**Title**
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**Publication Date**
1983-06-01

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## ENERGY & ENVIRONMENT DIVISION

Presented at PASSIVE 83, the National Passive Solar Conference, Glorieta, NM, September 7-9, 1983

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Prepared for the U.S. Department of Energy under Contract DE-AC03-76SF00098

LBL-15889
EEB-W 83-09
W-148

To be presented at PASSIVE 83, the National Passive Solar Conference, Glorieta NM, September 7-9, 1983.

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

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## ABSTRACT

Effective utilization of daylight is one of several design strategies that promise to provide substantial energy savings for commercial buildings. Despite the revived interest in the field, there are very few occupied buildings for which performance data verify the magnitude and cause of real savings. In order to optimize costs it is first necessary to understand building performance in sufficient detail to assess the contradictory component impacts. This can be done most effectively using an hour-by-hour energy analysis model, in this case DOE-2.1B

This paper reports conclusions of an extensive series of computer analyses in two climates to determine the energy use and demand impacts of fenestration in commercial buildings. Particular attention is paid to the tradeoffs involved in using fenestration to daylight perimeter zones. The study includes the effects of climate, orientation, window area, U-value, shading coefficient, visible transmittance, lighting power density, and lighting control strategy.

## INTRODUCTION

In commercial buildings, fenestration design is a major determinant of energy requirements for space conditioning. Using daylight effectively will greatly reduce electric lighting requirements and associated thermal loads. Fenestration's influence on total energy performance involves a complex interaction among the fenestration's thermal and optical characteristics and other building parameters within the context of climate and orientation.

When efficient energy utilization first became a national concern, it was suggested that reducing fenestration was the appropriate response to reducing energy use. This simplistic response is frequently incorrect, but definitive performance data that include potential daylighting benefits are not available to guide architectural solutions.

Defining these benefits has been a slow process for several reasons. First, the problem is inherently complex and is linked to many aspects of commercial building performance. Second, until recently the large computer models used for energy analysis were unable to model daylighting effects accurately. There is little or no operating experience, nor are there measured performance data, on fenestration's net thermal performance, and even less information on daylighting effects. In order to understand fully the energy conservation and economic benefits of daylighting, it is necessary to consider energy consumption, thermal performance, and peak electrical demand.

Detailed data on peak electrical demands are necessary to completely analyze the cost benefits of daylight-responsive electric lighting systems and to accurately determine total electrical costs. Reducing both consumption charges and demand should provide substantial operating savings.

The studies discussed here focus on improving the understanding of the relationship between fenestration parameters and 1) electric lighting reductions due to daylighting, 2) thermal loads both with and without daylighting, and 3) the impact of daylighting strategies on building electrical demand. This will help us develop the functional interrelationships from which future cost/benefit studies can be made. This paper summarizes results of several recent studies that have examined portions of the problem in greater detail (1,2,3).

## METHODOLOGY

In order to study the effects of fenestration on building energy performance, a representative five-zone commercial office module was designed. This module consists of four identical perimeter zones, each 4.8 m (15 ft) deep, surrounding a square common core zone. The ceiling and floor were modeled as adiabatic surfaces. The overall envelope thermal conductance was held constant in order to isolate solar gain and daylighting effects. Thus when glazing area or glazing U-value was changed, the wall U-value was adjusted to maintain a constant overall envelope conductance. After basic performance patterns were established, the overall conductance was varied over a representative range. Fenestration characteristics were varied by changing number of panes of glazing, glazing area, visible transmittance, shading coefficient, and exterior shading. As base-case conditions, we assumed that occupant requirements for thermal and visual comfort result in the use of drapes or shades for any hour in which transmitted direct solar radiation exceeds 63 $W/m^2$ (20 $Btu/hr\ ft^2$), or any hour in which window luminance produces a glare index greater than 20. The interior shading device reduces solar heat gain by 40% and visible transmittance by 65%.

Electric lighting power density was varied from 13 to 34 $W/m^2$ (1.2 to 3.2 $W/ft^2$) based on a design illuminance of 538 lux (50 fc). We examined the effects of stepped switching and continuous dimming in response to daylight. A continuous dimming system dims from 100% light output with 100% power to 0% light output with 10% residual power.

The DOE-2.1B building energy analysis program used as the modeling tool incorporates a daylighting model that calculates hourly interior daylight illuminance for each zone of a building based on architectural design and hourly weather data (4,5). The primary analysis was completed for five climates that range from cooling-dominated (Lake Charles, Louisiana) to heating-dominated (Madison, Wisconsin). Total plant energy consumption was calculated for the entire five-zone module; however, in order to examine the effects of orientation, we studied zone-by-zone requirements based on zone-level coil loads. The interactions among various HVAC systems and building envelope characteristics can be important, but were not a primary issue in this study.

## RESULTS

### Energy Usage

The numerous parametric runs we completed provide a data base that demonstrates the complexity of daylighting energy analysis relative to our primary concerns—climate, orientation, and fenestration—along with other physical and operational building parameters. To simplify interpretation of results, we define a new term, effective aperture, which is the product of the ratio of glass area to floor-to-ceiling wall area times visible transmittance (or, when appropriate, shading coefficient).

The dimming system is continuously responsive to variations in daylight level and maximizes the benefit from low daylight levels. The simple stepped system reduces electric lighting power only when daylight exceeds the design criteria and provides all required lighting; at zero electric light output there is zero power consumption. Thus the step-switching system is most effective at high interior daylight levels, where it outperforms the continuous dimming system with low-level losses; step switching is least effective in situations in which low daylight levels provide only a fraction of desired illuminance.

The principal effect of daylighting is to reduce electric lighting usage. As the effective aperture increases, electrical consumption for lighting first drops off sharply then levels off in all climates. For a given effective aperture, the fractional savings depend on the design illuminance level lighting power density and the lighting control strategy. Figure 1 illustrates the change in fractional lighting energy savings as a function of effective aperture for three design illuminance values with a stepped system. For small aperture areas the savings are not linear with respect to design illuminance level. For larger aperture areas the shape of the curves indicates that daylighting becomes saturated and further savings not possible.

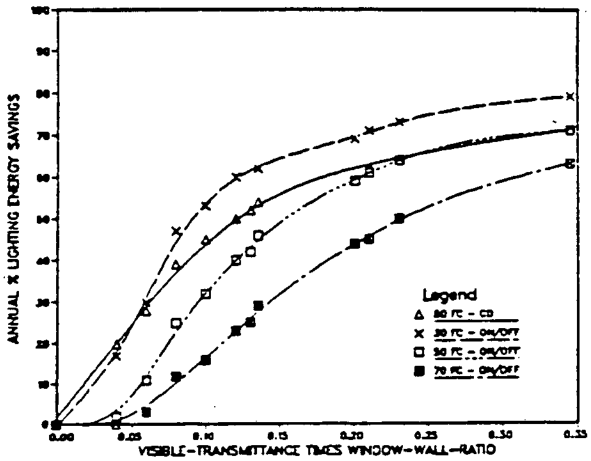


Fig. 1. Lighting energy savings as a function of effective aperture. Madison: 1.7 $W/ft^2$.

The choice of lighting control strategy has several consequences. Figure 2 illustrates lighting energy consumption in Madison with a dimming control and a stepped control both set to 538 lux (50 fc). For small apertures, the dimming control always outperforms the stepped system because for many hours the available daylight is below the control setpoint, allowing partial savings with the dimming system but none with the switched control. As the aperture increases, the difference between the two is reduced. Eventually the switched system outperforms the dimming system because of the dimming system's low-end operating characteristics. This pattern appears in all climates and orientations.

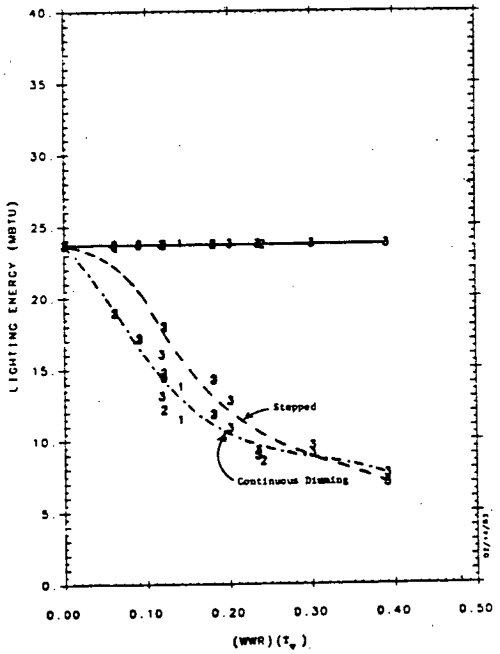


Fig. 2. Lighting energy use as a function of effective aperture. Madison: 1.7 W/ft$^2$.

Total electric lighting energy savings can be substantial. Approximately 50 to 80% of electric lighting in the perimeter can readily be saved. Note, however, that the savings saturate at moderate effective apertures of 0.2 to 0.3. This suggests that for a 538-lux (50-fc) setpoint, a 50% glazed wall with 50% transmittance or a 30% glazed wall with 80% transmittance will provide most of the possible daylighting savings in a typical perimeter zone. Walls that are fully glazed from a 0.8 m (30 in.) high sill to ceiling have 71% glazing and would provide most of the potential savings with a transmittance as low as 30%. These moderately-transmitting products may also reduce discomfort from glare. However, the highly reflective architectural glasses in common use, which have 8 to 14% daylight transmittance, provide substantially lower daylighting savings. These glazings emphasize sun and glare control at the expense of daylight transmittance. Note that if the design illuminance level was lowered to 323 lux (30 fc), a level that might be used for ambient lighting only, savings in all the above cases would increase, notably with the very low-transmittance glazings.

During winter months, the balance point of a zone shifts when the electric lighting is reduced and additional heating energy is consumed. The magnitude of the heating load increase depends on orientation. The worst case occurs in a north zone, which can show a 25% increase for large effective apertures. However, for the south zones the increase can be much smaller, about 5%. This is because the solar gain that was useless when the electric lights were on is now available to offset part of the increased heating load. In the summer, reduced electric lighting diminishes cooling loads. An overall picture of total zone energy consumption as a function of orientation, glazing parameters, and lighting load is shown in Fig. 3, which presents total energy results for a south zone in Madison for two different lighting loads: 12.9 and 23.7 W/m$^2$ (1.2 and 2.2 W/ft$^2$). The solid curves (for the nondaylighted cases) rise monotonically for all effective apertures. We show curves for the two daylighted cases, one for continuous dimming, and one for step switching. The continuous dimming system outperforms step switching for small effective apertures, but the curves cross and change relative positions for larger apertures.

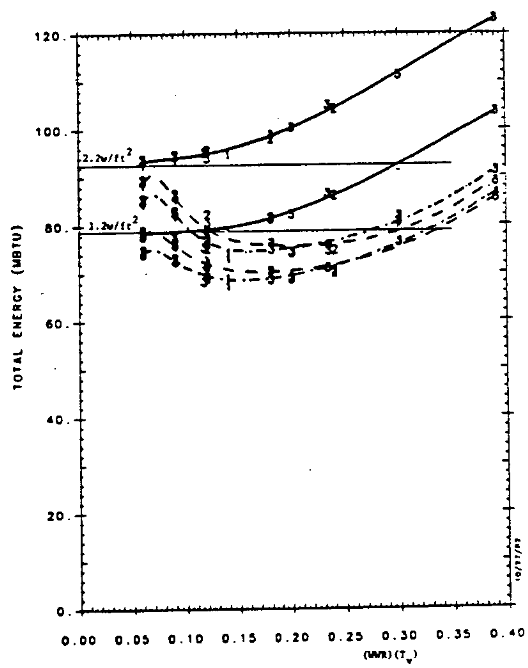


Fig. 3. Annual energy requirement as a function of effective aperture. Madison: south zone.

For this south orientation an optimum effective aperture is reached, after which total energy consumption increases, dominated by the rising cooling load. In this case there is a more obvious tradeoff between cooling and daylighting, and the optimum solution is more sensitive to installed lighting power. For 23.7 W/m$^2$ (2.2 W/ft$^2$) installed lighting load, the optimum effective aperture ranges between approximately 0.12 and 0.22. However, even at the largest value studied (approximately 0.4), the consumption with daylighting just equals that of an opaque insulated wall. If we drop to an installed lighting load of 12.9 W/m$^2$ (1.2 W/ft$^2$) on the south zone, the optimum shifts somewhat to smaller effective apertures and is less broad. In addition, the energy requirement in the daylighted case now equals that of an opaque wall for an effective aperture of 0.33 and exceeds it for greater aperture values. A comparison between north and south zone performance shows that the relative differences are small up to an effective aperture of 0.15 - 0.2 for the nondaylighted case, after which the south zone's total energy requirement rises steeply relative to the north's. This occurs even though heating requirements are reduced more rapidly in the south zone as effective aperture increases, results entirely from the large increase in cooling requirements.

Figure 3 also shows that the slope of the increase in energy consumption generally rises faster for the nondaylighted cases than for the daylighted cases through the range of interest. This rise indicates 1) that daylighting effectively reduces electric lighting consumption, and 2) daylighting's thermal impact is proportionally less than electric lighting's. However, for more efficient electric lighting systems with low installed power densities, the two curves are essentially parallel. This suggests that daylighting's contribution to cooling load is approximately the same as electric lighting's, which is to be expected with electric lighting of comparable efficacy.

This result challenges the popular belief that daylighting strategies always produce a lower cooling load than electric lighting. While the nominal efficacy of daylight as luminous flux (100 - 130 lumens/watt) is substantially higher than the efficacy typical of fluorescent lamps (60 - 90 lumens/watt), an "effective annual efficacy" for daylighting can be estimated in much the same way that lighting system efficacy can be calculated. The equivalent value for electric lighting is about 40 lumens per watt, which is obtained by dividing the design illuminance value (538 lux or 50 fc) by the installed power density (12.9 W/m$^2$ or 1.2 W/ft$^2$). The equivalent instantaneous value for a daylighted case could be calculated and then averaged over a year, but we observe that, for the specific power density at which the slopes of the curves are similar, the "effective annual efficacy" of the daylighted system must just equal that of the electric system, which can be readily calculated. This occurs at about 16.1 W/m$^2$ (1.5 W/ft$^2$), resulting in an efficacy of about 33 lumens/watt for daylight, far lower than the source characteristics. This is due primarily to variation in daylight intensity with time and to non-uniform distribution in the daylighted room.

## Peak Analysis

Unless electricity is the primary heat source in a cold climate, electrical consumption in office buildings typically peaks during summer months when cooling requirements are at a maximum. In this study heating was supplied with a gas-fired boiler and cooling was provided with an open centrifugal chiller. Therefore, the conclusions of this study are limited to summer peaking. Results might change if a heat-pump system was used.

Figure 4 shows that daylight from moderate-to-large effective apertures can reduce total building peak demand by 14-15% in Madison, compared to a nondaylighted building with identical glazing when the electric lighting is 18.3 W/m$^2$ (1.7 W/ft$^2$) (compare curves B and D). In this case the daylighted perimeter floor space is only 37% of the total. The fraction of total building peak demand saved will vary with the perimeter/core ratio.

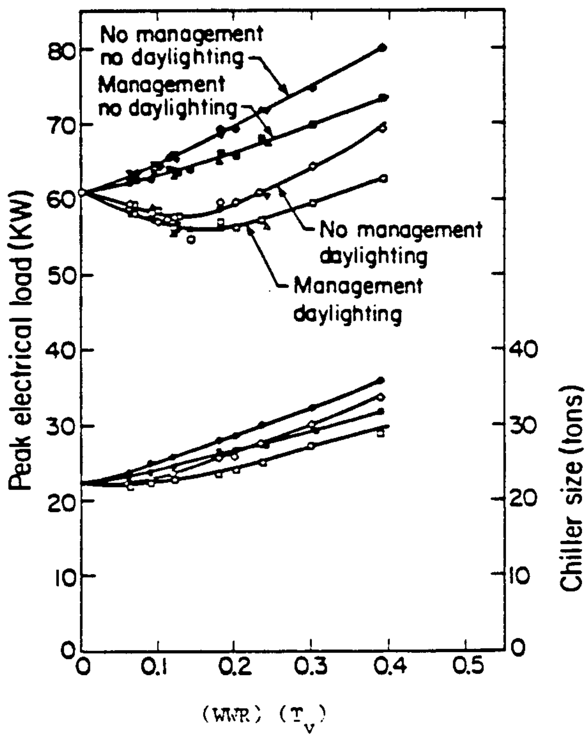


Fig. 4. Peak load and chiller size as a function of effective aperture. Madison: 1.7 W/ft$^2$.

A plot of required chiller size as a function of effective aperture is included in Fig. 4. Chiller size increases continuously with effective aperture even in the daylighted cases. This pattern contrasts with the peak load patterns, which show an intermediate value of effective aperture for the minimum peak loads. The data for Madison indicate that the incremental chiller savings due to reduced lighting loads occur at low aperture values and remain constant, while the incremental adverse impact of solar gain continues to increase as aperture size increases. These results emphasize the importance of control of solar gain if daylighting is to be successfully utilized to control peak demand.

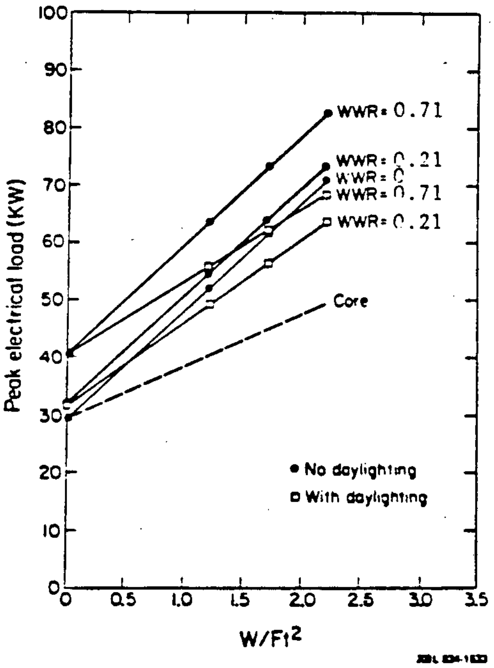


Fig. 5. Peak load as a function of lighting power density. Madison: $T_v$ = 0.69.

The results described above also depend on installed lighting power density. When the installed electric lighting is very efficient, daylighting without window management requires a larger chiller than window management without daylighting. When installed electric lighting power density is above 21.5 $W/m^2$ (2.0 $W/ft^2$), daylighting is always beneficial in terms of chiller size. Chiller size is approximately linearly dependent on electric lighting level regardless of daylighting and window management, although the rate of increase will vary with the conservation strategies utilized.

Peak electrical demand as a function of installed electric lighting power density for Madison is shown in Fig. 5. Changes in installed lighting power are assumed to represent hardware changes that increase or decrease luminous efficacy. In all cases the illuminance design criterion remains 538 lux (50 fc). For the nondaylighted cases, including a building having no windows, the relationship between peak demand and electric lighting power is linear and the plots for different values of window area or shading coefficient are parallel. However, for daylighted cases, the relationship between peak and lighting load becomes more complex.

In Madison the three nondaylighted cases (solid lines) represent glazing areas of 0%, 21%, and 71%, respectively. These have essentially the same slope. The value includes the cooling impact of lighting as well as the effect of operating schedules. These schedules assume that 90% of the installed lighting power is operating during most daytime hours. These values represent results for core and perimeter zones combined. If we examine results from the perimeter zone alone, we find that, at peak conditions with small windows (August 31, 3 pm), the electric lighting is operating at about 30% power. For large windows, the lighting is operating at its lowest limit, 10% power. All the peak demands plotted in Fig. 5 (both daylighted and nondaylighted) occurred between 3 and 5 pm on August 31.

## SUMMARY AND CONCLUSIONS

Daylighting is potentially an important design and conservation strategy in nonresidential buildings. Results from an hour-by-hour simulation model that accounts for daylighting impacts help refine our understanding of this complex subject. An extensive set of parametric analyses for a simple office module in several climates suggests the following generalizations:

1. Increasing window area and/or transmittance to increase daylighting savings reaches a point beyond which total energy consumption increases due to greater cooling loads.
2. Control of solar gain is vital if daylighting strategies are to provide net energy benefits.
3. Managed windows without daylighting controls may require less energy than unmanaged windows with daylighting.
4. Daylighting may not always be a "cooler" light source than fluorescent lighting—the conditions under which this statement holds true depend on the details of window management and installed lighting power.
5. Daylighting strategies provide peak demand management opportunties, but the results are climate-sensitive.
6. Daylighted buildings may have lower total peak electrical demand, but may require larger cooling systems than non-daylighted buildings with smaller windows.
7. Installed lighting power and the lighting control system characteristics are major factors in determining the real value of daylighting strategies.
8. Most of the conclusions above are sensitive to climate, orientation, and other building modeling assumptions.

While we believe that these results represent the most comprehensive perspective to date on this subject, we remind the reader that there are still very few measured building data to verify simulation results. Changes in base-case conditions and operating assumptions may also modify some conclusions.

Our work continues to extend these results to include a broader range of fenestration designs. Further development of the DOE-2 model to allow analysis of other architectural solutions (e.g., light shelves, atria) is in progress and is described in Ref. 6. We believe that the regression techniques that we used (3) to simplify the representation of a large data set could also be used to convert our data set to a simple, yet powerful, design tool (7). We are also working on experimental projects to provide the quantitative data required to build confidence in the algorithms used in the simulation models (8), and have begun to collect detailed performance data in several innovative daylighted buildings.

ACKNOWLEDGEMENT

We gratefully acknowedge the assistance of our colleagues Dariush Arasteh, Craig Conner, and Shirley Nozaki.

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

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