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ABSTRACT

Fenestration can have a significant impact on the net annual energy consumption of buildings. Proper design and effective management of fenestration can provide substantial energy savings. In order to maximize energy benefits and minimize costs, it is necessary to understand building energy performance in sufficient detail to assess component impacts. This paper reports conclusions of an extensive series of computer analyses of annual energy use and electrical peak demand in two climates as functions of fenestration parameters. Particular attention is paid to daylighting and its associated energy tradeoffs. The study includes the effects of climate, orientation, glazing area, U-value, shading coefficient, visible transmittance, lighting power density, and lighting control strategy.

The extensive set of parametric analyses generated in this study suggest that for a simple office module, fenestration can provide annual net energy savings in all climates if daylighting is used. Control of solar gain is critical to realization of energy benefits from daylighting. Fenestration and daylighting design strategies that reduce net annual energy consumption can also reduce peak electrical demand. The optimum combination of fenestration variables is a function of climate, orientation, and electric lighting power density.

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INTRODUCTION

Fenestration design in commercial buildings is a major determinant of energy requirements for space conditioning. The impact can be a severe penalty or a substantial benefit depending on both architectural design decisions and building operation. Fortunately, those solutions offering the maximum energy benefits also frequently offer the most comfort, both thermal and visual, to occupants. Achieving these benefits requires a detailed understanding of component energy impacts and interactions and a sensitivity to architectural design issues. Net annual energy performance involves a complex interaction among the thermal and optical characteristics of fenestration and other building parameters, both design and operational, within the context of climate, site, and orientation.

The best understanding of these complex interactions would ideally derive from performance data from real buildings. There are, however, few or no measured performance data of sufficient detail on fenestration's net thermal performance and even less information on daylighting effects. Additionally, even if such data were available it would be difficult or impossible to analyze because of the disparity among buildings. A viable alternative, then, is to use computer modeling to systematically examine the effects of fenestration variables.

In order to fully understand the energy and economic impacts of fenestration, it is necessary to consider energy consumption, thermal performance, lighting performance, and peak electrical demand. We have studied these issues in detail using DOE-2.1B as the primary analysis tool, parametrically varying the important fenestration and electrical lighting variables in two climates, one cooling-dominated and the other heating-dominated. Statistical analysis was then used to establish functional correlations from the results of an extensive number of DOE-2 runs. This paper summarizes results of these studies, which are discussed in more detail elsewhere. (1,2,3)

The results discussed here focus on improving the understanding of the energy performance relationships between fenestration parameters and 1) electric lighting reductions due to daylighting, 2) thermal loads both with and without daylighting, and 3) the impact of fenestration on peak electrical loads with and without daylighting. An understanding of these relationships will help in the future development of functional correlations from which cost/benefit studies can be made.

METHODOLOGY

In order to systematically study the effects of fenestration on building energy performance, a representative five-zone commercial office module was designed for which fenestration characteristics were parametrically varied. This module consists of four identical perimeter zones, each 4.8 m (15 ft) deep, surrounding a square common core zone (Fig. 1). The ceiling and floor were modeled as having no net heat transfer. The overall envelope thermal conductance was held constant in order to isolate solar gain and daylighting effects. Thus when glazing area or 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 U-value, glazing area, visible transmittance/shading coefficient (with visible transmittance always equal to two-thirds of shading coefficient), and exterior shading. A simple window management system was assumed in which 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%.

Based on a maintained design illuminance of 538 lux (50 fc), electric lighting power density was varied from 13 to 34 W/m^2 (1.2 to 3.2 W/ft^2). We examined the effects of stepped switching and continuous dimming in response to daylight. The 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) Extensive analysis was completed for five climates that range from cooling-dominated (Lake Charles, Louisiana) to heating-dominated (Madison, Wisconsin). More limited analysis was completed for an additional nine climates in order to provide sufficient data for climate generalization. This paper reports results from Madison and Lake Charles as the bounding case of the study.

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 using a separate, constant-volume, variable-temperature system in each zone. Heating is provided by a gas-fired boiler that has an efficiency of 0.6;

cooling is provided by an electrically-driven centrifugal chiller having a COP of 3.0. The interactions among various HVAC systems and building envelope characteristics can be important, but were not a primary issue in this study.

RESULTS: ENERGY USE

From the numerous parametric runs completed we compiled a data base that demonstrates the complexity of fenestration energy analysis relative to our primary concerns of climate and orientation, along with other physical and operational building parameters. To simplify interpretation of results, we use a lumped parameter that is the product of the ratio of glass area to floor-to-ceiling wall area times visible transmittance (WWR)(T_v). We call this lumped parameter the effective aperture; its use allows one conveniently to compare energy performance of dissimilar fenestration designs. Plotting annual energy use in a perimeter zone as a function of effective aperture allows one quickly to assess the potential impact of fenenstration.

Looking first at the cold climate of Madison, annual energy use for the north zone is presented in Fig. 2 and for the south zone in Fig. 3. In both cases, the glazed condition, represented by the solid curve, marginally outperforms the opaque wall, represented by the horizontal line. In this heating-dominated climate with a moderate lighting power density of 1.7 W/ft^2, internal loads are sufficiently low that solar gain offsets enough heating load to more than compensate for the cooling penalty. Higher lighting power densities or different HVAC operating efficiencies can easily change this relationship. If one, however, takes advantage of available daylight to offset electric lighting, then substantial energy benefits are available, as represented by the dashed curves. Clearly, daylight utilization is the key to energy savings with windows.

The electric lighting energy requirements shown in Fig. 4 explain the major contribution to these savings and why daylighting is important. The dimming system continuously responds 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. The step-switching system, thus, is most effectively applied when high interior daylight levels prevail; here it outperforms the continuous dimming system with its low-level losses. Step switching is least effective in situations in which low daylight levels provide only a fraction of desired illuminance.

For small apertures, dimming control always outperforms the stepped system because for many hours the available daylight level is below the control setpoint, allowing partial savings with the dimming system but none with the switched control. As aperture size increases, the difference between the two is reduced. Eventually the switched system outperforms the dimming system because of the dimming system's low-end power requirement. This pattern appears in all climates and orientations.

The principal effect of daylighting is to reduce electric lighting use. As 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 and the lighting control strategy. Figure 5 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 apertures, the savings are not linear with respect to design illuminance level. For larger apertures the shape of the curves indicates that daylighting saturates and further savings are not possible.

Total electric lighting energy savings can be substantial. Approximately 50-80% of electric lighting in the perimeter can readily be saved. Note, however, that the savings approach maximum 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. The highly reflective architectural glasses in common use, however, 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.

For the 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 an obvious tradeoff between cooling and daylighting, and the optimum effective aperture ranges between approximately 0.20 and 0.30. A comparison between north and south zone performance shows that the relative differences are small with small effective apertures (0.0 - 0.2) for the nondaylighted case, but with larger apertures the south zone's total energy requirement rises while the north's continues to decline. This occurs even though heating requirements are reduced more rapidly in the south zone as effective aperture increases, and is due entirely to the large increase in cooling requirements. The daylighted cases exhibit the same trends, but the negative impact of cooling in the south zone is considerably diminished.

These curves indicate 1) that daylighting effectively reduces electric lighting consumption, and 2) that daylighting's thermal impact is less than that of electric lighting. However, for more efficient electric lighting systems having lower installed power densities, the daylighting benefits diminish. The daylighted and nondaylighted curves are then 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.

Analogous results for Lake Charles are presented in Figs. 6 and Fig. 7. With minimal heating requirements, solar gain offers no heating season benefit and any amount of glazing results in a cooling load penalty. In this nondaylighted condition, increasing effective aperture increases the net annual energy consumption. The rate of increase on the north orientation is rather small, being a function primarily of diffuse radiation. On the south, however, the rate of increase nearly doubles. Daylighting, however, turns windows from energy liabilities to energy assets in this cooling-dominated climate. Now both north and south orientations exhibit optimum effective apertures. The south zone optimum effective aperture is quite small, about 0.11, indicating a requirement for both small glass areas and low shading coefficients. Even with this severe cooling penalty, the largest effective aperture studied, 0.3, gives lower annual energy consumption with daylighting than an opaque wall.

RESULTS: 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 electrically driven 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 8 shows that fenestration imposes substantial peak demand penalties unless daylighting is used. 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). Furthermore, daylighting can reduce peak load to below that of opaque wall, (WWR)(T_v) = 0.0. In this case the perimeter zone floor space is only 37% of the total. The fraction of total building peak demand saved will vary with the perimeter/core ratio.

A plot of required chiller size as a function of effective aperture is included in Fig. 8. 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 with daylighting. The data for Madison indicate that chiller size reductions with daylighting occur at low aperture values. While daylighting benefits continue to increase, the incremental adverse impact of solar gain increases more rapidly as effective aperture increases. These results emphasize the importance of controlling solar gain if daylighting is to be successfully utilized to control peak demand.

The results described above also depend on installed lighting power density. When the 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 used.

Peak electrical demand as a function of installed electric lighting power density for Madison is shown in Fig. 9. 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 effective aperture are parallel. However, for daylighted cases, the relationship between peak and lighting load is not parallel.

In Madison the three nondaylighted cases (solid lines) represent effective apertures of 0, 0.14, and 0.49, respectively. These have essentially the same slope. The value of peak demand includes the cooling impact of lighting as well as the effect of operating schedules. These schedules assume that 90% of the installed lighting power operates during most daytime hours. These peak demands represent results for core and perimeter zones combined. If we examine results from the daylighted 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. 9 (both daylighted and nondaylighted) occurred between 3 and 5 pm on August 31.

SUMMARY AND CONCLUSIONS

Fenestration is potentially an important design and conservation strategy in nonresidential buildings. The importance is intimately related to daylighting and solar control. 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 frequently reaches a point, depending on climate and orientation, 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 opportunities, but the results are climate-sensitive.

6. Daylighted buildings may have lower <u>total peak electrical demand</u>, but may require larger cooling systems than nondaylighted buildings having 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 above conclusions 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 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 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, as 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

This paper summarizes results of a number of studies (see references) on the energy and peak load impacts of fenestration in nonresidential buildings. Our colleagues D. Arasteh, S. Choi, C. Conner, and S. Nozaki provided essential contributions to those studies.

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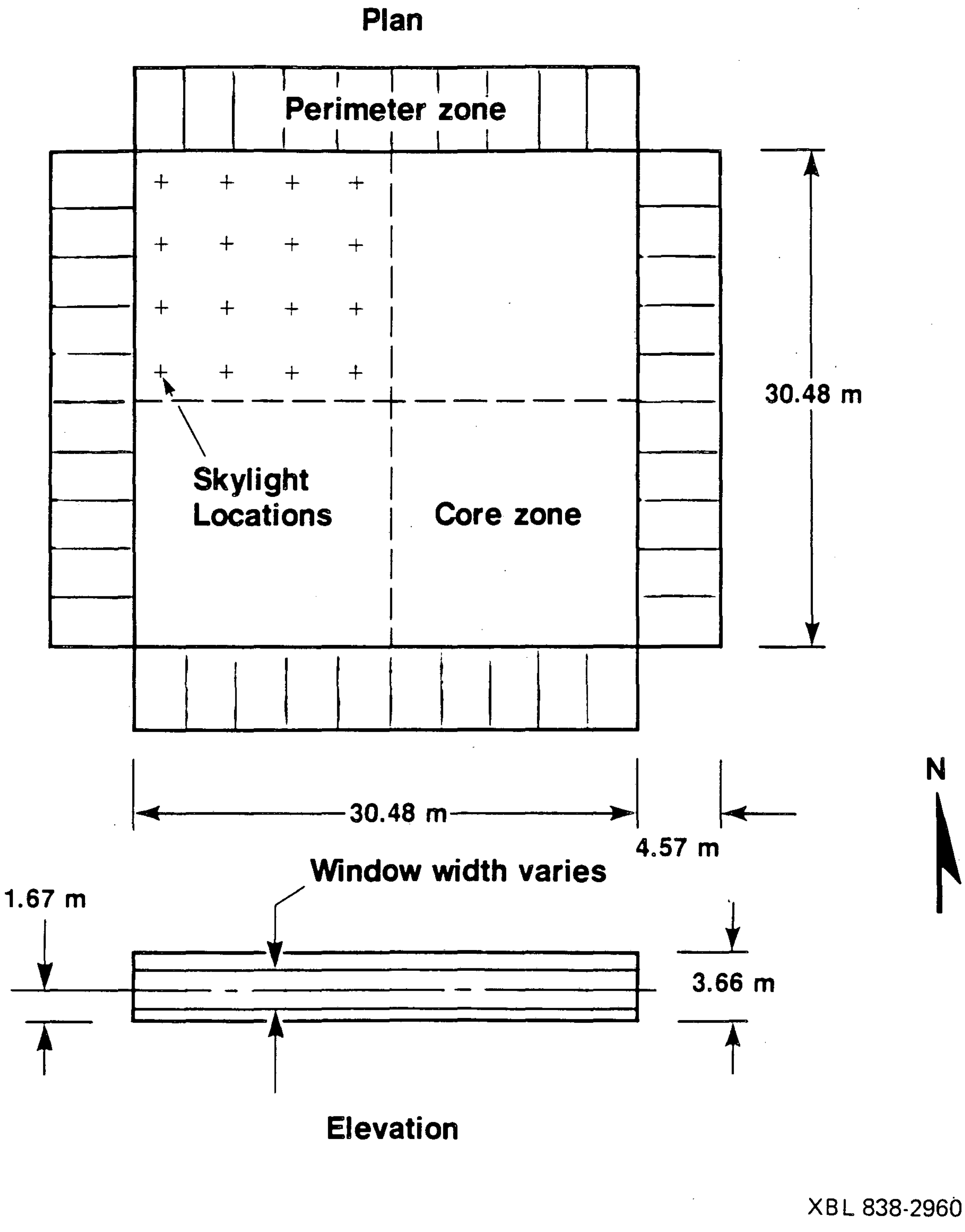


Figure 1 Building module floor plan and elevation.

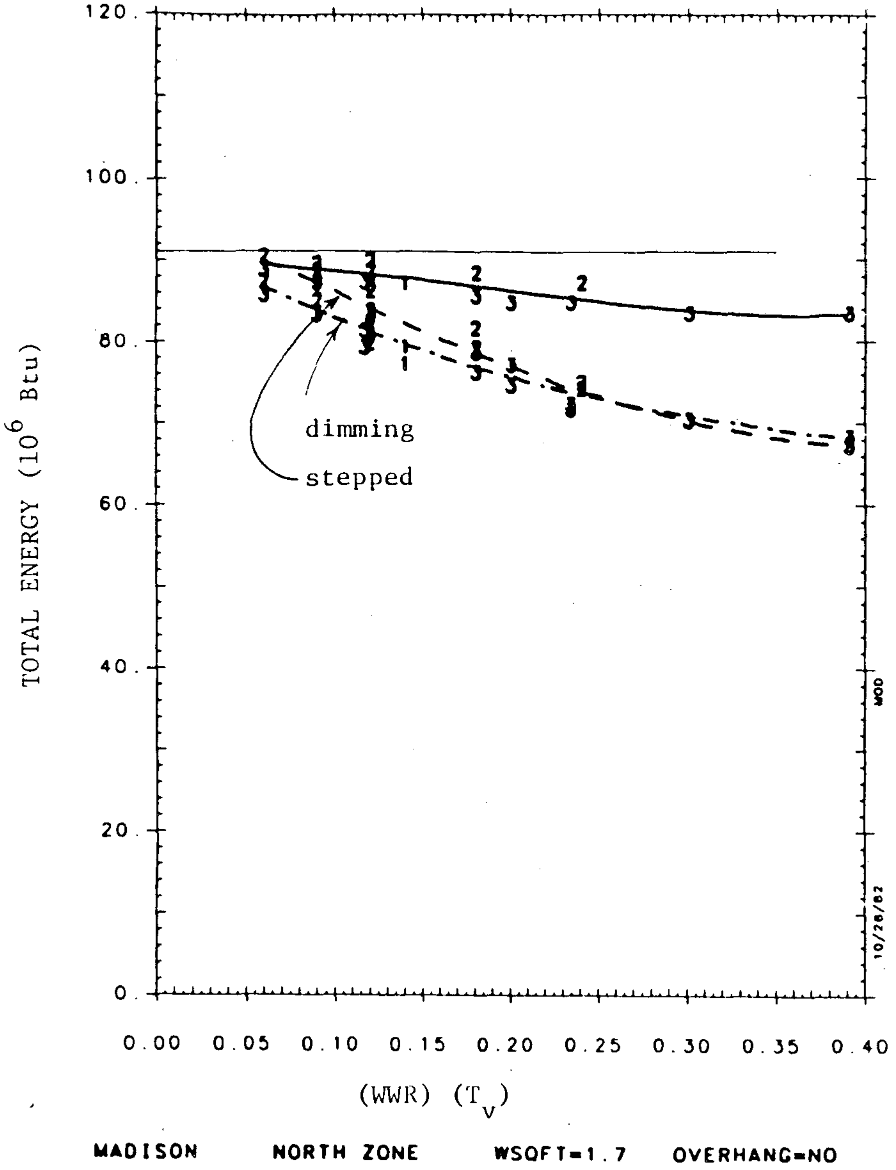


Figure 2 Annual energy consumption with and without daylighting.

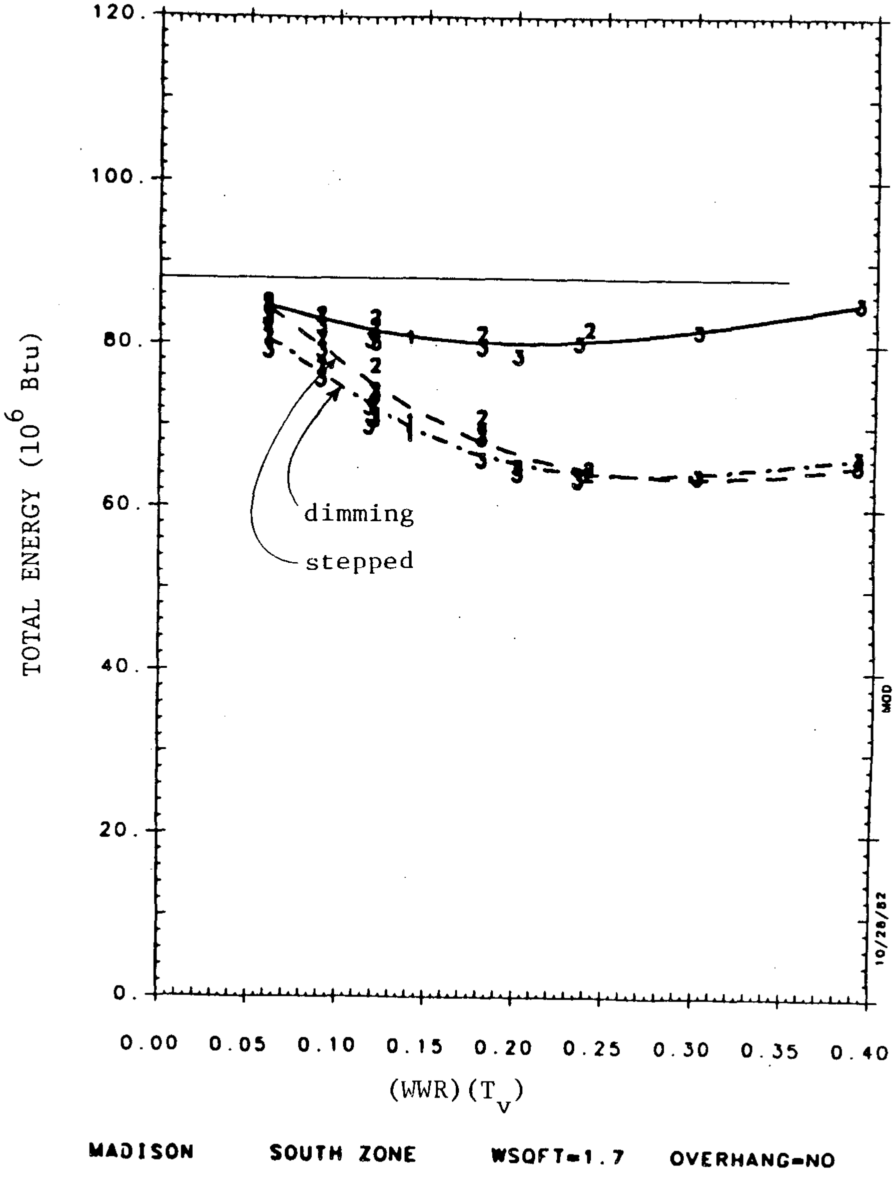
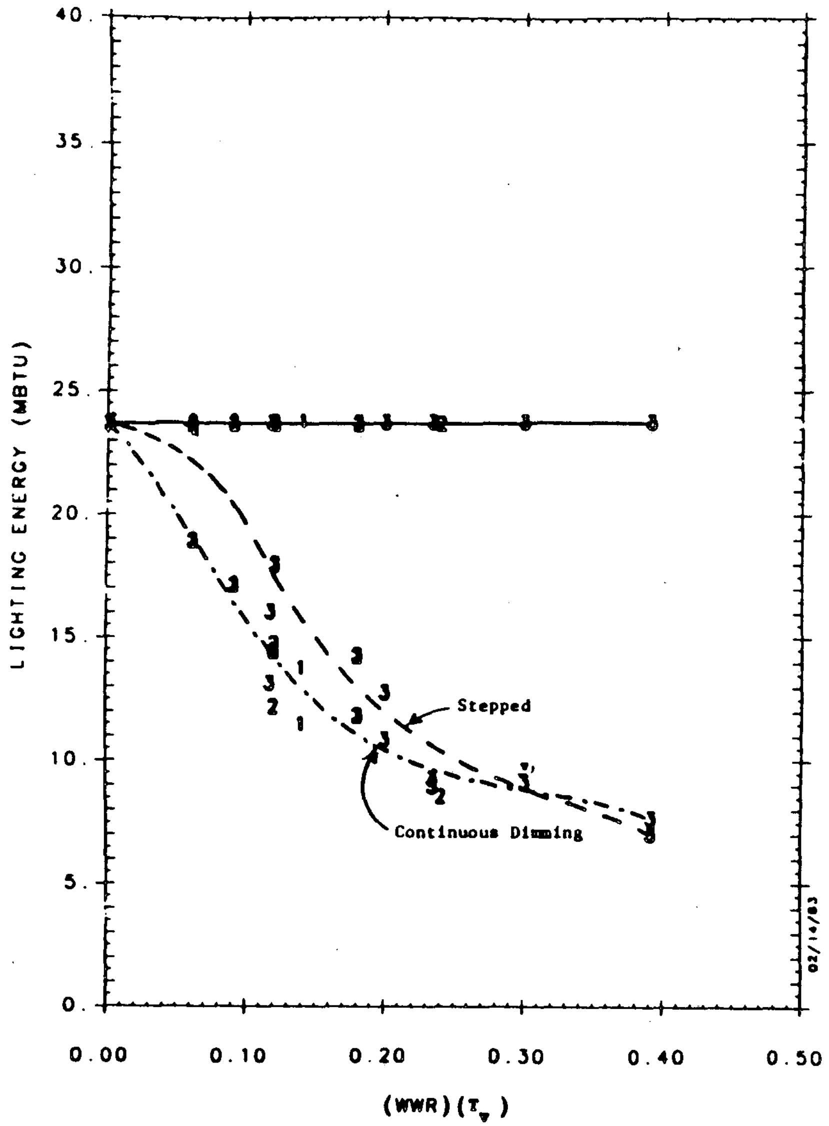
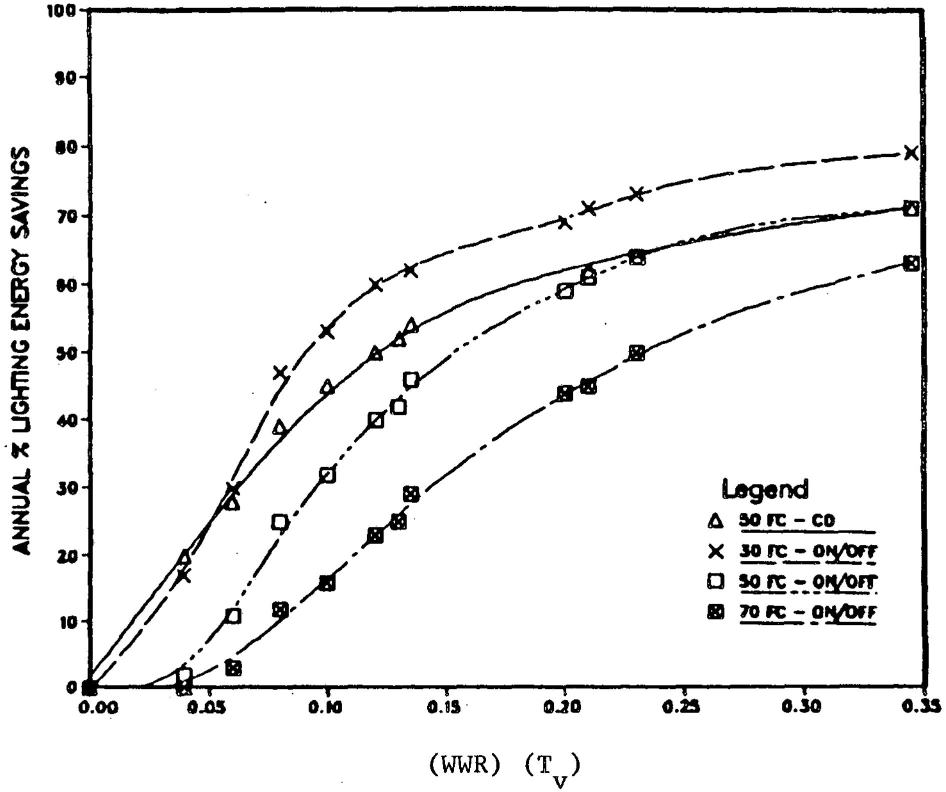


Figure 3 Annual energy consumption with and without daylighting.



MADISON SOUTH ZONE WSQFT=1.7

Figure 4 Annual electric lighting energy requirements using stepped and dimming controls with daylighting.



Madison: 1.7 W/ft^2

Figure 5 Annual electric lighting energy savings with daylighting.

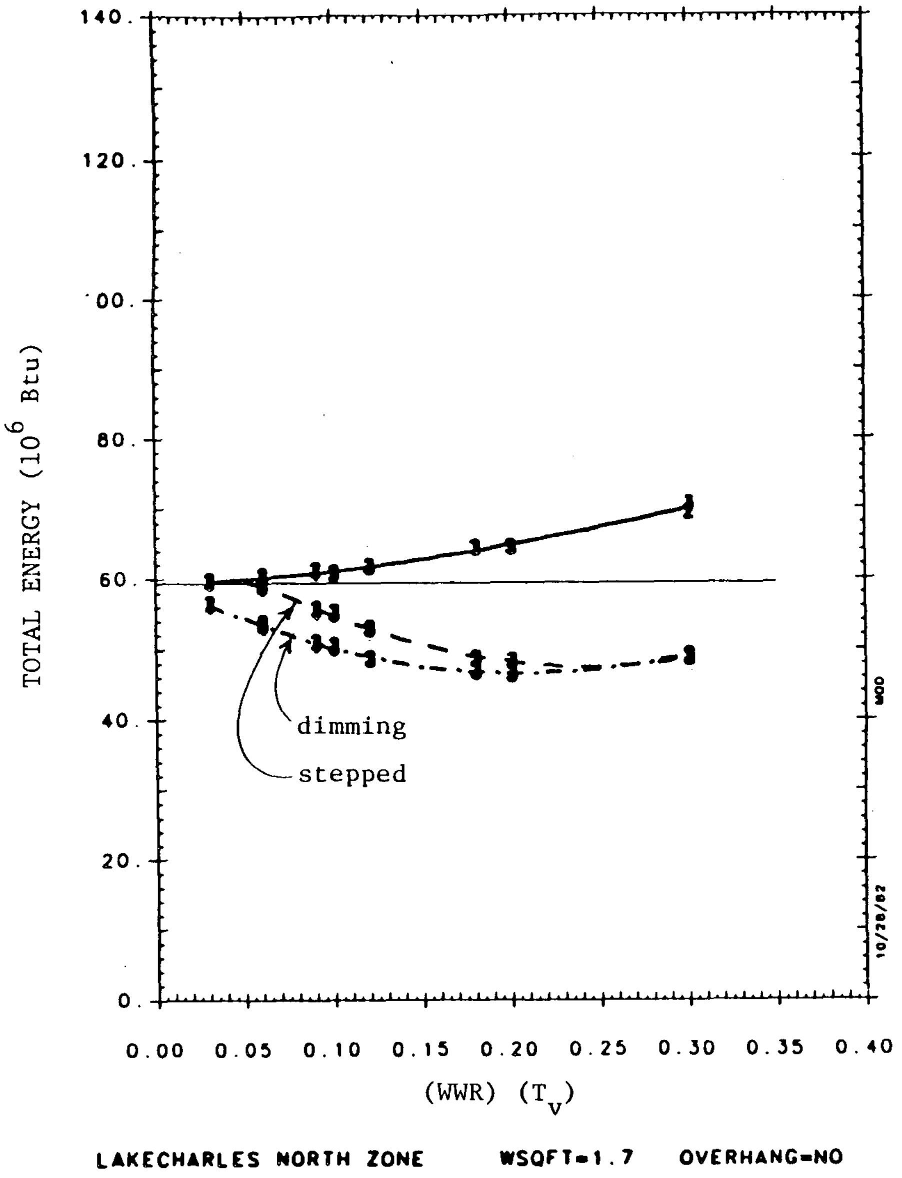


Figure 6 Annual energy consumption with and without daylighting.

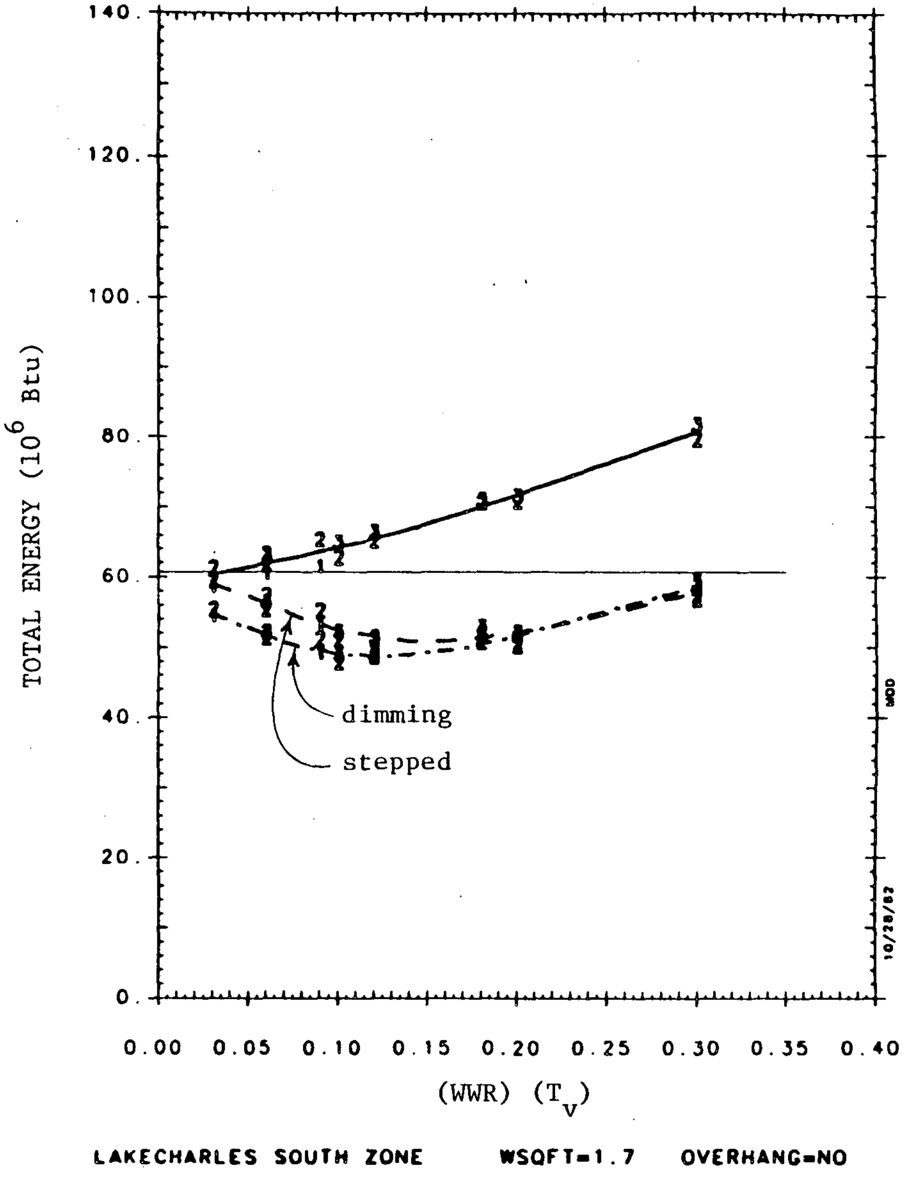


Figure 7 Annual energy consumption with and without daylighting.

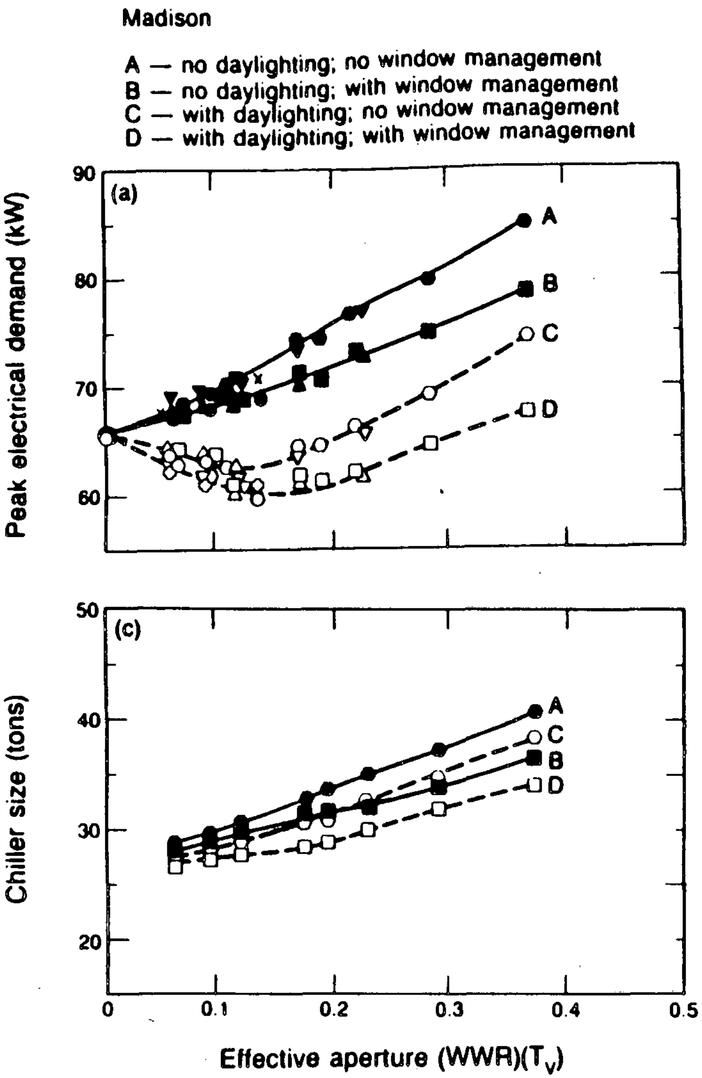


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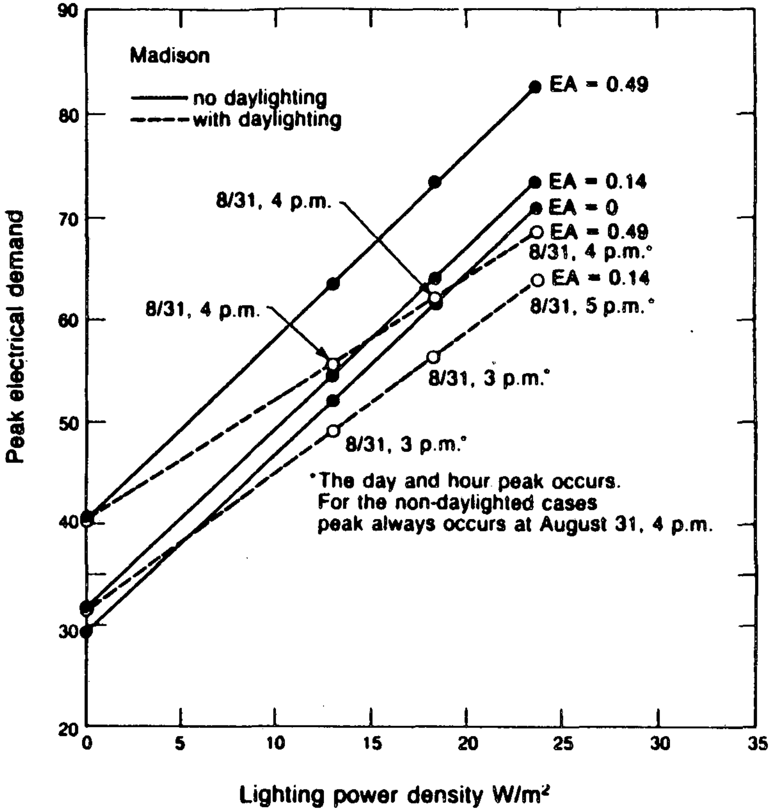
Figure 8 Peak electrical demand and chiller size with and without daylighting.



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EA = effective aperture

Figure 9 Peak electrical demand as a function of electric lighting power density.

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