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ABSTRACT

A complete analysis of the cost-effectiveness of daylighting strategies should include the impact of daylighting on peak electrical demand as well as on energy consumption. We utilized an hour-by-hour building energy analysis program to study the thermal and daylighting impacts of fenestration on peak demand. Fenestration properties and lighting system characteristics were varied parametrically for office buildings in Madison WI and Lake Charles LA. Peak electrical demand was disaggregated by component and by zone, monthly patterns of peak demand were examined, and impacts of fenestration performance on chiller size were studied. The results suggest that for daylighted office buildings, the peak electrical demand results from a complex trade-off between cooling load due to fenestration parameters, lighting load reductions due to glazing and lighting system characteristics. Lowest peak demands generally occur with small to moderate size apertures. With daylighting, peak electrical demand is reduced by 10 to 20% for the building configuration studied (37% perimeter zone, 63% core zone). This work indicates that solar gain through fenestration must be effectively controlled in order to realize the potential of daylighting to significantly reduce peak electrical demand.

INTRODUCTION

Electric lighting is generally a large component of energy consumption in commercial buildings. Daylighting, which can reduce both electric lighting energy consumption and peak electrical demand, has become widely accepted as an important energy-conserving strategy. The benefits of daylighting in reducing annual energy consumption are discussed in a companion paper and in several other publications [1-5]. Fully understanding all the cost benefits of daylight utilization requires considering daylighting´s potential for reducing peak electrical demand.

A utility system must provide sufficient generating capacity to meet the coincident peak electrical load from residential, commercial, and industrial customers. For a variety of reasons, the marginal cost of adding new generating capacity has escalated rapidly during the past few years. Utility rate structures for non-residential users frequently include very high peak demand charges to reflect the cost of providing new peak generating capacity [5,6]. These high charges should provide an incentive for building owners to adopt design features that minimize building peak electrical demand. For the building owner, strategies that may reduce annual energy consumption and peak electrical demand, such as daylighting, should reduce operating costs and may even provide some first-cost reductions. For the utility, bringing peak demand closer to average loads minimizes capital expenditures for constructing and maintaining additional generating capacity and provides higher operating efficiencies.

Detailed data on peak electrical demand are necessary to completely analyze the costs and benefits of daylight-responsive electric lighting systems. Reducing both consumption and demand charges should produce substantial operating savings, although we know of no studies that provide detailed calculated or measured data to predict the peak savings possible with daylighting.

This study uses computer simulations to investigate the impact of daylighting strategies on building electrical demand and begins developing functional interrelationships for use in future cost/benefit studies. Reducing electric lighting in a daylighted space will reduce electrical demand; however, windows that admit daylight may, at the same time, increase cooling load because of increased solar gain. Thus the net impact of daylighting on peak electrical demand is a complex function of fenestration properties and lighting system characteristics. We used the DOE-2.1B computer program to vary fenestration and lighting system characteristics over a wide range and to analyze peak demand performance. Peak electrical loads were determined for a building both with and without daylight utilization. Total loads were broken down into contributing components and analyzed; peak load reductions and trade-offs due to daylighting were then established.

APPROACH

A five-zone building module representing a single story of a multistory office building was modeled. The modeled floor had a square core zone surrounded by four identical perimeter zones, each 4.6 m (15 ft) deep and oriented to a cardinal point of the compass. The core area is 929 m^2 (10,000 ft^2); the total perimeter area is 558 m^2 (6000 ft^2). The schematic floor plan of this prototype office building is shown in Fig. 1. The ceiling and floor were modeled as adiabatic surfaces (no net heat transfer). Building envelope effects were thus limited to those of the walls and windows, so that fenestration effects could be more readily isolated.

Fenestration and lighting system parameters were varied over a wide range. Glazing area was varied from 0 to 71% of floor-to-ceiling height. As glazing area was varied, the thermal conductance of the opaque wall portion was also varied to maintain a constant overall conductance. The conductance satisfies minimum wall thermal resistance requirements that currently must be met by most building designers to follow ASHRAE prescriptive standards. Because our study emphasized buildings that have summer peaking conditions, conductance effects should have only a small impact on the results. Shading coefficient was varied from 0 to 0.93. Visible transmittance was assumed to be 67% of the shading coefficient, a very conservative relationship for clear glazing but one that holds for many heat-absorbing glasses. (Future studies will examine variations in the relationship between visible transmittance and shading coefficient.)

To simplify analysis and interpretation we define a new term, effective aperture (EA), which is the product of the ratio of glass area to floor-to-ceiling wall area times the visible transmittance of the glass (WWR x T_v).

Window management was assumed to be based on a desire for comfort and glare control rather than energy management. Window management was simulated as the deployment of a shade/drape/blind every hour that direct solar gain through the glass exceeded 63 W/m^2 (20 Btu/ft^2-hr) or when the glare index at the window exceeded a value of 20. The glare index is a measure of the degree of visual discomfort that results from excessive brightness in the visual field [7]. The operable shading device reduced solar heat gain by 40% and reduced light transmittance by 65%, which represents the performance characteristics of many typical interior shading devices. Devices having other properties are commercially available but were not examined in this phase of the study. Our choice of window management model is based on the use of automatic controls (or attentive occupants). Occupants will operate window devices to control comfort, although it is not yet possible to say to what degree their behavior is consistent and reproducible [7]. More research is needed to define the problems and potential of manual operation of window management systems.

Lighting power density was varied from 0 to 34 W/m^2 (3.2 W/ft^2). A design illuminance value of 538 lux (50 footcandles) was maintained at all lighting power densities. Therefore the variation in lighting power density can be interpreted as a range of lighting system efficiencies, rather than a change in illuminance values. A continuous dimming system reduced electric light output linearly from 100% to 0% in response to daylight. Electric power consumption was, correspondingly, reduced linearly from 100% to a minimum of 10%, which represents auxiliary power requirements of the lamp/ballast systems.

The hourly schedules for lighting, occupancy, equipment, and infiltration are based on typical office occupancy and were taken from "Standard Building Operating Conditions"[9]. The schedules are shown in Fig. 2. In order to study zone-by-zone effects, thermal loads in each zone are satisfied by a separate single-zone constant-volume variable-temperature system with an economizer. Use of other systems, such as a multi-zone variable air volume system, could change results. 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 by a gas-fired boiler and cooling was provided by an electrically driven open centrifugal chiller. The results of this study are, therefore, limited to summer peaking. Results might change if heating loads were satisfied with an electrically driven source such as a heat-pump system.

Madison, Wisconsin and Lake Charles, Louisiana were chosen to represent the extremes of climatic conditions in the contiguous United States.

We used the DOE-2.1B building energy analysis program to determine annual energy performance and peak electrical demands. The DOE-2.1B program incorporates a daylighting model that calculates hourly interior daylight illuminance for each zone of a building based on architectural design and hourly weather data [10-13]. Detailed peak load breakdowns were obtained from standard DOE-2.1B output reports and from new reports created for this study.

Procedure for Determining Peak Demand

A DOE-2 PLANT report was used to determine the day and hour of the building's peak electrical demand. The DOE-2 LOADS program was then used to obtain hourly reports on the peak day. These hourly reports show the zone values for each electrical load component, such as lighting, cooling, equipment, and fan.

In order to study the contribution of cooling load components to peak electrical demand, it is necessary to break down the cooling electrical demand into its components. Cooling load components cannot be directly related to peak electrical demand in the current version of the DOE-2 program. When information on cooling loads is passed from the LOADS through the SYSTEMS to the PLANT programs, where peak demand is calculated, cooling load components lose their identity. For the hour in which the building peak occurred, the fractional cooling electrical demand was apportioned between cooling load components based on the relative size of the hourly component loads as reported in the LOADS section of DOE-2. In this way the cooling electrical load was broken down into lighting, solar gain through glass, glass conduction, wall conduction, people, and equipment. Cooling load due to ventilation is calculated in the SYSTEMS section of DOE-2 and was estimated from SYSTEMS hourly reports.

RESULTS

Core and Perimeter Peak Demand

Figure 3 shows the distribution of total peak electrical load between core and perimeter zones. These representative values are for a window/wall ratio (WWR) of 71% and a visible transmittance (Tv) of 0.69 in Madison. Distribution of peak load components in Lake Charles is very similar. These results show that with this large effective aperture of 0.49, the peak demand in the perimeter zones exceeds the core zone peak, even though the core area is 62.5% of the floor space and the total perimeter area is 37.5% of the floor space. Daylighting substantially reduces perimeter zone peaks and in both cities can provide enough savings to reduce perimeter peaks below those of the core, as will be shown later.

The power density of peak electrical demand for each component is shown in Fig. 3 in watts per square meter (W/m^2). In both daylighted and nondaylighted cases, lighting is the primary component of the peak demand in the core zone (16.46 W/m^2), and cooling is the primary component in the perimeter zones (30-34 W/m^2). Note that in this case the power density (W/m^2) for peak demand in the perimeter is greater than in the core even when the perimeter is daylighted because the large effective aperture drives up the cooling component.

Comparison of the building perimeter zone peak with and without daylight utilization shows that daylighting reduces peak electrical demand in the perimeter by approximately 28% for both Madison and Lake Charles. In both cases the core load remains almost constant. The small electrical consumption in the perimeter zone for lighting in the daylighted case is attributable to the residual 10% power consumption at full dimming of the dimmable lighting control system being modeled. For these specific hourly conditions and fenestration configurations, this represents the maximum potential for peak load reduction because the lighting system was operating at its lowest set-point. For the daylighted case, peak demand for the entire building was reduced by approximately 15% in Madison and Lake Charles. In typical building configurations consisting of both core and perimeter zones, the overall building savings potential will vary in proportion to the relative size of the daylighted perimeter zone.

Peak Breakdown by End-Use Components

Figure 4 shows the breakdown of total building peak demand, for this same fenestration configuration, into end-use components for Madison. The pattern in Lake Charles is similar. Electricity used for cooling and lighting are the major components. Each additional watt per unit floor area of installed lighting adds 1.19 watt per unit floor area under peak load conditions. This ratio of change in peak to change in installed lighting power represents the combined effect of the hourly operating profile for lighting (typically 0.9 of installed power), and the COP of the chiller system. If the cooling load resulting from lighting is added to lighting's share of the load, then total peak in nondaylighted cases is approximately 40% lighting and 30% cooling. The direct and indirect contribution of lighting, therefore, is the most significant component of total peak demand. In the daylighted cases, when lighting is reduced, the relative importance of the components is reversed, with cooling at 40% and lighting at 30%. In both Madison and Lake Charles, daylighting reduced total electric lighting demand by 34%, providing a 15% reduction in total peak demand. These relationships are based on an installed lighting power density of 18.3 W/m^2 (1.7 W/ft^2) and large, moderate-transmittance windows, which represents a fairly typical non-optimized design. Changes in window area and transmittance will alter the relative importance of the lighting and cooling components of peak demand.

Relative Magnitude of Peak Savings vs Energy Savings

Peak load as a function of effective aperture is plotted in Figs. 5a and 6a for Madison and Lake Charles, respectively. These figures show that daylight from moderate-to-large effective apertures can reduce total building peak demand by up to 14 to 15% in both cities, 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.) These savings increase for higher installed lighting loads, as discussed later. The fraction of total building peak load saved would also vary with the perimeter/core ratio.

Daylight utilization will usually provide energy savings and reduce peak demand. Annual electricity consumption as a function of effective aperture is plotted in Figs. 5b and 6b for Madison and Lake Charles, respectively. The figures show that energy savings of 13% correspond to the peak reductions described above for both cities. Daylighted designs that reduce peaks will tend to lower annual electrical energy consumption, but the annual energy savings percentage will generally be less than the percentage of peak reduction. In the case of large effective apertures, the percentage reduction in total electrical energy consumption approximated that of peak load reduction. However, for small effective apertures, energy savings, as a percent of base case, are lower than peak load savings. This is consistent with the observation that electric lighting consumes minimum power at the peak hour for a wide range of values of effective aperture, but the annual energy savings will increase more slowly over the same range of effective apertures. For the cases considered here, the effective aperture that minimizes peak demand is always smaller than the value that minimizes annual electrical energy consumption.

Peak as a Function of Fenestration System Characteristics

Figures 5a and 6a show the relationship between peak load and effective aperture with window management as a parameter. The effect of window management will be discussed later. The change in peak demand due to variations in glazing conductance was negligible in this study because overall envelope conductance was held constant and shading coefficient was varied independently. For the nondaylighted case, the variation in peak load in response to effective aperture is similar for Madison and Lake Charles, as peak demand continuously increases with increasing effective aperture. However, for the daylighted cases, there is an optimum value of effective aperture that minimizes peak electrical demand. This results from the interplay between lighting load reductions from daylighting and cooling load increases from solar gain. The optimum design value for effective aperture ranges from 0.1 to 0.2 for Madison and from 0.05 to 0.15 for Lake Charles for an installed lighting load of 18.3 W/m^2 (1.7 W/ft^2) and for glazing that has a visible transmittance that is 0.67 of the shading coefficient. Similar relationships occur for annual electricity consumption, as shown in Figs. 5b and 6b.

These figures show that there is a climate-dependent optimum window area for minimizing peak load and that this optimum is a function of shading coefficient, visible transmittance, and installed lighting power density. It is interesting to notice that, with the exception of the largest effective apertures, the daylighted cases with window management almost always have peak demands below the peak of a building that has no windows.

Window Management Effects

The base case in most of our analysis assumes that windows are "managed" with simple interior shading devices to control glare and improve thermal comfort. Because peak demand depends on cooling load and because solar gain is a major determinant of cooling load, it is reasonable to expect that management assumptions may alter some conclusions. The effect on peak demand of deleting the window management assumption for both daylighted and nondaylighted buildings is included in Figs. 5a and 6a (curves A and C). Figures 5b and 6b show similar patterns in annual electrical consumption. We observe that daylighting is more effective than window management as a single peak-load management strategy, but that the maximum peak savings are realized when both daylighting and window management are used. Compared to an unmanaged window having an effective aperture of 0.2, the use of daylighting and window management strategies reduces peak demand by 20% in Madison and 18% in Lake Charles.

Monthly distributions of peak load with and without window management and daylighting are shown in Figs. 7 and 8, both of which are based on a 0.28 effective aperture. In summer months window management is more effective in Madison than in Lake Charles. This appears to result from differences in latent load and in the relative importance of direct and diffuse irradiance in each climate. In the DOE-2 simulation, window management is employed based on the hourly direct component of solar gain through windows. An examination of hourly solar data at the time of building peak loads shows a substantial difference in solar gain between the management and no-management cases for Madison, and but little difference for Lake Charles. This suggests that, although the total solar gain may be large in Lake Charles, much of it arrives at the building as diffuse irradiance rather than direct beam radiation and thus does not activate the operable shading system. The high latent load in Lake Charles imposes a higher base cooling load that is independent of solar gain. Comparing results for Madison and Lake Charles, we note that the monthly total peak load and the savings due to management and daylighting are relatively constant throughout the year in Lake Charles. However, in Madison there is a distinct summer and winter season peak profile. For April through October the monthly savings for management and daylighting are relatively constant and similar to those of Lake Charles. However, for November through March the total building peak load is substantially reduced and the savings from both strategies are also much lower than in summer. The peak load differences between the nondaylighted cases (curves A and B) and the daylighted cases (curves C and D), which were large in summer, are reduced in winter, so that all four cases run together. This results from the combined effect of reduced daylight availability in winter in Madison and the substantial reduction in chiller load.

Monthly Pattern of Peak Demand

A further comparison of monthly patterns of peak demand for different fenestration systems reinforces the above conclusions regarding the distinctions between the two climates. A comparison of the peak monthly demand profiles for Madison and Lake Charles (Figs. 9 and 10) for different fenestration parameters shows two distinct patterns. Madison has a definite summer peaking period for seven months and has five winter months that show sharply reduced peaks; Lake Charles shows much less monthly variation throughout the year. In Lake Charles the monthly peak variation between daylighted and nondaylighted cases ranged from 7 kW in winter to 11 kW in summer. The summer savings in Madison were also 11 kW, but the winter savings dropped to only 1 kW. (Note that the glazing in both cities was not identical.) Winter peaks in Madison were already 40% below summer peaks, so that reduced winter peak savings have an insignificant effect on billing, particularly when there are ratchet clauses in the utility rate structure.

The potential for electric lighting energy reductions from daylighting is at a maximum during summer months because of higher outdoor illuminance levels and less frequent heavy overcast conditions. Consequently, electric lighting requirements can often be substantially reduced coincidently with weather-induced peak cooling requirements. Peak savings from daylighting are not as great during winter months when daylight availability is reduced; peak demand, however, is much lower in winter than in summer. This characteristic of daylighting potential (i.e., potential maximum utilization of daylight during the seasonal peak load period) makes daylighting an attractive load-control strategy (assuming a utility with a summer peak electrical demand). These data also suggest that the use of moderate-size windows with daylight utilization will result in lower monthly peaks than the use of smaller windows without daylight utilization.

Load Duration Plots

Cumulative hours at each electrical demand level are plotted in Figs. 11 and 12. We observe that daylighting and window management cause substantial changes in the load duration at high electrical demand. Note that although the peak for the managed-window, nondaylighted case is virtually the same for both cities (75 vs 74 kW), the slope of the curve for Lake Charles is much steeper, indicating many more hours at high electrical load levels. The data for Madison indicate 800 hours of electrical loads of 60 kW or greater, while Lake Charles has more than 1500 hours above 60 kW. Daylighting is more effective than window management not only because the demand curves are lower but also because there are fewer hours in which demand is just below peak level, particularly in Madison. We speculate that further peak savings by other methods, such as load-shedding and energy storage, would be more effective with daylighted buildings than with nondaylighted buildings because daylighted buildings have fewer cumulative hours just below the peak.

Peak Demand vs Installed Electric Lighting Power Density

Peak electrical demand as a function of installed electric lighting power density is shown in Fig. 13 for Madison; Lake Charles is similar. 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 footcandles). For the nondaylighted cases (solid lines), 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. For the daylighted cases, however, the relationship between peak and lighting load becomes more complex.

In Madison (Fig. 13), the three nondaylighted cases (solid lines) represent effective apertures of 0, 0.14, and 0.49 respectively. These have essentially the same slope, which is constant at 1.19 W/m^2 for each W/m^2 increase in installed lighting power. This value includes the cooling impact of lighting as well as the effect of lighting operation schedules. These schedules assume that 90% of the installed lighting power is operating during most daytime hours. The slope of 1.19 for peak load vs installed lighting power in the nondaylighted case is reduced in the daylighted case to 0.88 for small windows and to 0.8 for large windows. 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 of the peak loads plotted in Fig. 13 (both daylighted and nondaylighted) occurred between 3 and 5 pm on August 31.

In Fig. 14 we show similar results for Lake Charles, with effective apertures of 0.09 and 0.28, with and without daylight. Although the initial trends for small values of installed lighting power are similar to the Madison results, all four curves have similar slopes above a lighting power density of 18.3 W/m^2 (1.7 W/ft^2). In this portion of the figure, daylighting has little or no effect. A further examination of detailed hourly reports revealed that, for the higher lighting load, the peak occurs at a different day and time than for the lower values. Furthermore, the peak hour occurs during heavy overcast with very low exterior illuminance values, thus requiring nearly full electric lighting. The cooling load remains high due to hot, humid weather and solar gain that entered the building during previous hours.

These results lead to the speculation that some of the irradiance values on the weather tape used for the DOE-2 Lake Charles runs may be erroneous. However, our results point to a condition that could be expected in a real building in which daylighting was used as a load-management strategy. Solar-induced cooling loads might remain high due to short-term storage in the building interior, and persistent high latent load, while exterior daylight illuminance values drop sharply for a short period of time due to cloud conditions. This emphasizes the need for field measurements to complement simulation results.

The Effect of Daylighting on Chiller Size

An electrically driven open centrifugal compression chiller was modeled in this study. The DOE-2 program automatically sizes the chiller based on peak cooling load. A plot of chiller size as a function of effective aperture is shown in Figs. 5c and 6c. Chiller size increases continuously with increasing effective aperture, even in the daylighted cases. This pattern contrasts with the peak load patterns shown in Figs. 5a and 6a, which show an intermediate value of effective aperture for the minimum peak demand. Note that in Madison there is a crossover point at which daylighting without window management requires a larger chiller than no daylighting with window management (see Fig. 5c). In Lake Charles, however, at any specific value of effective aperture, daylighted buildings always require smaller chillers than nondaylighted buildings in regardless of window management (Fig. 6c). The data for Madison indicate that the incremental chiller savings due to reduced lighting loads occur at low aperture values and then remain constant (A vs C or B vs D on Fig. 5c), while the incremental adverse impact of solar gain continues to increase as aperture size increases (A vs C or B vs D on Fig. 5c). These results emphasize the importance of control of solar gain if daylight is to be successfully utilized to control peak demand.

Chiller size also depends on installed lighting load. Figure 15 shows chiller size as a function of installed electric lighting load for an effective aperture of 0.28. This corresponds to the crossover point in Fig. 5c, described earlier. It can be seen that the crossover depends on installed lighting power. When the installed electric lighting is efficient, that is, lighting power density is low, 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 more beneficial than window management in terms of chiller size. Chiller size is approximately linearly dependent on electric lighting power regardless of daylighting and window management, although the rate of increase will vary with the conservation strategies utilized.

CONCLUSIONS

The discussion above suggests that, if lighting controls are responsive to interior daylight levels, the optimal fenestration system is a complex function of fenestration parameters (area, shading coefficient, visible transmittance) and of lighting system characteristics (installed lighting power density and control strategy). Our results suggest the following generalizations:

1) Primary savings result from direct reduction in the lighting component of peak electrical load, with additional savings from reduced cooling loads.

2) The peak load trends relative to fenestration and lighting parameters are similar in all climates where summer peaks dominate, although specific results differ by climate.

3) There is an optimum window area for minimizing peak load, which optimum is a climate-specific function of the parameters mentioned above. Windows smaller than optimum slightly increase peak loads; windows larger than optimum can substantially increase peak loads.

4) The hour at which building peak electrical load occurs in a daylighted building will not necessarily be the same hour that shows maximum daylighting savings.

5) Solar gain causes peak loads in perimeter zones generally to exceed core zone peaks. Efficient electric lighting will reduce total building peaks, but daylighting appears to be the primary design strategy that can reduce perimeter peaks below those of the core.

6) Designs that minimize peaks will generally lower energy consumption, but exceptions are possible. Designs that minimize annual energy consumption will produce lower peaks if fenestration and lighting systems are effectively managed. Minimizing electricity costs requires considering both consumption patterns and peak demand.

7) Solar gain through fenestration and resulting cooling loads must be effectively managed if daylighting is to provide maximum load reductions. The real luminous efficacy of daylighting depends greatly on fenestration properties, solar gain management, and installed lighting power density. This paper suggests limits to the conditions under which daylighting is a "cooler" light source than electric lighting and describes the resultant impact on chiller sizing.

While this study adds to our understanding of the load-management potential of daylighting, it raises many new questions and concerns. These preliminary results are based on the use of an hour-by-hour simulation program. Despite the limitations of energy analysis programs for predicting real building performance, they are an invaluable tool for systematically investigating complex interactions in buildings. However, we emphasize that results from this study must be considered tentative until sufficient experimental data are collected to validate or modify results and conclusions. An outdoor experimental facility with dual test chambers to measure the impact of fenestration on building cooling loads (with and without daylighting) has been constructed at LBL and should be operational in 1984 [14]. A measurement program in daylighted buildings is also necessary. The simulation model uses a one-hour time step, while events that can significantly effect peak demand may occur on a much shorter time scale. Detailed measurements of component and subsystem performance in buildings are required to determine whether these might alter our conclusions.

Our results hold only for the specific HVAC system modeled. There are major differences in the response of different types of HVAC systems to the same set of thermal loads. We are now investigating the impact of changes in HVAC system type and operation on peak demand. Finally, the proper use of lighting controls and window management techniques may depend, in part, on occupant participation. Further studies are required to compare the relative performance of manual vs automated control systems. Experience to date suggests that automated systems are required to maximize energy and demand savings, but there is little hard evidence to suggest that existing hardware systems and controls will consistently provide desired levels of visual and thermal comfort. The potentially large first-cost savings that might be possible based on reduced chiller and HVAC system size, in addition to annual energy and demand savings, will remain as potentials until additional studies address several of the issues raised above.

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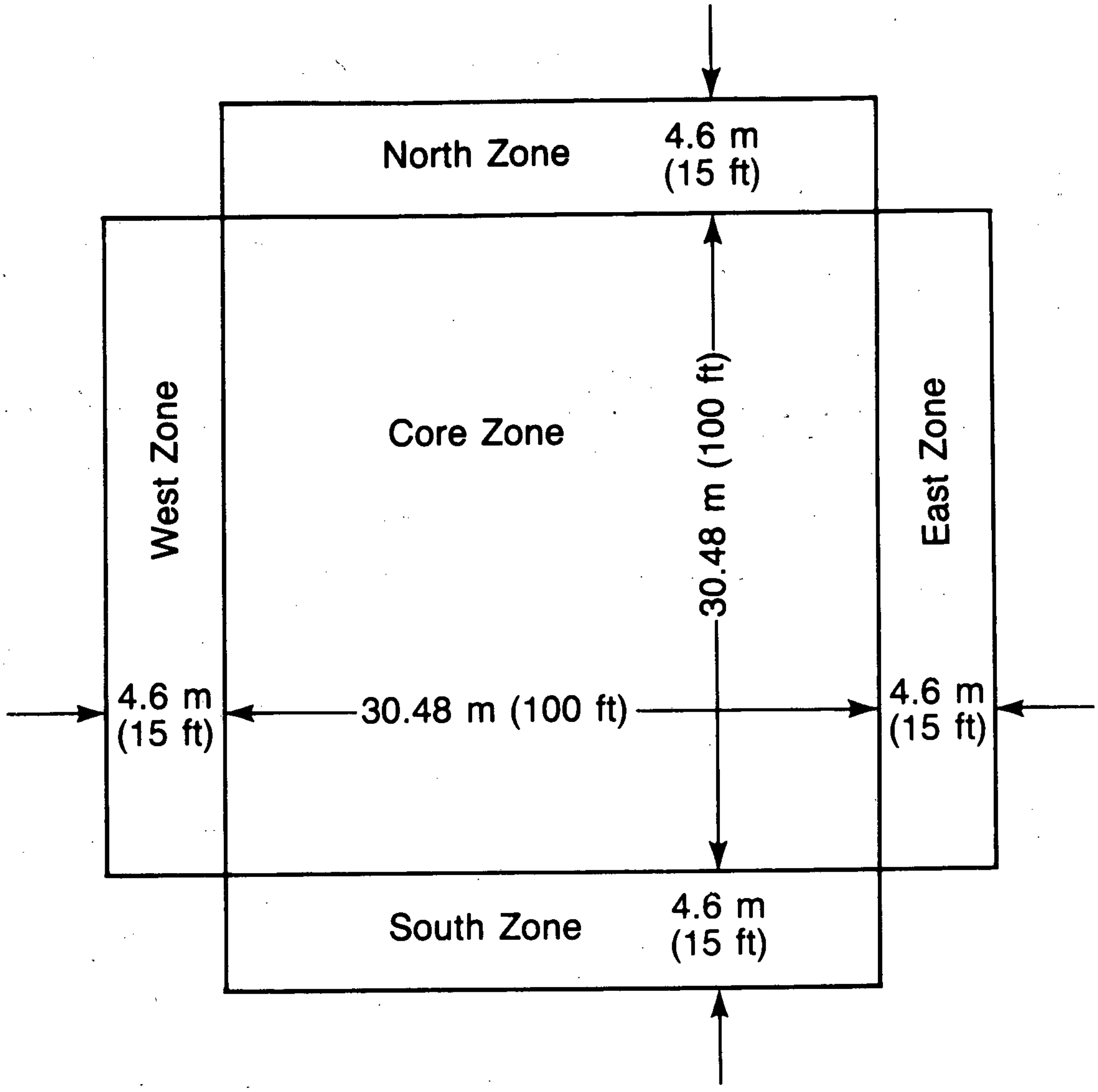

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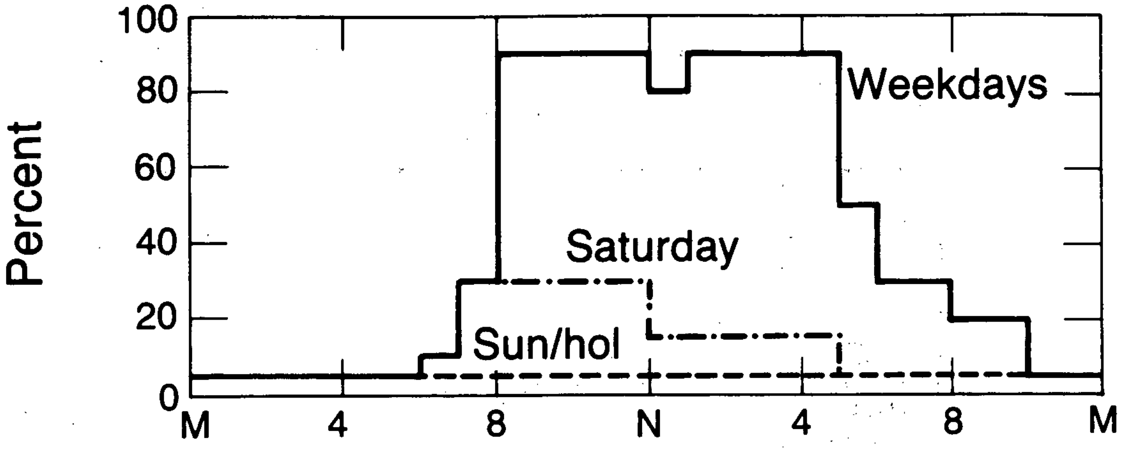
Figure 1. Schematic floor plan of prototype office building.



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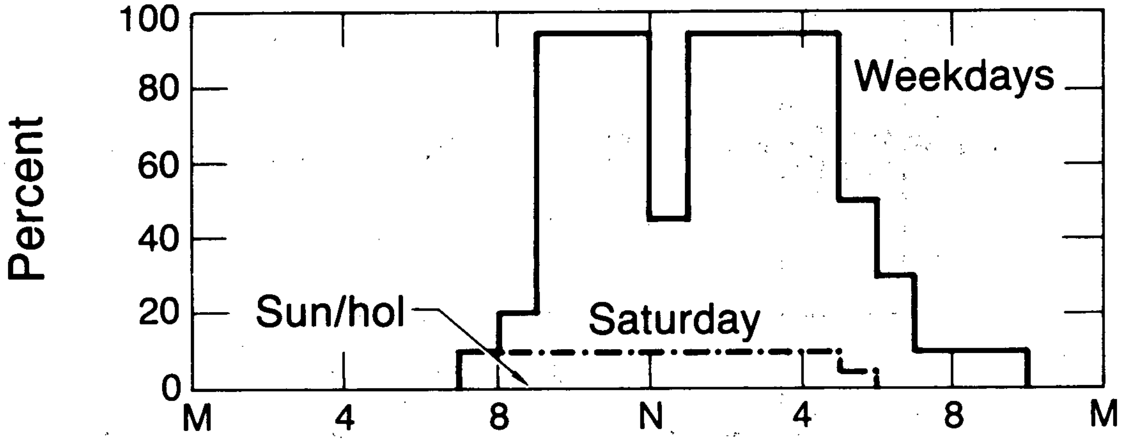
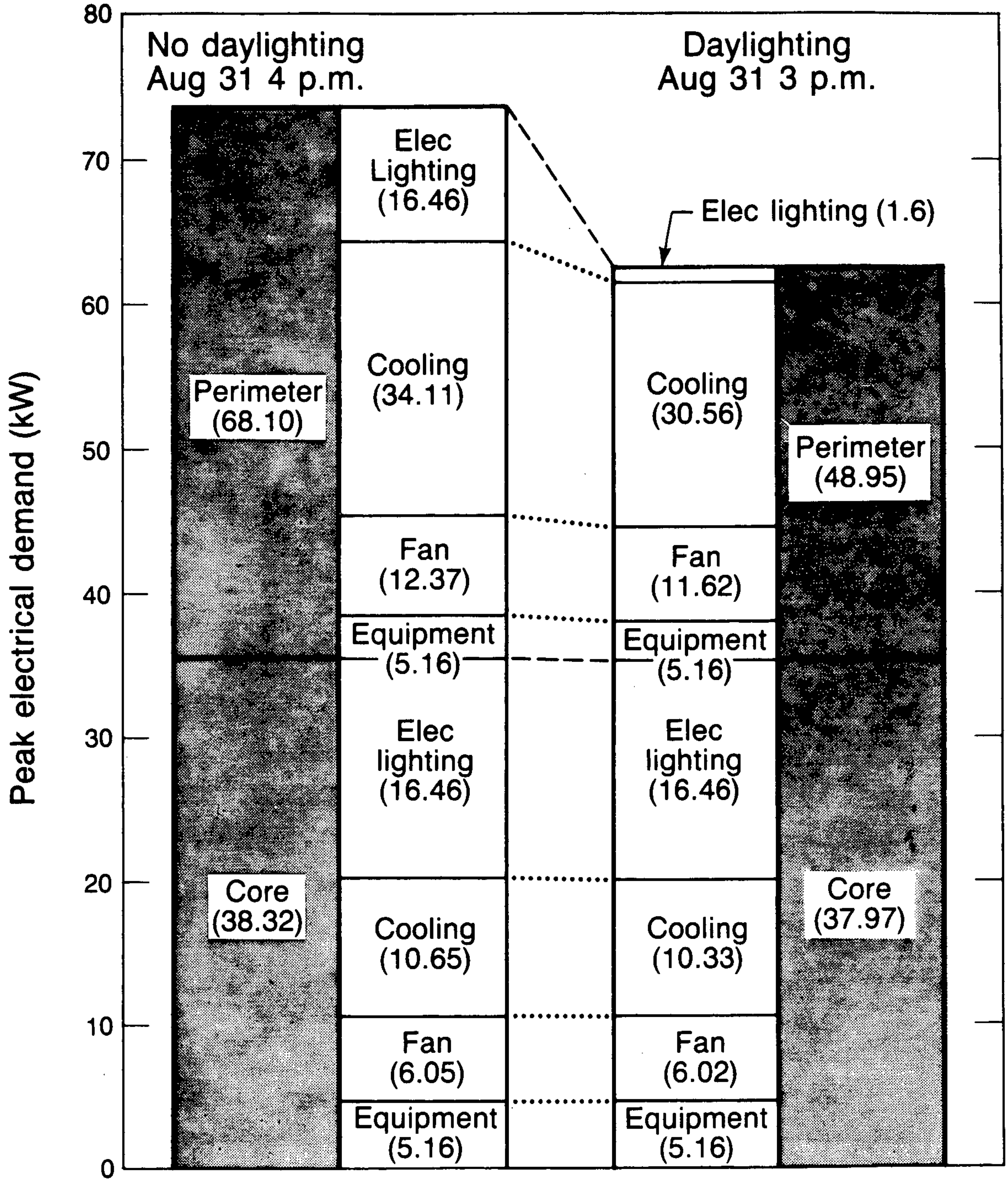


Occupancy and equipment

XBL 8312-7485

Figure 2. Operating schedules.



XBL 8312-7444

THE LIGHTING POWER DENSITY IN ALL FIGURES IS 18.3 W/m^3 (1.7 W/ft^2) UNLESS OTHERWISE SPECIFIED.

Figure 3. Distribution of peak electrical demand between core and perimeter, EA = 0.49, Madison.

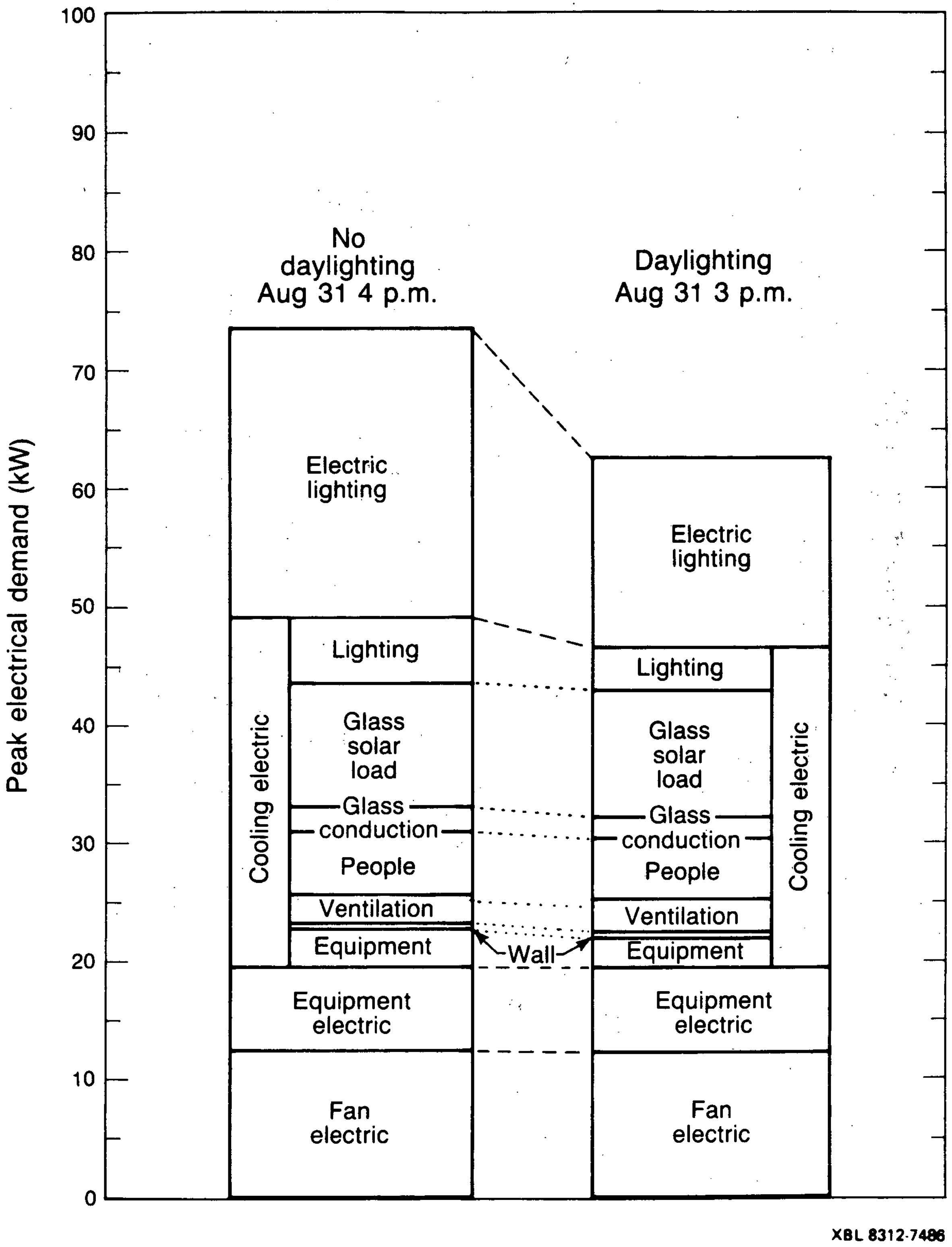
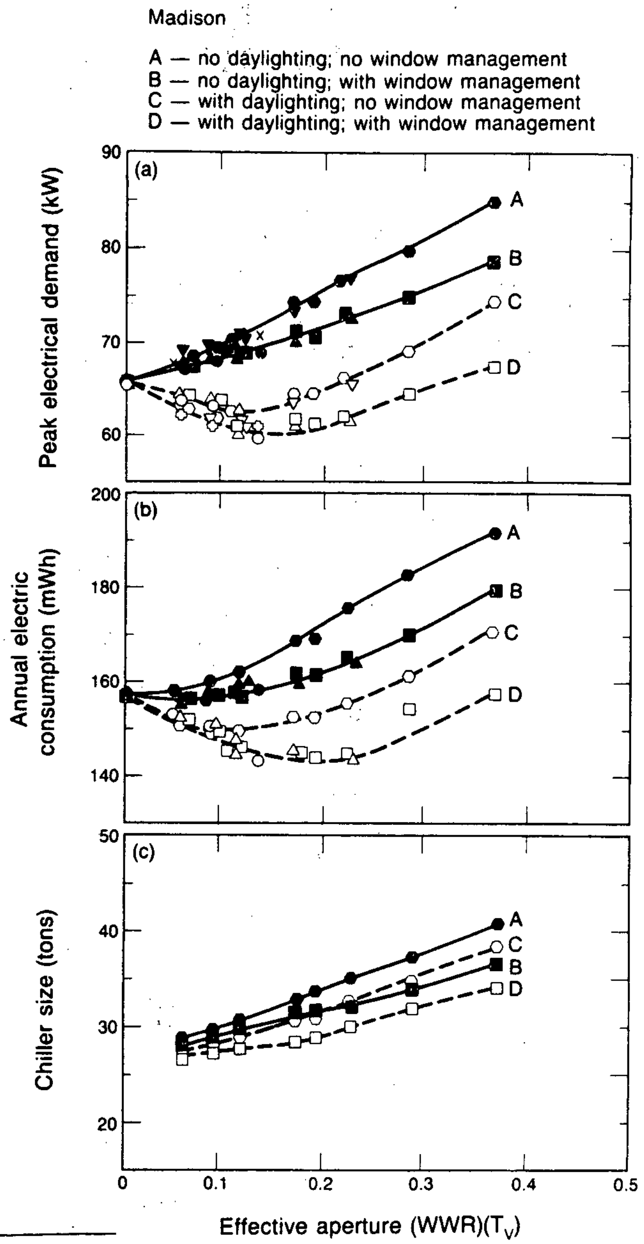


Figure 4. Peak electrical demand by component, EA = 0.49, Madison.

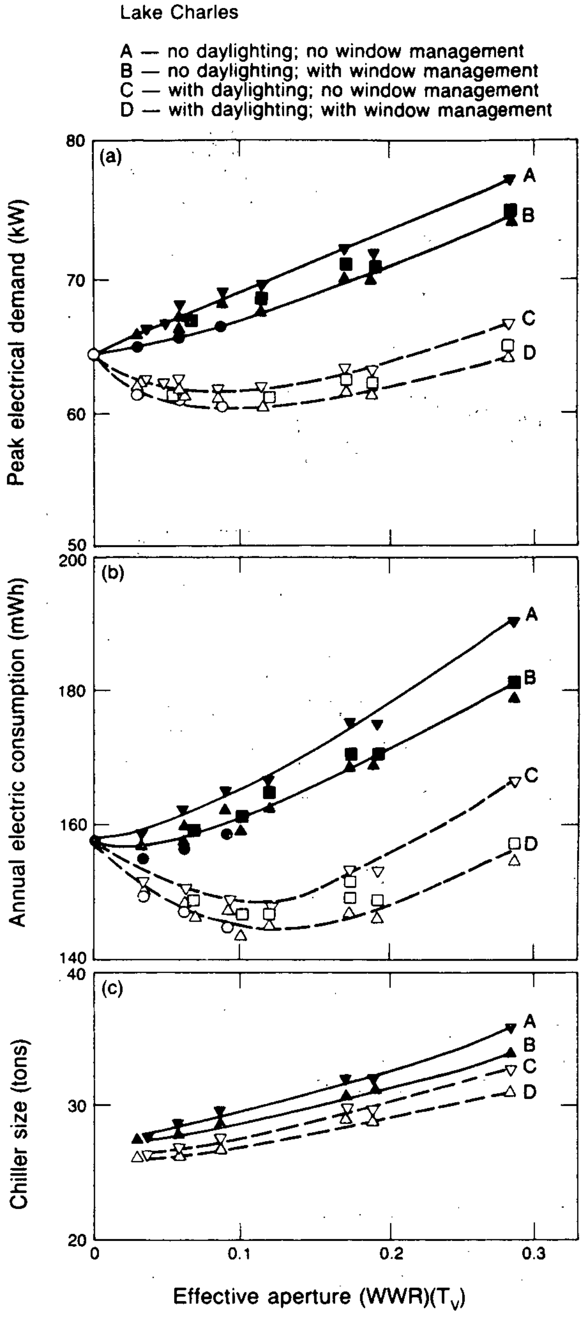


XBL 8312-7474

Legend

	No Daylighting		With Daylighting	
With Window Management	NP = 1	●	NP = 1	○
	NP = 2	▲	NP = 2	△
	NP = 3	■	NP = 3	□
No Window Management	NP = 1	×	NP = 1	✥
	NP = 2	▼	NP = 2	▽
	NP = 3	⬢	NP = 3	⬡

Figure 5a. Peak demand as a function of effective aperture, Madison.
5b. Electric consumption as a function of effective aperture, Madison.
5c. Chiller size as a function of effective aperture, Madison.

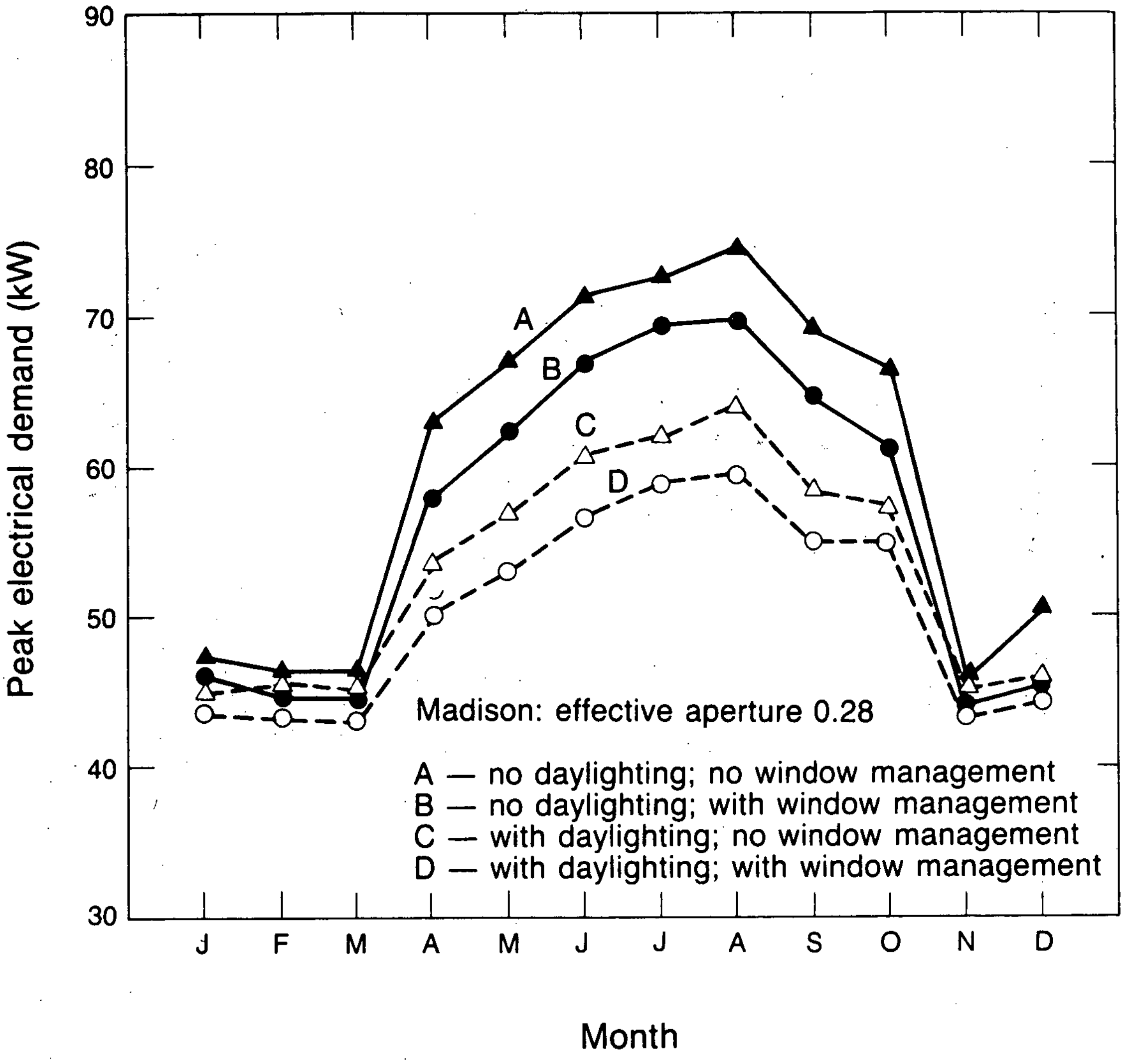


XBL 8312-7483

Legend

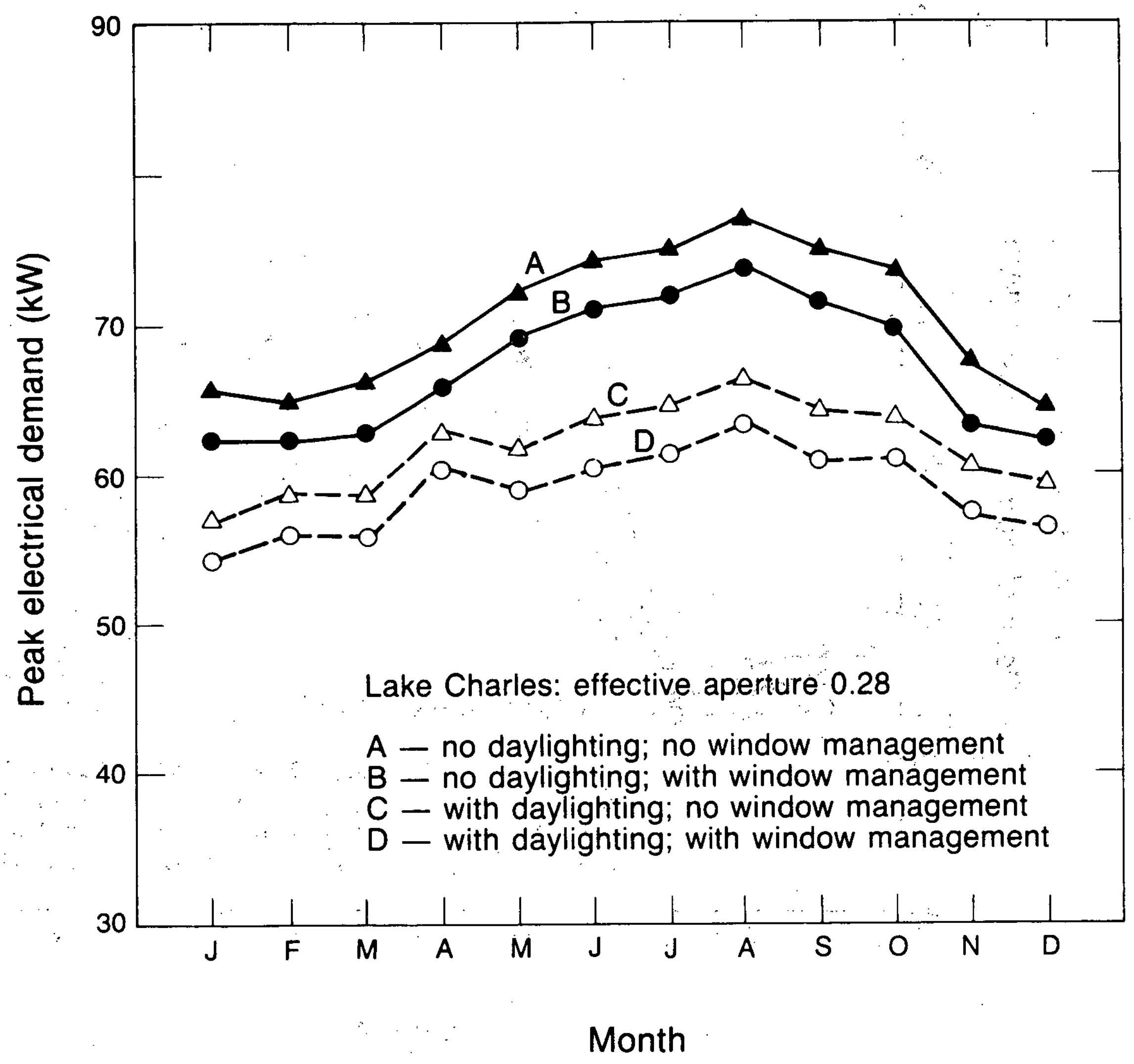
	No Daylighting		With Daylighting	
With Window Management	NP = 1	●	NP = 1	○
	NP = 2	▲	NP = 2	△
	NP = 3	■	NP = 3	□
No Window Management	NP = 1	×	NP = 1	⬡
	NP = 2	▼	NP = 2	▽
	NP = 3	⬢	NP = 3	○

Figure 6a. Peak demand as a function of effective aperture, Lake Charles.
6b. Electric consumption as a function of effective aperture, Lake Charles.
6c. Chiller size as a function of effective apertures, Lake Charles.



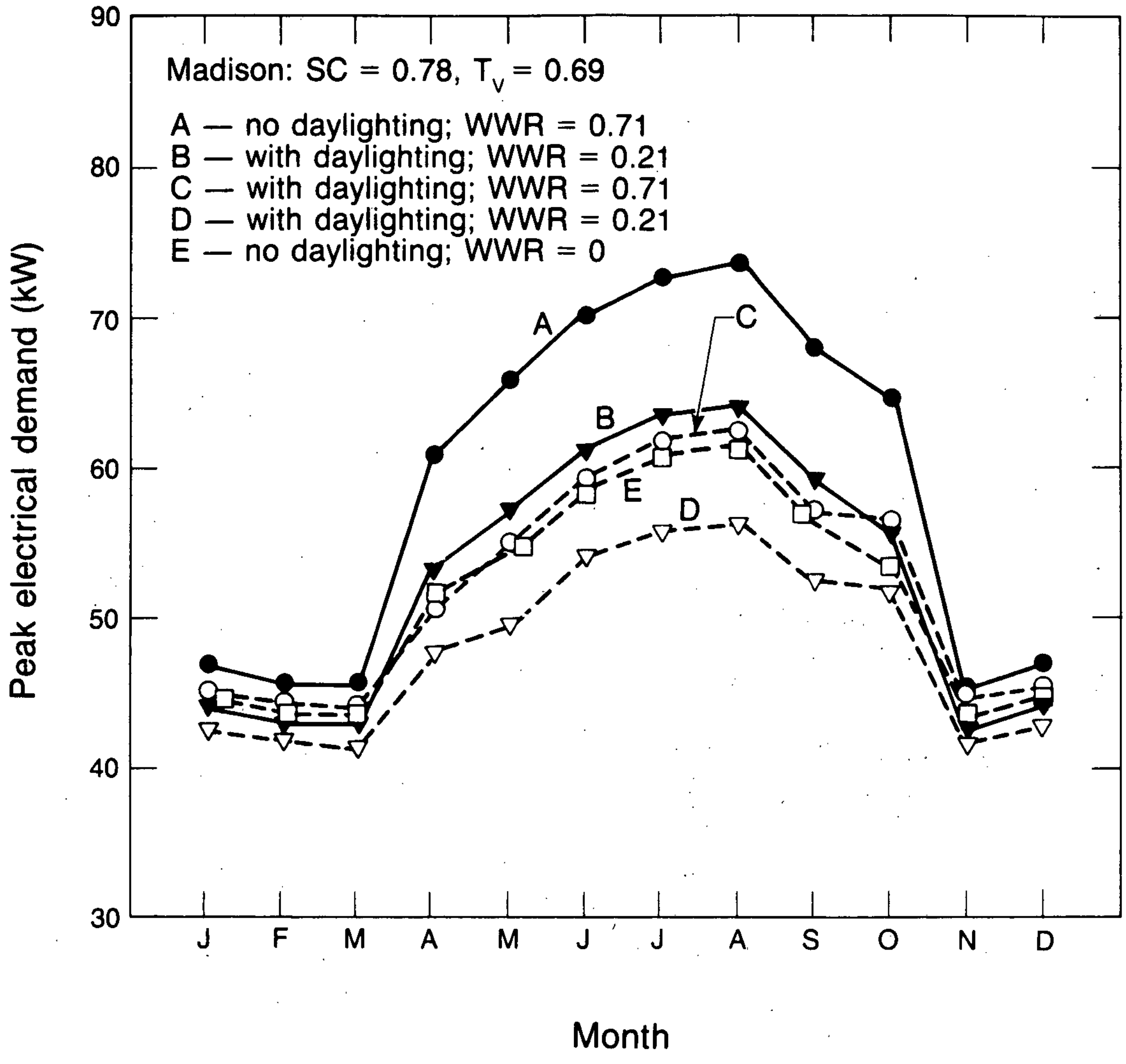
XBL 8312-7476

Figure 7. Peak demand vs month of the year, EA = 0.28, Madison.



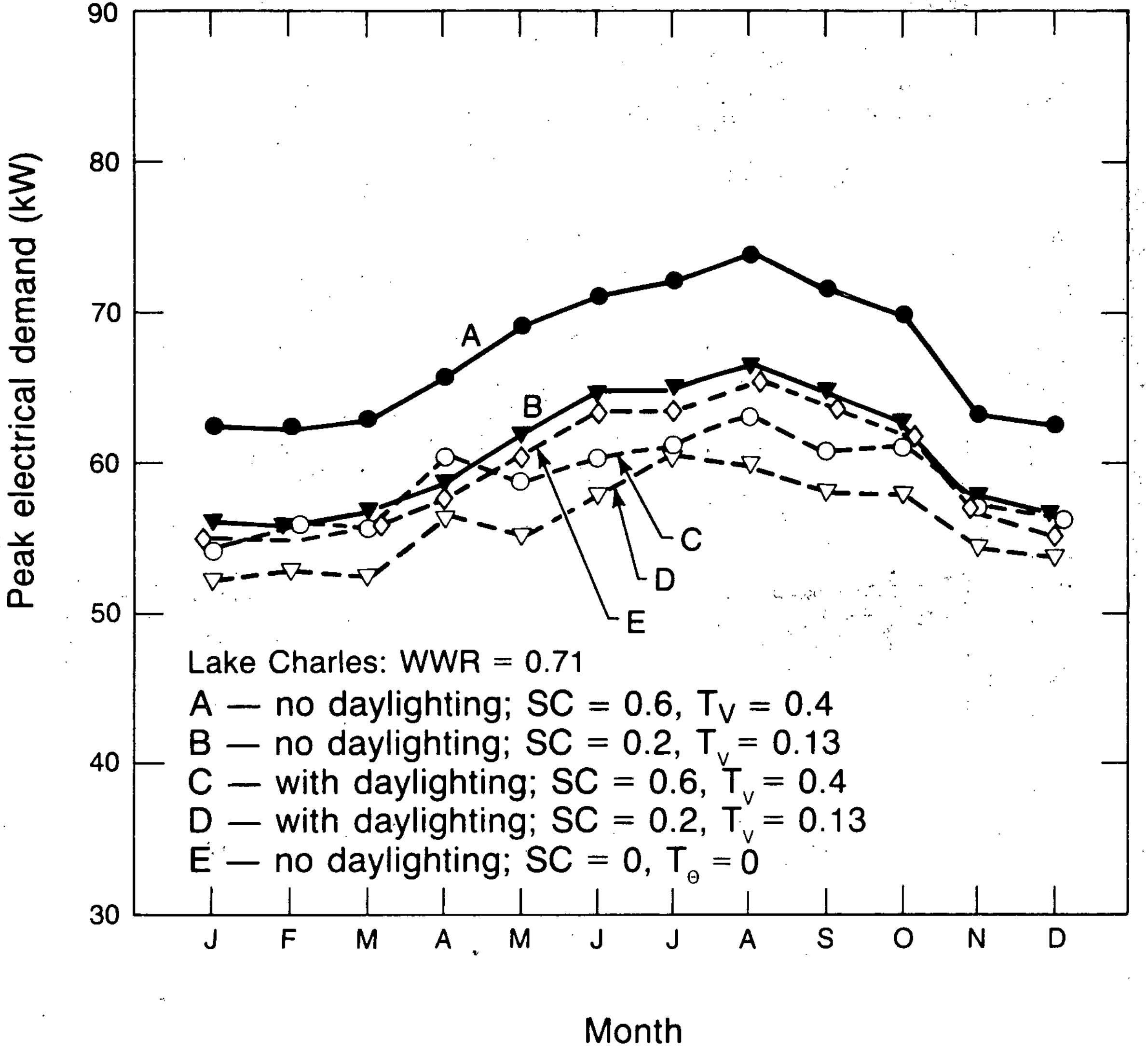
XBL 8312-7478

Figure 8. Peak demand vs month of the year, EA = 0.28, Lake Charles.



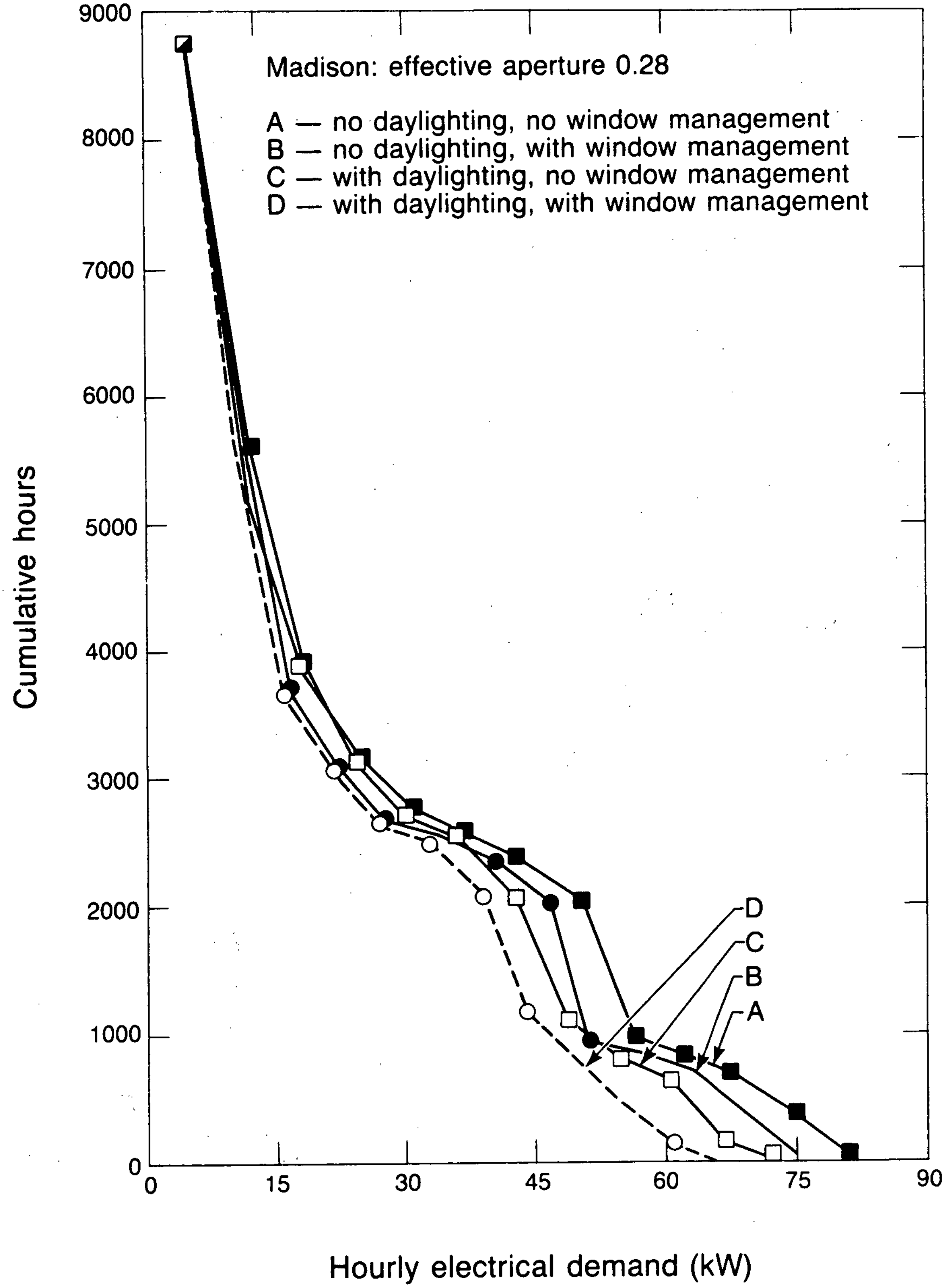
XBL 8312-7480

Figure 9. Peak demand vs month of the year, SC = 0.78, Madison.



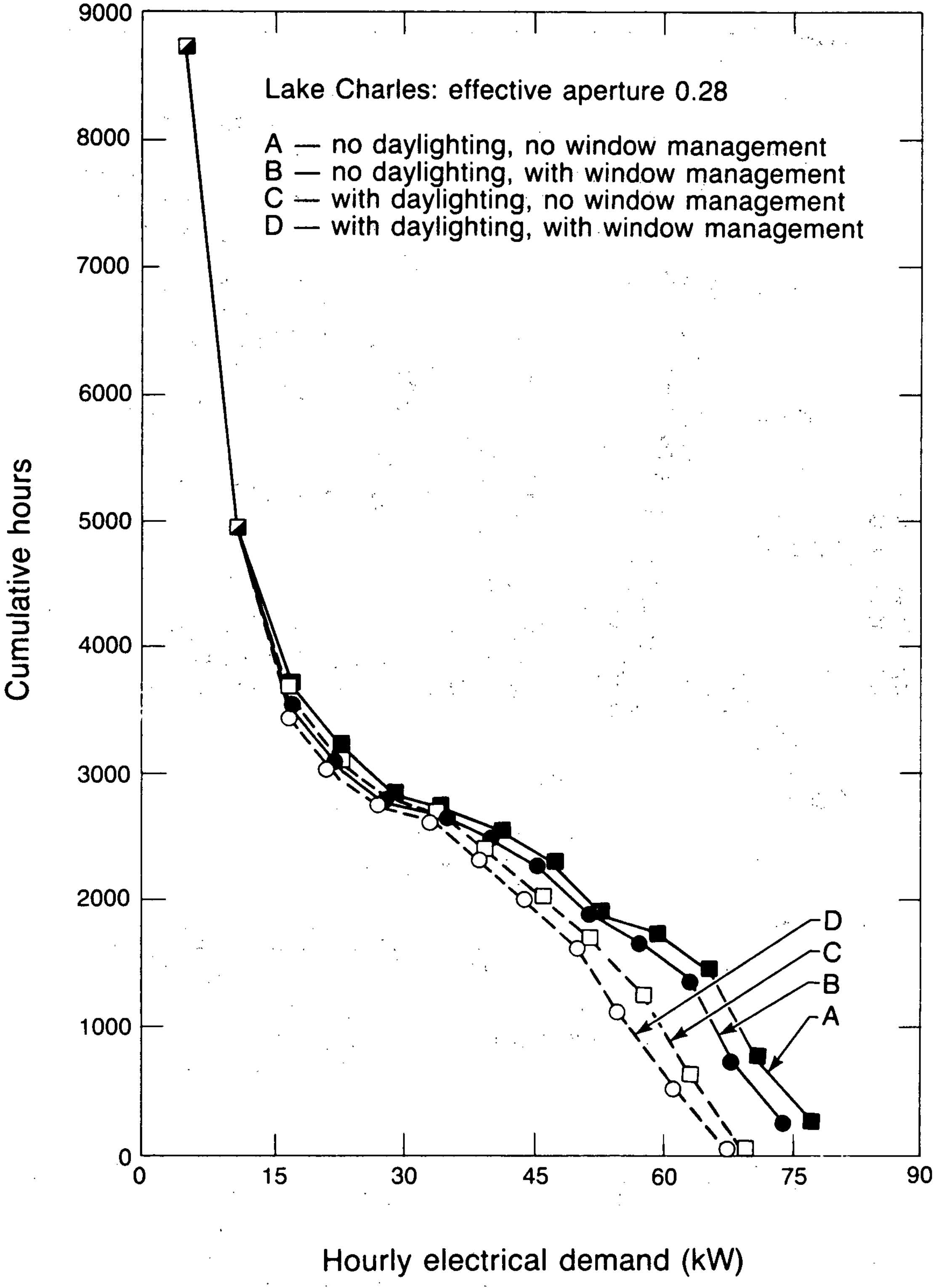
XBL 8312-7475

Figure 10. Peak demand vs. month of the year, WWR = 0.71, Lake Charles.



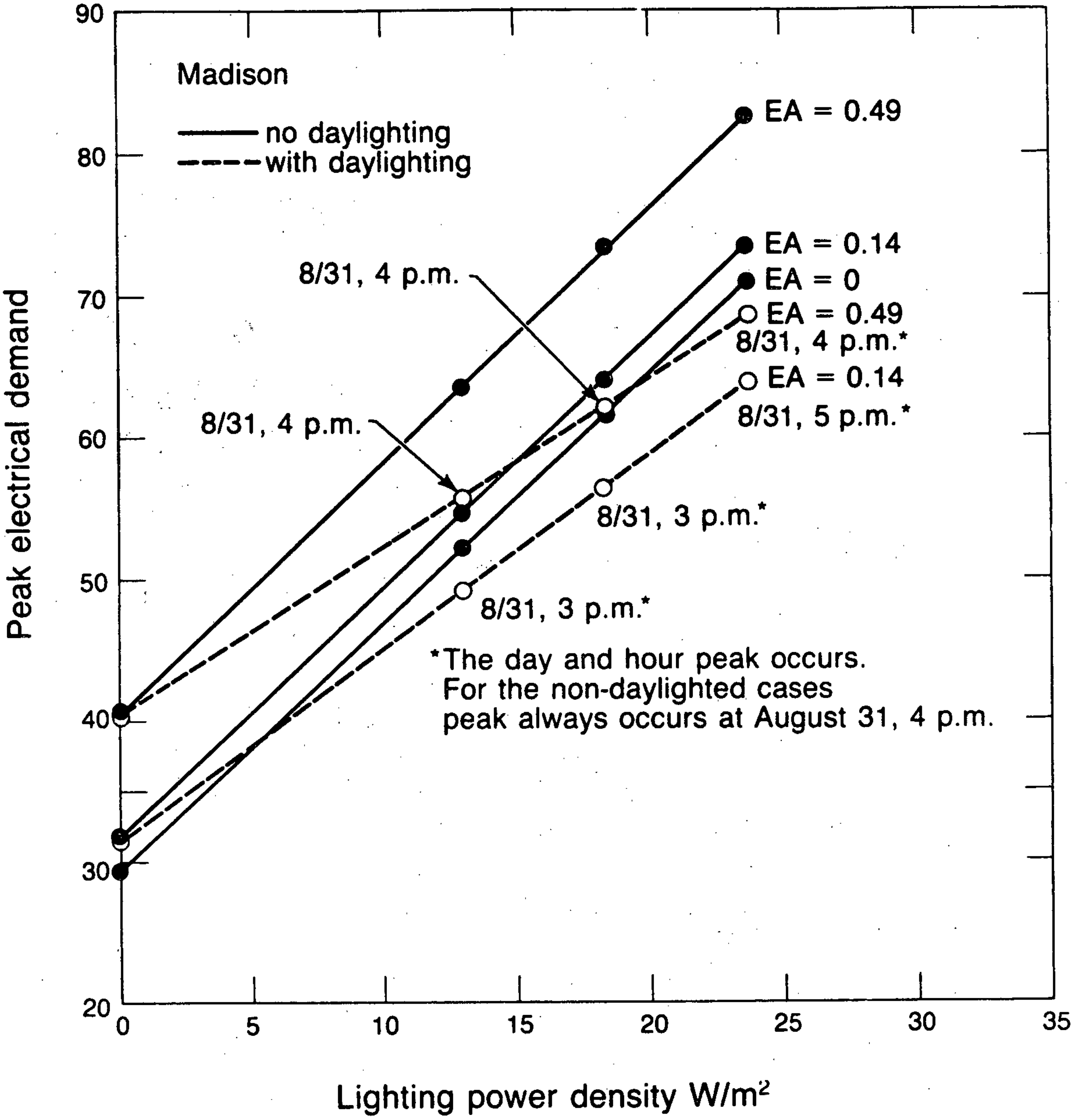
XBL 8312-7482

Figure 11. Cumulative hours of peak demand, EA = 0.28, Madison.



XBL 8312-7477

Figure 12. Cumulative hours of peak demand, EA = 0.28, Lake Charles.



XBL 8312-7484

Figure 13. Peak demand vs lighting power density, Madison.

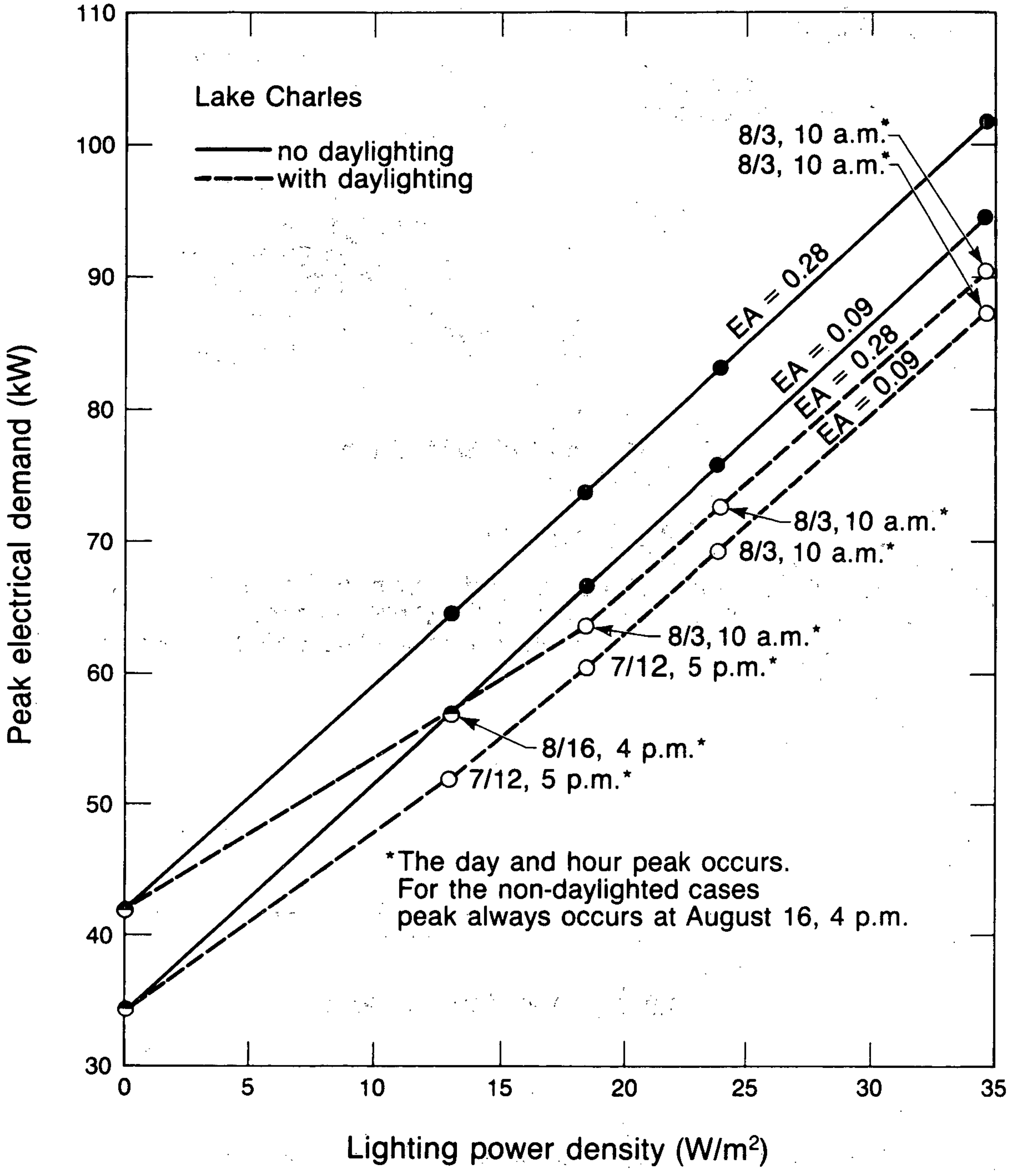
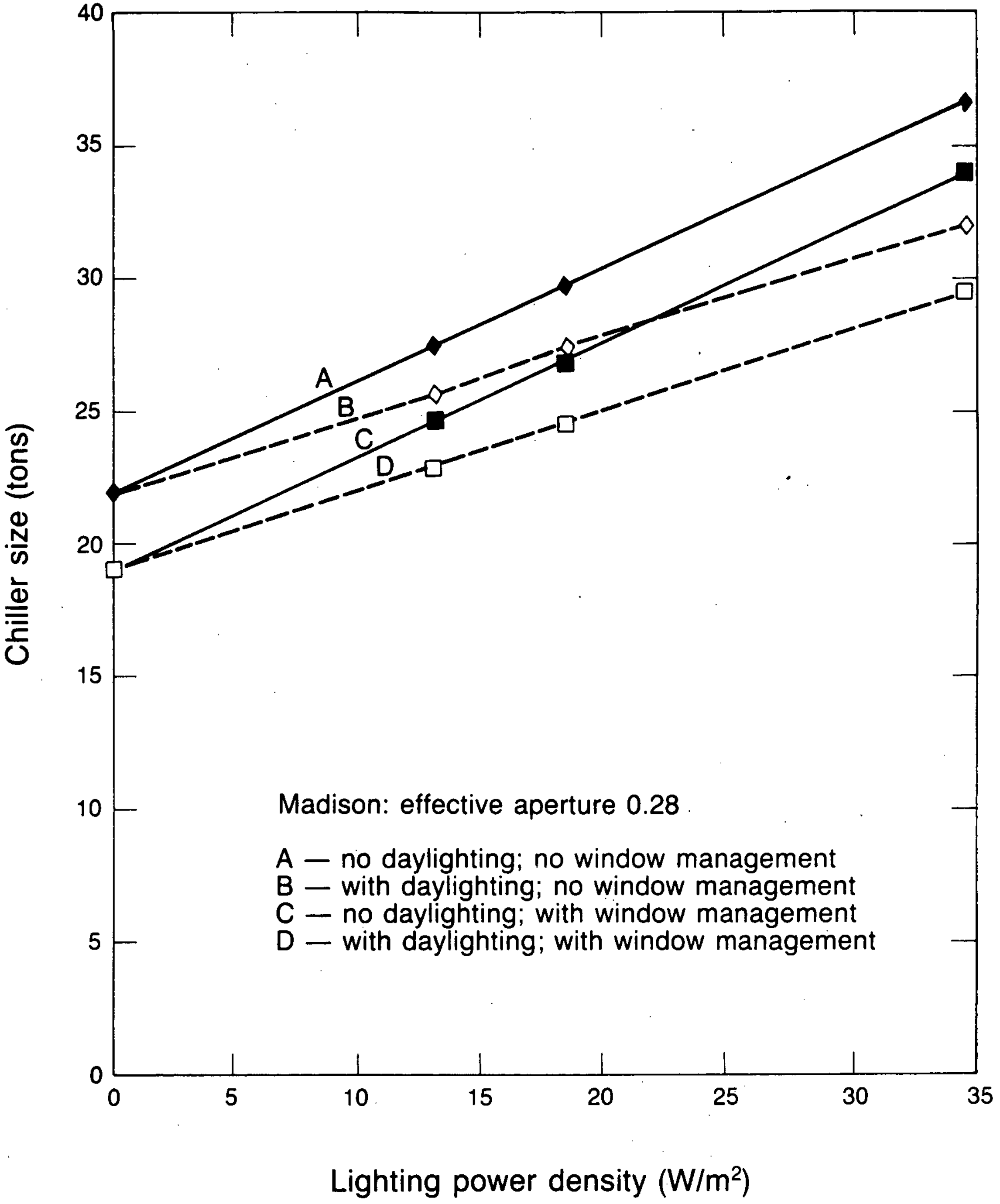


Figure 14. Peak demand vs lighting power density, Lake Charles.



XBL 8312-7479

Figure 15. Chiller size as a function of lighting power density, EA = 0.28, Madison.

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