energy reductions for all perimeter zones for three design illuminance levels (30 fc, 50 fc, and 70 fc) with continuous dimming switching and for an on/off (one-step) switching system and a two-step switching system (50-fc design illuminance). Lighting energy savings from skylights (not shown), follow a similar trend; however, because the skylights are diffusing and are placed above (and not to the side of) the workplane, daylight saturation is reached at an effective aperture on the order of 0.02 - 0.03.

While there are specific differences between these five curves, we see one overall trend. Lighting energy as a function of effective aperture follows a roughly exponential decrease leading to a saturation of useful daylight and no significant further savings in electric lighting energy. This daylight saturation effect begins at effective apertures between 0.10 and 0.25 for typical curtain wall designs in a perimeter zone. Beyond this point, small additional daylighting savings occur in the early morning and late afternoon while imposing heavy solar gain loads throughout the rest of the day.

References 5 and 6 provide more detailed descriptions of lighting energy savings through windows and skylights, respectively. These references show minimal climatic effects in lighting energy savings trends and only moderate differences in the overall magnitude of energy savings between climates. Because of window management, direct beam radiation is mitigated and orientation differences in lighting energy savings are small.

TOTAL ENERGY CONSUMPTION

Figure 3 shows the total annual energy and component consumption for the five-zone module, with and without daylighting. This figure assumes a continuous dimming system, an illumination setpoint of 50 fc, and an installed lighting power density of 1.7 W/ft^2. We see for both daylighted and nondaylighted cases that (1) lighting, cooling, and fan energy are the primary energy components, and (2) cooling and fan energy rise with increasing effective aperture (solar gains).

For a given aperture, daylighting lowers energy use for lighting significantly and for fans and cooling moderately. In the daylighted case, until the effective aperture at which daylight saturates the space, total energy consumption decreases or is roughly constant. After this point, the daylighting curve rises with a slope similar to that of the nondaylighted case, indicating that maximum energy savings have been attained and additional glazing only increases solar-induced cooling loads to the spaces.

PEAK DEMAND

For an effective aperture of 0.2, a near optimum with daylighting at an installed lighting power density of 1.7 W/ft^2, we present a peak electrical demand component breakdown for cases with and without daylighting in Figure 4. In both cases the annual hourly peaks occur during the same hot, humid, and sunny afternoon. The cooling component of the peak drops 7% with almost all reductions coming from that portion due to lights. The absolute level of the other portions of the cooling component (solar, equipment, ventilation, people, wall conduction, glass conduction) remain approximately the same. The largest peak component reduction is from lighting where that component drops to its minimum possible value, when perimeter lighting requirements have been reduced to the residual power requirements of the continuous dimming system.

COST SAVINGS

Annual operating energy cost savings from daylighting will largely be a function of local utility rates. In this analysis we use May 1985 utility rates for Houston, Texas, which has a relatively low peak demand charge ($0.55/kW). Peak demand charges in other Texas utilities are similar and in the Southeast somewhat higher (7). Where peak charges are more expensive, building operating costs (and thus daylighting's potential cost savings) can be greater even in climates with less extreme hot and humid weather conditions. For example, peak reductions are much more significant in New York City where charges are on the order of $15 - $20/kW. Figure 5 presents annual electricity costs per square foot of total perimeter floor area. For typical office buildings designed in the last few years with installed lighting power densities of 2.0 - 2.5 W/ft^2 the daylighting electricity savings would be approximately $0.50 - 0.60/ft^2-yr.

In new building construction, first-cost savings can be realized through reductions in required cooling equipment sizes. These savings can partially compensate for or even exceed the additional cost of installing dimming controls. In new construction, the additional cost of adding continuous dimming systems is $1.00 to $1.50/ft^2, while for retrofit construction the cost can rise to $4.00 to $5.00/ft^2. More information on lighting controls and their potential is given in references 8 and 9. The range of first-cost savings from reduced cooling system sizes is given in Figure 6 for effective apertures between 0.1 and 0.4. We assume cooling system cost reductions to be approximately $2,000/ton, which includes chillers, fans, ducts, pumps, chilled water pipes, cooling towers, etc.

Unfortunately, not all HVAC designers will necessarily downsize cooling equipment when designing for a building with daylight. We hope that these simulation studies and measured data

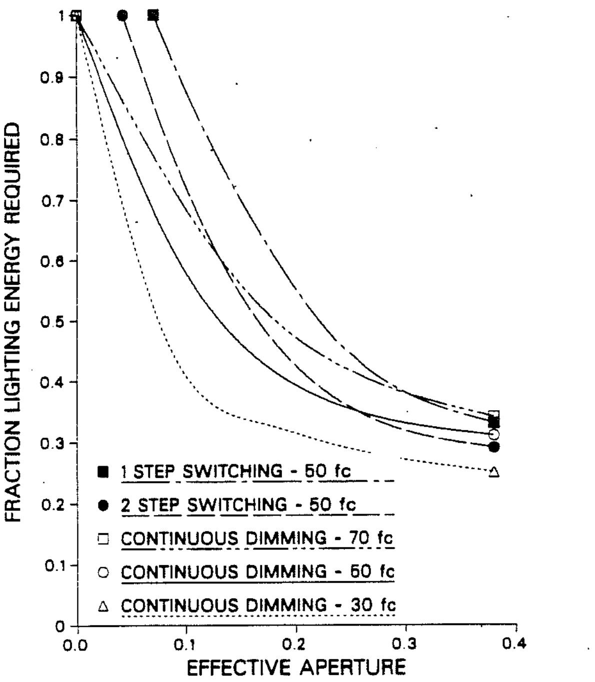

Fig. 2. Fraction of electric lighting energy required with daylighting in perimeter zones with vertical fenestration as a function of effective aperture.

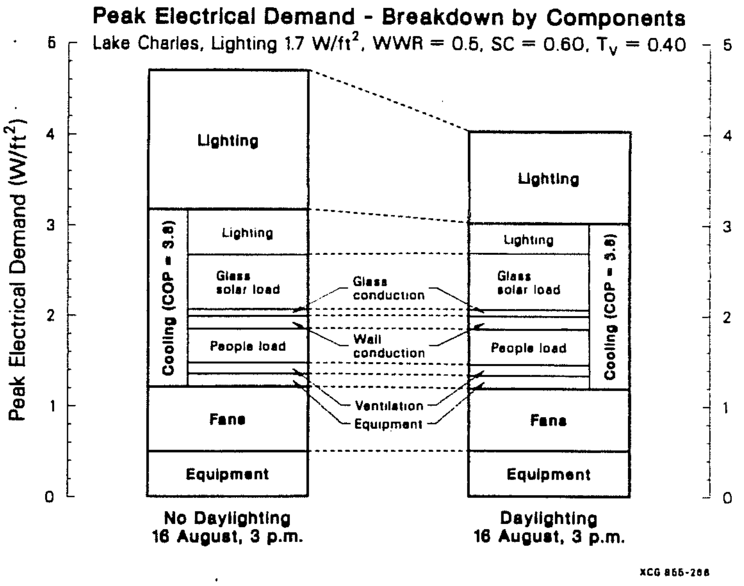

Fig. 4. Peak electrical demand, with breakdown by components, for total module. Vertical fenestration with effective aperture of 0.2 in perimeter zones.

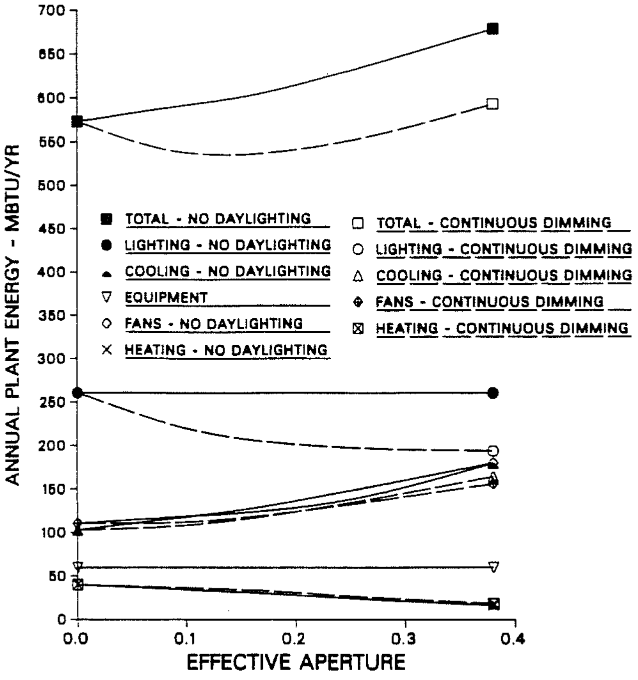

Fig. 3. Annual plant energy requirements with and without daylighting for total module as a function of effective aperture.

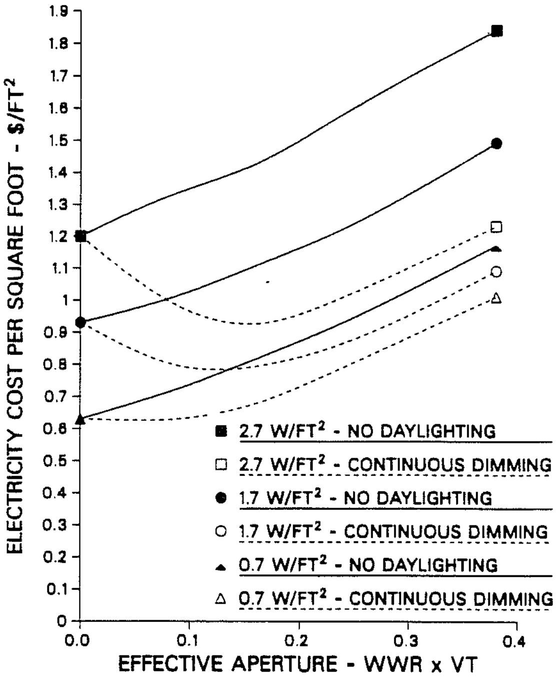

Fig. 5. Annual electricity consumption and demand costs per square foot of perimeter zones as a function of effective aperture.

from well-designed daylighted buildings will help convince the HVAC design profession to offer appropriate credit for proper daylighting and window management when sizing cooling equipment.

DAYLIGHTING'S "COOLNESS" AS A LIGHTING SOURCE

It is often stated that because the luminous efficacy of daylight (100-120 lumens/Watt) is higher than that from electric lighting systems today (60-90 lumens/Watt), daylighting is a cooler lighting source. However, this is not always true. Previous studies have examined the relationship between aperture characteristics or solar gains and interior daylight levels (2,3,10) or have assumed a constant relationship between daylight and cooling loads (11), but none have really discussed the factors governing daylight's coolness. The contribution of daylighting to cooling loads compared to other lighting sources is a function of three characteristics of the fenestration system, described below.

(1) The relative shading coefficient and visible transmittance of the fenestration system. We define the ratio of net visible transmittance to shading coefficient by K_e. (For skylights the net visible transmittance includes a well factor term and is thus T_v x WF.) For daylighting purposes, the higher the K_e, the less solar gain for a given quantity of daylight or effective aperture. Typical grey or bronze-tinted glazings have a K_e on the order of 0.67. Skylight glazings generally have a higher K_e of approximately 1.0 (not including well-light losses). Commercially available blue-green glass is the most widely available daylight-oriented glazing material, with a K_e on the order of 1.1. New selective coatings on glass can push the K_e even higher. The theoretical maximum K_e is approximately 2.0.

(2) The lighting distribution within the space as a function of fenestration orientation and glazing and room characteristics. In a sidelighted space average annual illumination levels are often three to four times higher near the window than in the back of the room. In our skylighted space, however, the average annual maximum and minimum workplane illumination differs by only about 50%. This difference is due to the fact that the skylights are diffusing and that they are uniformly distributed over the daylighted area.

(3) The time-dependent absolute solar energy transmitted through the fenestration. Because of the varying intensity of the transmitted solar radiation, interior daylight levels vary significantly depending on time of day, season and sky conditions. Moderate and large apertures provide daylighting savings on cloudy days and/or on early mornings or late afternoons. At other times (e.g., clear sky with sun) these apertures provide excess daylight (and thus excess solar gains). Fixed or operable window shading devices are one means of alleviating this. Optically switching

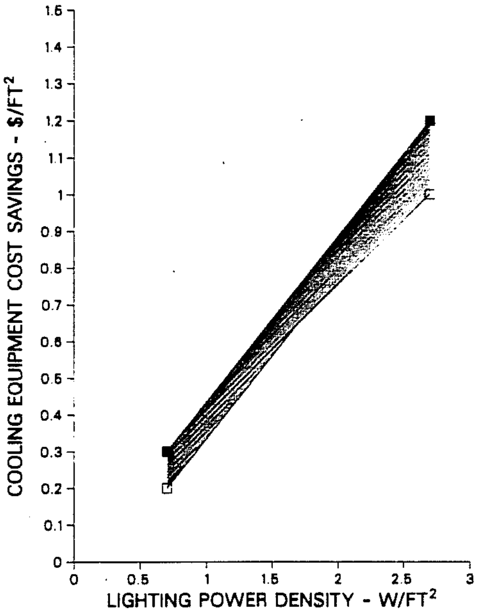

Figure 6. Potential cooling system cost savings (Houston) per square foot of daylighted floor area as a function of lighting power density.

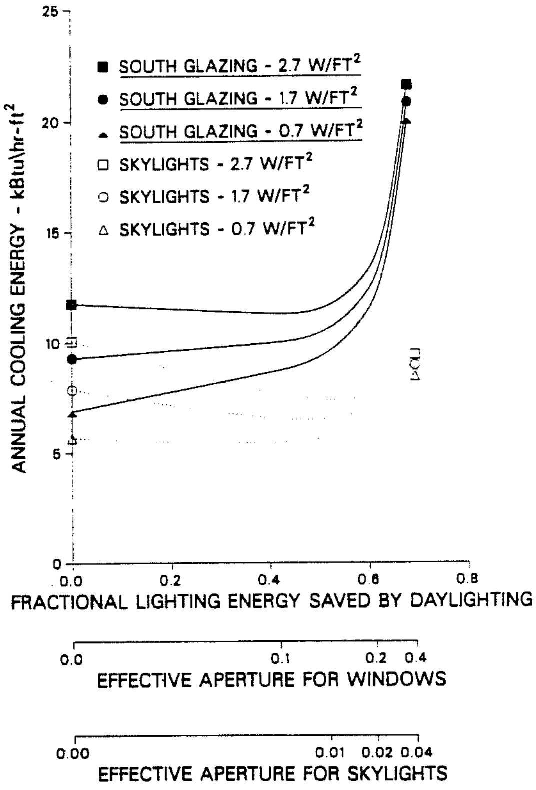

Figure 7. Annual cooling energy required per unit area of daylighted space versus the fractional electric lighting energy saved by daylighting.

glazing materials, a promising future option, are the subject of current research.

We see the results of these three trends in Figure 7, which shows annual cooling energy per square foot of floor area as a function of the fractional lighting energy saved by daylighting for both windows and skylights. Lighting energy savings from daylighting are limited because lighting is required during hours when daylight is not available and because of the minimum power fraction (10%) of the dimming system.

We first consider the cooling-lighting interactions from south vertical glazing as shown by the three solid lines in Figure 7. As the effective aperture increases from 0.0, the slope of each curve is constant until the fraction of the lighting energy savings reaches approximately 0.5. At this fractional lighting energy savings the effective aperture is approximately 0.1. Here the space is saturated with daylight. These curves then rise, soon becoming vertical. This indicates a heavy cooling penalty for minimal or no additional daylighting savings; hence we see the importance of time-dependent control of solar transmittance. We also notice that, compared to the case of an opaque wall ($A_e=0$) and all electric lighting, it is only for the daylighted case with backup lighting of 2.7 W/ft^2 (top solid curve, Figure 7) that cooling energy drops as lighting savings from daylighting increase. This implies that on an annual average, daylight is a "cooler" source of light than electric light at 2.7 W/ft^2. However, where electric lighting is more efficient than approximately 2.0 - 2.5 W/ft^2 or beyond 50% fractional lighting savings at higher lighting power densities, electric lighting is a cooler source of light. A lighting power density of 2.0 - 2.5 W/ft^2 is typical of current systems. With more advanced and energy-efficient lighting sources, the control of solar gains will become more crucial. The relative performance of daylighting with vertical glazing can be improved by addressing one or more of the three performance issues identified above.

Looking at the case of annual cooling energy as a function of fractional lighting energy saved with skylights (dotted curves, Figure 7), we see a different set of circumstances. Because the skylights modeled have a higher K_e (1.0) and because they efficiently distribute light throughout the space, daylight can lower annual cooling energy requirements relative to electric lighting power densities of 2.7 W/ft^2 and 1.7 W/ft^2 and keep cooling energy constant relative to 0.7 W/ft^2 of lighting. This implies that up to the daylight saturation point, daylight from skylights is as cool a light source as lights consuming only 0.7 W/ft^2 and maintaining 50 fc.

CONCLUSIONS

This analysis of a typical office module in a hot and humid climate shows that fenestration design, control of solar gains, and the use of daylighting are important factors in office building energy consumption. Our results, based on an hour-by-hour building energy simulation model that incorporates daylighting, first suggests several basic trends and conclusions:

(1) The concept of an effective aperture, the product of the glazing's window-to-wall ratio (or skylight-to-roof ratio) and net visible transmittance, is very useful for comparing and evaluating alternative fenestration designs.

(2) The effective use of daylight and lighting controls will provide major savings in electric lighting energy consumption.

(3) With daylighting, total annual energy consumption and the peak electrical demand can be reduced to levels below that of an opaque wall. Increasing the effective aperture too much, however, will lead to an upswing in cooling loads (and thus annual energy and electrical peak). Depending on aperture size and installed lighting power density, daylighting can result in annual cost savings of up to 40% in perimeter zones.

(4) Without daylighting, cooling equipment sizes will increase with effective aperture. With daylighting, this increase will not be as great, leading to first-cost savings which, depending on the installed lighting power density, can offset a portion of or even exceed the entire cost of daylighting controls.

(5) The installed lighting power and lighting control strategy are major factors in determining the impact of daylighting on lighting and thermal energy savings.

(6) The control of solar gains is vital if daylighting is to provide net cooling energy savings. To ensure that daylight is a "cooler" source of light than electric lights, the designer needs to:

(i) choose a fenestration system with a high daylight transmittance and a relatively low solar heat gain transmittance by using daylight-oriented glazing and/or appropriate shading systems;

(ii) consider design strategies that improve the uniformity of daylight distribution within the space, and;

(iii) if moderate or large apertures are used, be able to actively control the glazing's transmission when transmitted daylight and solar gain levels are excessive.

We remind the reader that these results are based largely on simulation studies and there are still few measured building data to verify simulation results. Changes in operating conditions or assumptions may modify some conclusions. Further developments in the DOE-2 model and its integration with other simulation models and experimental results will allow analysis of other architectural solutions (e.g., light shelves, atria, and operable shading systems). Much of the data already generated has been condensed using a multiple regression technique (12); this data base on fenestration performance could be converted into a simple but powerful design tool. We are also working on a field experimental test facility to provide the quantitative data required to further validate the algorithms used in DOE-2 (13), and have begun to collect detailed performance data on buildings.

REFERENCES

1. Building Energy Simulation Group, Lawrence Berkeley Laboratory, DOE-2 Supplement, Version 2.1B, Lawrence Berkeley Laboratory report, LBL-8706 Rev. 3 Suppl., Berkeley CA 94720, January 1983.

2. Johnson, R., Sullivan, R., Nozaki, S., Selkowitz, S., Conner, C., and Arasteh, D., "Building Envelope Thermal And Daylighting Analysis in Support of Recommendations to Upgrade ASHRAE/IES Standard 90," Lawrence Berkeley Laboratory Report, LBL-16770, Berkeley CA 92740, 1983.

3. Arasteh, D., Johnson, R., and Selkowitz, S., "The Effects of Skylight Parameters on Daylighting Energy Savings," Lawrence Berkeley Laboratory report, LBL-17456, Berkeley CA 94720, 1985.

4. Crow, Loren W., "Weather Year for Energy Calculations," ASHRAE Journal, Vol 26, No 6, pp. 42-47.

5. Johnson, R., Sullivan, R., Selkowitz, S., Nozaki, S., Conner, C., and Arasteh, D., "Glazing Energy Performance and Design Optimization with Daylighting," Energy and Buildings, Vol 6, 1984, pp. 305-317.

6. Arasteh, D., Johnson, R., Selkowitz, S., and Sullivan, R., "Energy Performance and Savings Potentials with Skylights," ASHRAE Transactions, Vol 91, Pt 1, 1985.

7. Energy Information Agency, Typical Electric Bills, DOE1E1A-0040(84), January 1984.

8. Verderber, R. R., and Rubinstein, F. M., "Mutual Impacts of Lighting Controls and Daylighting Applications," Energy and Buildings, Vol 6, 1984, pp. 133-140.

9. Verderber, R. R., and Rubinstein, F. M., "Lighting Controls: Survey of Market Potential," Energy, Vol 8, No 6, 1983, pp. 433-449.

10. Davenport, Mark R., and Nall, Daniel H., "The Correlation of Measured Interior Daylight with Calculated Solar Gains," Proceedings of the 1983 International Daylighting Conference, Phoenix, AZ, February 16-18, 1983, pp. 109-114.

11. Place, W. et. al., "The Predicted Impact of Roof Aperture Design on the Energy Performance of Office Buildings," Energy and Buildings, Vol 6, 1984, pp. 361-373.

12. Sullivan, R., and Nozaki, S., "Multiple Regression Techniques Applied to Fenestration Effects on Commercial Building Energy Performance," ASHRAE Transactions, Vol 90, Pt 1, 1984.

13. Klems, J. H., "Measurement of Fenestration Net Energy Performance: Considerations Leading to Development of the Mobile Window Thermal Test (MoWitt) Facility," Journal of Solar Energy Engineering, in press, 1985.