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ABSTRACT

This study systematically explores the influence of glazing systems on component loads and annual energy use in prototypical office buildings. The DOE-2.1B building energy simulation program, which contains an integrated daylighting model, is used to determine fenestration energy performance in diverse climates. The sensitivity of total energy use to orientation, window area, glazing properties (U-value, shading coefficient, visible transmittance), window management strategy, installed lighting power, and lighting control strategy are all described. We examine the conditions under which daylighting reduces net annual energy use as well as those conditions under which energy use may increase. Combinations of wall and fenestration properties that minimize net energy requirements as a function of climate and orientation are described.

INTRODUCTION

In commercial buildings, the combined effect of electric lighting and fenestration design is a major determinant of energy requirements for space conditioning. Using daylight effectively greatly reduces 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.

Building occupants, for various reasons, have always desired daylight and view from windows. Building designers have responded to this desire but have also used fenestration as a formal element of design. When efficient energy use became a national concern, it was suggested by some that reducing fenestration area would reduce energy consumption and therefore was the appropriate response to diminishing energy supplies and rising utility bills. Today we recognize that this response is simplistic and frequently incorrect, but available building energy performance data are not adequate to definitively guide architectural practices. In the past few years energy savings from daylighting have been added to the list of fenestration's benefits, which compounds the problem of energy analysis since our ability to assess the net energy performance (thermal and daylighting effects) of fenestration is still quite limited.

While all buildings that have windows or skylights are technically "daylighted", i.e., daylight flux penetrates the interior spaces, for convenience we refer to a building that has fenestration but no lighting controls for reducing electric lighting as a "nondaylighted" building. The case in which no daylight penetrates because there are no windows is referred to as an opaque or windowless wall. We examine and compare all three cases (opaque wall, nondaylighted building, and daylighted building). We have also examined the related problem of skylight performance, which will be reported separately [1].

A principal concern of this study is to identify fenestration designs that will maximize energy conservation benefits with the use of daylight, and to compare the energy performances of these and other design options. Several published studies have examined various aspects of the problem but a definitive analysis of fenestration performance has not yet emerged from these works [2-7].

Defining fenestration´s net 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. The critical issue is the balance of the positive and negative influences of solar radiation on building energy use. Solar gain accompanies the admission of daylight and always imposes a cooling-season load but may provide a heating-season benefit. Annual energy use depends on internal loads, climate, orientation, and fenestration. Daylighting provides benefits by reducing electric lighting energy requirements and by altering the balance between heating and cooling, reducing the heat gains to the space from electric lighting. Second, there is little or no operating experience, nor are there measured performance data on fenestration´s net thermal performance. There is even less information that includes daylighting effects. Third, until recently the large computer models used for energy analysis could not model daylighting effects accurately. Finally, economic effects are related to peak electrical demand as well as to annual energy use.

This study provides technical data that can help us understand how fenestration affects various aspects of energy performance. Our work is intended to improve understanding of the relationship between fenestration parameters and electric lighting energy reductions due to daylighting, and of the relationship between fenestration design and resulting thermal loads, both with and without daylighting. This should provide a basis for cost benefits studies and for fenestration design guidelines that can lead to more energy-efficient architectural solutions.

We use an hour-by-hour energy analysis program, DOE-2.1B, as our primary simulation tool [8-10]. Multiple regression analysis used in this study to examine results from the large set of DOE-2.1B simulation data and to establish correlations among the relevant variables has allowed us to generate simple predictive equations to determine energy use as a function of key building fenestration parameters. These results and other aspects of our work on this subject are discussed elsewhere [11-12].

DESIGN OF THE PARAMETRIC STUDY

In order to study systematically the effects of fenestration design on building energy performance, a five-zone module was designed as representative of commercial office design. Details were developed through a series of sensitivity studies in which basic building design and operating parameters were varied systematically and then held fixed for the base case. The module consists of four identical perimeter zones, each 4.8 m (15 ft) deep and 30.48 m (100 ft) long, surrounding a common core (Fig. 1). The ceiling and floor were modeled as adiabatic surfaces (no net heat transfer to adjacent zones).

In order to isolate solar thermal and daylighting effects, the overall thermal conductance, U_o, of the wall (including glass) was fixed at a value that is related to heating degree days, with a decreasing U_o for increasing heating degree days characteristic of ASHRAE 90 standards. The thermal conductance of the glass (single, double, or triple) exceeds the maximum U_o so, as glass area increases, the thermal conductance of the opaque wall is decreased in order to maintain a constant U_o.

Installed electric lighting power was varied from 8 to 34 W/m^2 (0.7 to 3.2 W/ft^2) based on a design illuminance value of 538 lux (50 fc). This range covers the values of office lighting power densities one would expect to find today and in the near future. Since the design illuminance level is held constant, the varying power densities assume a wide range of lamp, ballast, fixture, and design solutions.

We model two types of lighting controls. A continuous dimming system dims from 100% light output with 100% power to 0% light output with 10% power. The residual power level is assumed to come from low-level losses associated with design characteristics of this type of control system. The system is continuously responsive to variations in daylight level and maximizes the benefit from low daylight levels. The second system provides multi-level step switching, the number of levels depending on the electric lighting power density. The simple two-step, or on/off system, reduces electric lighting power only when daylight 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 its low-level losses. Step switching is least effective in situations in which daylight provides only a small fraction of desired illuminance.

Fenestration characteristics were varied by changing the number of panes of glazing, glazing area, visible transmittance, shading coefficient, and exterior shading. To simplify analysis, a single lumped parameter consisting of the product of the floor-to-ceiling window-to-wall ratio (WWR) and the visible transmittance (T_v) was used. We call this new lumped parameter the effective aperture. Results in this paper are expressed as a function of effective aperture. The effects of mullions and other opaque fenestration elements can be accounted for in the WWR term, and dirt depreciation factors can be incorporated into the visible transmittance term for the window assembly. A constant relationship between shading coefficient (SC) and visible transmittance is assumed in this phase of our work: $SC = 1.5 \times T_v$. This relationship is characteristic of many fenestration products, but represents a somewhat conservative selection from the perspective of optimizing glazing performance.

We assumed that occupants' thermal and visual comfort requires that simple interior shading devices (shades or blinds) are used for any hour in which transmitted direct solar radiation exceeds 63 W/m^2 (20 Btu/hr ft^2), or any hour in which the glare index is greater than 20. The glare index is a measure of visual discomfort induced by the luminance of the window as viewed by an occupant. This window management system reduces solar heat gain by 40% and visible transmittance by 65% and is thus characteristic of many conventional interior shading devices.

The DOE-2.1B building energy simulation program was used to predict annual energy consumption. Simulations using WYEC (Weather-Year for Energy Calculations) weather tapes were completed for five climates that range from cooling-dominated (Lake Charles, Louisiana) to heating-dominated (Madison, Wisconsin) as well as Seattle WA, El Paso TX, and Washington D.C.

In DOE-2.1B, total plant energy consumption is calculated for the entire five-zone module. In order to examine the effects of orientation, we studied zone-level coil loads in which each zone represents one compass orientation, or the core. These coil loads include the effects of thermostat setbacks, floating temperatures and use of an economizer cycle. Coil loads for each orientation were converted to annual plant energy use using an average annual cooling system coefficient of performance (COP) of 3.0 and an average annual heating system efficiency of 0.6. When the plant energy use is summed over all zones, the total is close to the plant total given by DOE-2 for each of the climates analyzed. We therefore considered this method appropriate for the comparative approach of this study. Figure 2 shows the comparison between zone-level coil loads, plant (or site-level) energy consumption and source energy (assuming a fossil-fired electric generating plant with 33% conversion efficiency) use for effective apertures of 0 and 0.23.

The interactions between daylight and peak electrical demand are also important to a comprehensive fenestration study and are necessary for any economic optimization. Results of investigations into these issues are described elsewhere [13,14].

RESULTS

The numerous parametric runs completed to date provide a data base that demonstrates the complexity of daylighting energy analysis relative to our primary concerns--climate, orientation, and fenestration--along with other building physical and operational parameters. Certain distinct trends can be identified in the data, but results from a great number and range of building designs and climates make it apparent that generalizations from a small set of data can be misleading. The conclusions drawn from this study are limited by the specific parameters considered and are not necessarily applicable to other combinations of conditions. Although some broad generalizations can be made, the effect of daylighting on annual energy performance will be a function of the mix of heating and cooling requirements as determined by climate. Therefore, results are discussed relative to two specific climates: Lake Charles, dominated by cooling load and Madison, dominated by heating load.

Lighting Energy Impacts

Daylighting's principal effect is to reduce electric lighting usage, with secondary effects on heating and cooling loads. As effective aperture increases, electrical consumption for lighting first drops off sharply and then levels off in both climates (Fig. 3). For a given effective aperture, the fractional savings depend on the design illuminance level and the lighting control strategy. Figure 4 illustrates the change in fractional lighting energy savings as a function of effective aperture for three design illuminance values with an on-off system and for the standard continuous dimming system used in most of our simulations. For small effective apertures the savings are not linear with respect to design illuminance level. For larger apertures the curves approach a maximum, indicating a saturation of useful daylight with no further savings in electric lighting energy. This maximum is due to interaction between the building's occupancy schedule and the daily and seasonal pattern of daylight availability. This interaction is illustrated by a sample DOE-2 daylighting output report (Fig. 5), which shows average hourly and monthly savings for a south zone with a small effective aperture (0.11). Midday summer values come close to the maximum savings level of 0.90, while morning and afternoon values, particularly in winter, are much lower. Each additional increase in aperture area provides smaller and smaller incremental lighting savings. Figure 6 presents the average monthly percentage savings as a function of effective aperture, showing the significant difference between fractional savings from summer to winter. Note that while the fractional savings are a function of design illuminance criteria and lighting control type, and are independent of installed lighting power, the electrical energy savings in kWh are directly related to installed power. The associated thermal effects are treated in the following sections.

Savings would also be expected to vary with orientation, but, because the use of window management (shades or drapes) is assumed in our simulations, net annual energy consumption for lighting is similar in all perimeter zones. Use of a shading device mitigates the differences between daylight availability on north and south elevations. Without window management, the differences in lighting savings due to orientation are greatest for small effective apertures, and diminish as aperture increases. With large apertures, daylight levels become saturated on all orientations and electric lighting savings are similar.

The choice of lighting control strategy has several consequences. Figures 7 and 8 illustrate lighting energy consumption in Madison and Lake Charles with a dimming control and an on-off control both set to maintain a minimum of 538 lux (50 fc). For small apertures, the dimming control always outperforms the on-off 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 (0% light/10% power). This pattern appears in all climates and orientations, although the shapes of the curves and the crossover point depend on specifics of the climate, the lighting control system, and the design illuminance level.

Total electric lighting energy savings can be substantial. Even for the simple fenestration solutions shown here, 50 to 80% of electric lighting in the perimeter can readily be saved. Note, however, that the savings reach maximum at moderate effective apertures of 0.2 to 0.3. This suggests that for a 538-lux (50-fc) illuminance criterion, a 50% glazed wall with 50% transmittance or a 30% glazed wall with 80% transmittance will provide most of the possible daylighting savings. Walls that are fully glazed from a 30-in. high sill to an 8.5-ft. 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 due to glare from the sky. The highly reflective architectural glasses in common use, which have 8 to 14% daylight transmittance, provide substantially lower daylighting savings, generally much less than the available potential. These glazings emphasize sun and glare control at the expense of daylight transmittance. Note that if the design illuminance level were lowered to 323 lux (30 fc), which is 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.

Cold-Climate Performance

Madison, Wisconsin, was selected as a typical northerly cold climate with 4176° C (7517° F) heating degree days at base 18° C (65° F), 91° C (164° F) cooling degree days at base 24° C (75° F), and at 43.1° north latitude. In addition to lighting energy reductions from daylighting, we studied the thermal and daylighting influences of fenestration on heating and cooling zone coil loads and on total energy consumption. The relative magnitudes of heating and cooling zone coil and lighting loads for the north and south zones can be seen in Figs. 9 and 10. In this comparison, cooling load is always a monotonically rising function of effective aperture. Heating load monotonically decreases to a lower limit for all orientations. This heating trend results from the constraint that overall envelope conductance is held constant as window area is changed. If envelope conductance increases as window area increases, heating load will not decrease as rapidly or may increase, depending on window type and climate.

We first consider thermal effects for the nondaylighted case, represented as a solid line. Heating load is reduced with increased glazing because the added solar gain offsets conductive losses through the envelope. For the north zone, with only minimal direct radiation available, heating load is reduced approximately 30% with an effective aperture of 0.4 as compared to the opaque wall. For a south-oriented zone the reduction approaches 60%. Results for east and west zones fall between these two extremes. The magnitude of these reductions is largely independent of lighting load within the range considered. Adding simple overhangs increases heating loads relative to a bare window for all orientations because solar gains are reduced.

Increasing effective aperture always increases cooling loads. South, east, and west orientations show approximately the same increases, due in part to the smoothing effect of the window management strategy. Over a range of effective apertures from 0 to 0.4, the cooling load more than **triples** for the south, east, and west zones and more than **doubles** for the north. These fractional increases are constant for a lighting load ranging from 12.9 to 23.7 W/m^2 (1.2 to 2.2 W/ft^2). Overhangs substantially reduce cooling loads and, if sufficient shading is provided, reduce the south, east, and west cooling loads to the level of the north zone.

Daylighting strategies directly affect electric lighting loads and indirectly affect heating and cooling loads by altering the thermal balance of the space. For large effective apertures, a dimming control saves approximately 67% of the electric lighting consumption as compared to the nondaylighted case. During winter months, the thermal balance point of the zone shifts when the electric lighting is dimmed and additional heating energy is required. The magnitude of the increase in heating load depends on orientation, even though window management mitigates these differences. The worst case occurs in the north zone, which shows a 25% increase in heating load for large effective aperture (Fig. 9) compared to the nondaylighted case. For the south zone, however, the increase is much smaller, approximately 5%, because the solar gain that was not useful when the electric lights were on now offsets part of the increased heating load (Fig. 10).

In the summer, reduced electric lighting diminishes cooling loads compared to the nondaylighted case. Cooling load reductions in the north and south zones show similar patterns, both decreasing in proportion to the thermal reduction in lighting load. These results can be seen in Figs. 9 and 10, where we show changes in cooling load relative to an opaque wall for both the daylighted and nondaylighted cases.

These data can now be assembled and factored by boiler efficiency and chiller COP to provide an overall picture of total zone energy consumption as a function of orientation, glazing parameters, and lighting load. Figures 11 and 12 show sample results for north and south zones for two different lighting loads: 12.9 and 23.7 W/m^2 (1.2 and 2.2 W/ft^2). The solid line curve (for the nondaylighted case) drops initially to reflect heating energy savings but then rises, due to increased cooling energy requirements, as aperture size increases. We show two curves for the daylighted cases, one for continuous dimming and one for step switching. As described earlier, a continuous dimming system outperforms step switching with small effective apertures, but the curves cross and change relative positions for larger apertures. Note that for large effective apertures, the fractional lighting energy savings are so large that annual energy use does not depend heavily on installed lighting power density.

Energy consumption for a daylighted north zone decreases continually through the range of effective apertures studied here for both lighting power densities. We conclude that for north orientations daylighting with relatively large windows outperforms a solid insulated wall and the performance is substantially better than that of the nondaylighted case. This conclusion includes the assumption described earlier that overall wall conductance is held constant.

For the south orientation (Fig. 12), the initial trends remain the same. However, because the cooling impact is more severe, an optimum effective aperture is reached after which total energy consumption, dominated by the rising cooling load, increases. In this case there is an obvious tradeoff between cooling and daylighting, and the optimum solution is somewhat 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 0.22 and 0.30. However, even at the largest value studied (approximately 0.4), the energy consumption with daylighting is much less than that of an opaque insulated wall and not much more than the minimum value. 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 is not as sharply defined. Again, the energy requirement with daylight is still less than that of an opaque wall for all effective apertures in our range.

The perspective on fenestration performance would change if utility costs were compared. A proper economic cost/benefit analysis would add a substantial cost penalty to cooling and lighting energy (electric energy plus peak demand charges) relative to heating energy (gas). This would tend to shift the "optimum" perspective to emphasize lighting and cooling effects at the expense of heating. A detailed economic analysis is beyond the scope of this paper.

Hot-Climate Performance

The hot climate used in this study is Lake Charles, Louisiana with 1051^{o} C (1892^{o} F), heating degree days at base 18^{o} C (65^{o} F), 464^{o} C (835^{o} F), cooling degree days at base 24^{o} C (75^{o} F), and at 30.1^{o} north latitude. A summary of some of our simulation results is presented in Figs. 13 and 14. This climate is dominated by cooling loads to the point that the net annual thermal effect of solar gain through even modest amounts of glass is a potentially serious energy penalty. Heating requirements are so minimal that solar thermal gain is essentially unusable to offset heating needs, and only daylighting can reverse the negative energy contribution of windows. The energy consumption of all nondaylighted cases increases with increasing effective aperture.

Fenestration systems that admit daylight will offset electric lighting but will increase cooling loads. Their benefit is thus a function of differences between electric lighting savings and solar-induced cooling loads. In the north zone (Fig. 13), where the daylighting source is less variable and direct sunlight is not often present, potential benefits (compared to identical nondaylighted cases) increase with electric lighting power density. The effective aperture that minimizes energy consumption is between 0.15 and 0.25 for the case of efficient electric lighting and increases to between to 0.20 and 0.30 for the case with higher installed power density. In both cases, however, the optima are rather flat, allowing a range of fenestration design options with only small differences in energy performance. As was seen in the case of Madison, large apertures minimize lighting energy consumption and thus reduce the importance of installed lighting power density.

In several respects the trends for the south orientation (Fig. 14) are similar to those for the north. Window shading management modulates solar radiation so that daylighting produces electric lighting savings for the south zone that are similar in magnitude to those of the north zone (although they occur at smaller effective apertures). Although maximum savings are similar to those in the north zone, the range of beneficial effective apertures is substantially reduced and the design optimum occurs at a smaller effective aperture. With an efficient electric lighting system requiring 12.9 W/m^2 (1.2 W/ft^2), the effective aperture must be less than 0.25 for the daylighting case to have an energy consumption comparable to that of a windowless building, although larger windows will still save energy relative to the nondaylighted case.

The importance of the balance between lighting savings and cooling costs cannot be overestimated. It has often been stated that since the efficacy of daylight (90-130 lm/W) is higher than that of electric lighting systems (60-90 lm/W), daylighting always produces a lower cooling load impact than electric lighting. We believe this is an incorrect generalization, although there are circumstances in which it will be true. A significant result of this study is to explain, below, why the generalization is incorrect, to give examples of specific instances in which it holds, and to suggest that this issue be critically explored in greater depth.

Figure 15 shows the cooling loads as a function of effective aperture for three values of installed lighting power density for both nondaylighted and daylighted cases. Note that for the case of 7.5 W/m^2 (0.7 W/ft^2), and 18.3 W/m^2 (1.7 W/ft^2), cooling loads for the daylighted cases rise monotonically with increasing aperture. Daylighting never results in lower cooling loads than with an opaque wall, although it obviously results in lower cooling loads than for the equivalent nondaylighted case. Stated differently, each increment of additional glazing reduces lighting energy consumption by displacing electric lighting, but in doing so increases cooling loads. Thus the cooling load increase due to solar gain with daylighting is greater than the cooling load impact of the equivalent electric lighting that was replaced. For the highest installed power density, 29.1 W/m^2 (2.7 W/ft^2) the cooling load for the daylighted case first falls slowly and then rises through the rest of the aperture size ranges. This indicates that there are conditions under which the cooling load impact of daylight is less than that of electric light.

The fallacy of the comparative efficacies of daylight and electric light is based on a misuse of the term efficacy. The cooling load impact of any source of radiant energy is dependent not only on the intrinsic spectral distribution of the source but also on how that source contributes to heat gain and lighting requirements in the building. In the case of electric lighting, we can define an "effective efficacy" as the ratio of useful illuminance (in this case, the design illuminance), 538 lux (50 fc), to the input power density, which varies. This results in an effective efficacy of 19 lumens/Watt (lm/W), 29 lm/W, and 72 lm/W, corresponding to lighting power densities of 29.2 W/m^2, 18.3 W/m^2, and 7.5 W/m^2, respectively. The reason that these values differ from the typically quoted fluorescent system values is that the effective efficacy accounts for light that never contributes to useful workplane illuminance.

Direct calculation of an effective efficacy for daylight is much harder because the illuminance distribution varies in time and space. Two primary effects reduce the effective efficacy of daylight: the non-uniform distribution of daylight and the design of simple lighting control systems. Our lighting control system adjusts the electric light in response to the illuminance at a point 2/3 of the distance from the window to the back wall of the room. Under typical sky conditions in a small perimeter room, the illuminance falls off sharply from the window to the back wall. The average illuminance throughout the space is approximately twice the illuminance at the control point. Since the electric lighting power is set based on the control point value at any given time, there is approximately twice the average luminous flux (and thus twice the radiant gain) at the workplane than is accounted for by the value measured at the lighting control point. This reduces the effective efficacy by a factor of two. In addition, just as in the case of electric lighting, a fraction of the admitted luminous flux is absorbed by room surfaces and never provides useful illuminance. In a sidelighted space this fraction will normally be greater than in the case of ceiling-mounted electric light since the flux is admitted from the side. There are additional losses in the window system and other factors that further reduce effective efficacy. When we account for all these factors, using the perimeter office we have modeled, we find the nominal efficacy of daylight has been reduced to an effective efficacy of about 30 lm/W. This suggests that of the three electric lighting power densities we considered, the daylight strategy reduces cooling loads only in the case of the least efficient electric lighting system and then only for small apertures. This approximate analytical result is confirmed by the simulation results shown in Fig. 15. As aperture size increases, the effective efficacy of daylight will always be further reduced.

Daylight can reduce cooling loads relative to many electric lighting designs if we alter the parameters of this study. For example, in our studies of a skylighted space [1, 14] with properly distributed skylights, the illuminance distribution is more uniform and the room optical losses are lower so the effective efficacy is much higher than in the sidelit perimeter office. Furthermore, the nature of this problem suggests that advanced glazing systems having better spectral and directional control properties, and improved lighting controls would also greatly improve the cooling load impacts. Until these interrelated effects are better understood, claims regarding the impacts of daylighting on cooling loads should be examined carefully on a case-by-case basis.

In the cooling-dominated case, the most effective energy-conservation strategy would be to maximize the efficacy of the electric lighting system as well as using daylight. For an opaque wall, reducing electric lighting power from 23.7 to 12.9 W/m^2 (2.2 to 1.2 W/ft^2) reduces total annual south-zone consumption by 25%. With optimum daylighting design and a lighting power density of 12.9 W/m^2 (1.2 W/ft^2), total annual consumption is further reduced by 9%.

SUMMARY AND CONCLUSIONS

Fenestration design is an important element of an overall design strategy for energy conservation in nonresidential buildings. Potential performance is intimately related to daylighting and the solar control measures used. Results from an hour-by-hour simulation model that accounts for the influence of daylighting help develop our understanding of this complex subject. An extensive set of parametric analyses for a simple office module in several climates suggests the following conclusions:

1. Effective use of daylight and lighting controls will produce large reductions in electric lighting energy consumption.

2. 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.

3. Control of solar gain is vital if daylighting strategies are to provide net energy benefits.

4. Daylighting may not always be a "cooler" light source than electric lighting--the conditions under which this statement holds true depend on the details of window management, electric lighting control design, and installed lighting power.

5. Installed lighting power and the lighting control system characteristics are major factors in determining the real value of daylighting strategies.

6. Daylighting optimization is sensitive to climate, orientation, and other modeling assumptions.

7. Effective aperture is a useful concept for evaluating and comparing alternative fenestration design.

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. 9. We believe that the regression techniques that we used to simplify the representation of a large data set on fenestration performance could also be used to convert our data set to a simple, yet powerful, design tool [11]. We are also working on experimental projects to provide the quantitative data required to build confidence in the algorithms used in the simulation models [15], and have begun to collect detailed performance data in several innovative daylighted buildings.

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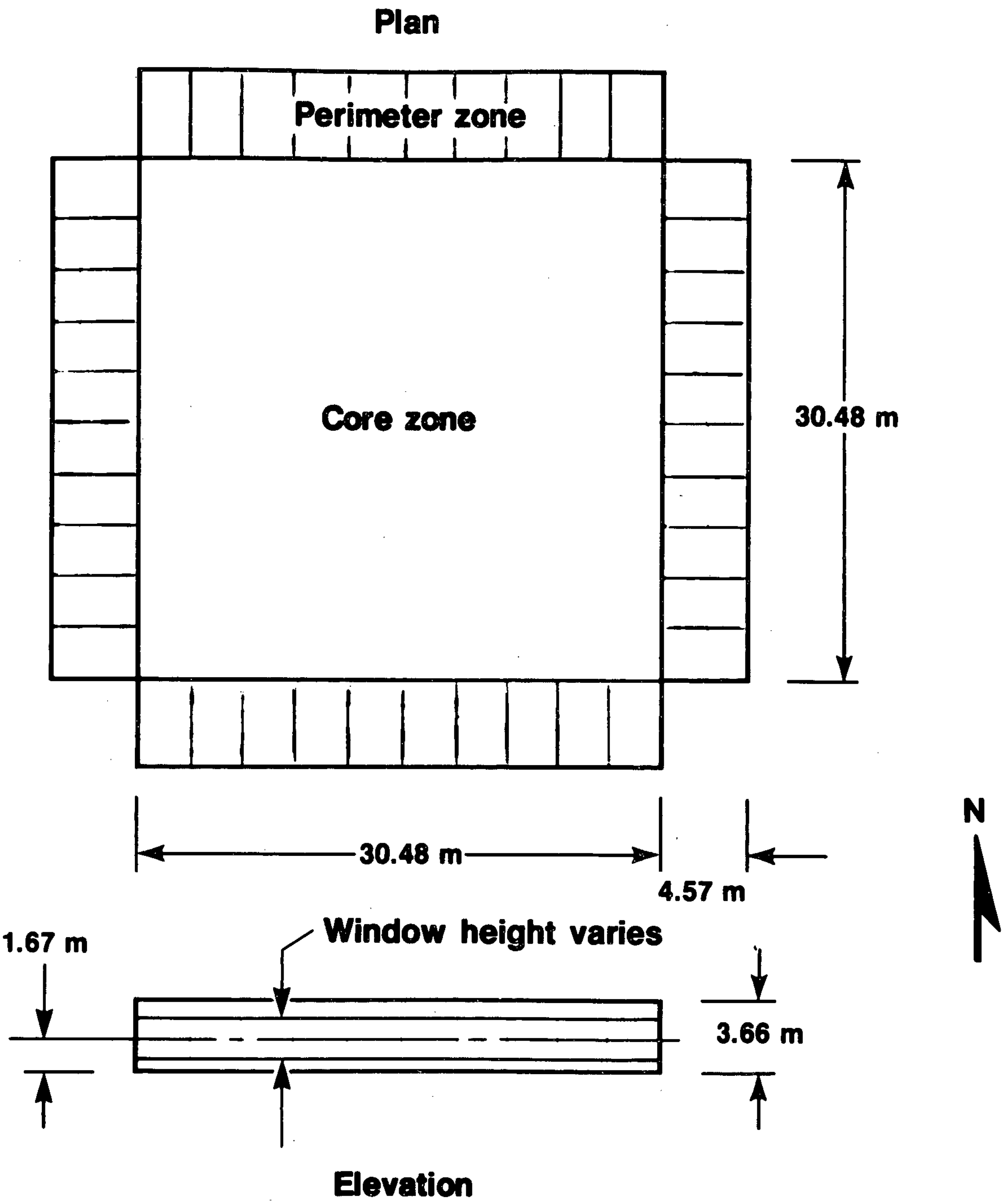
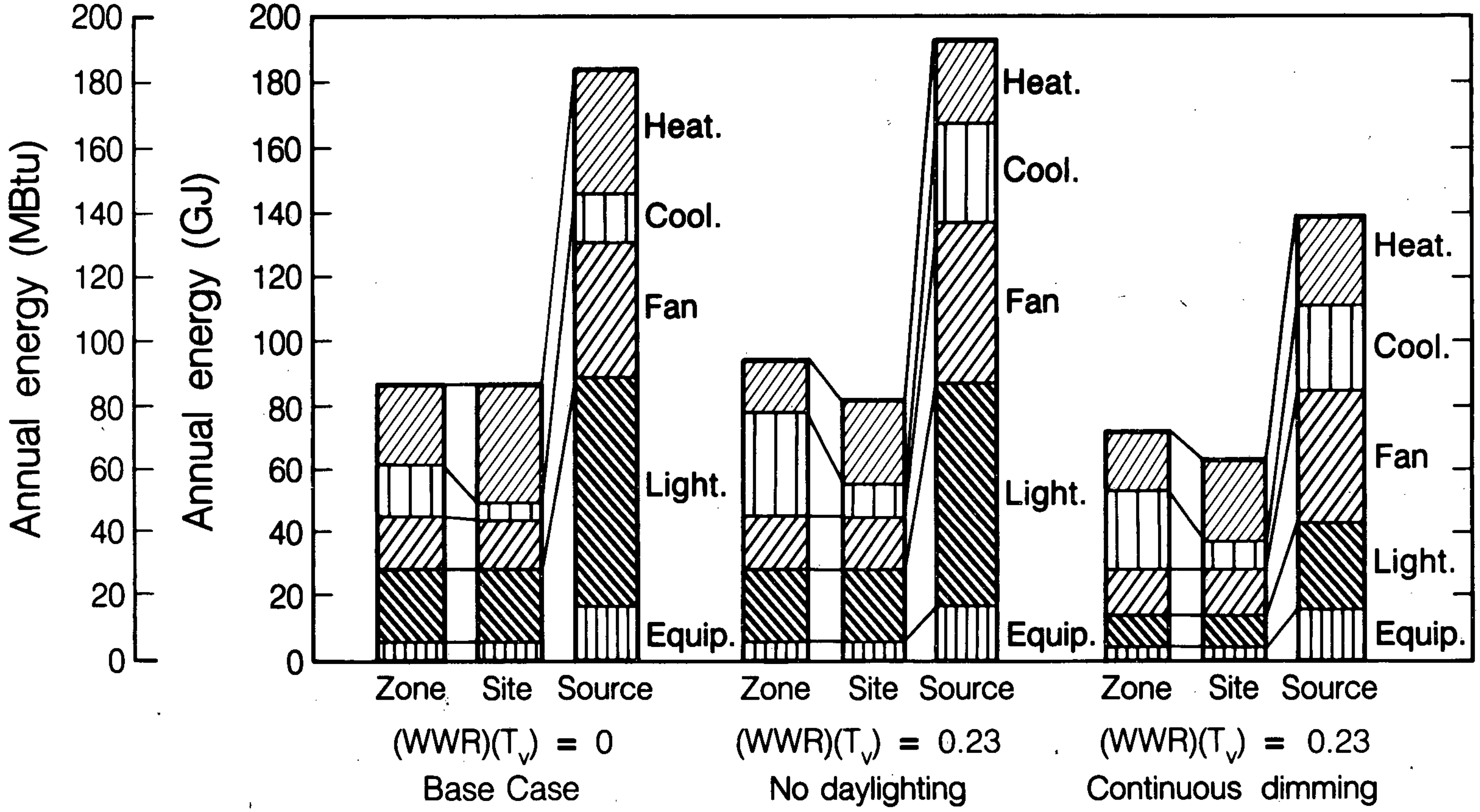


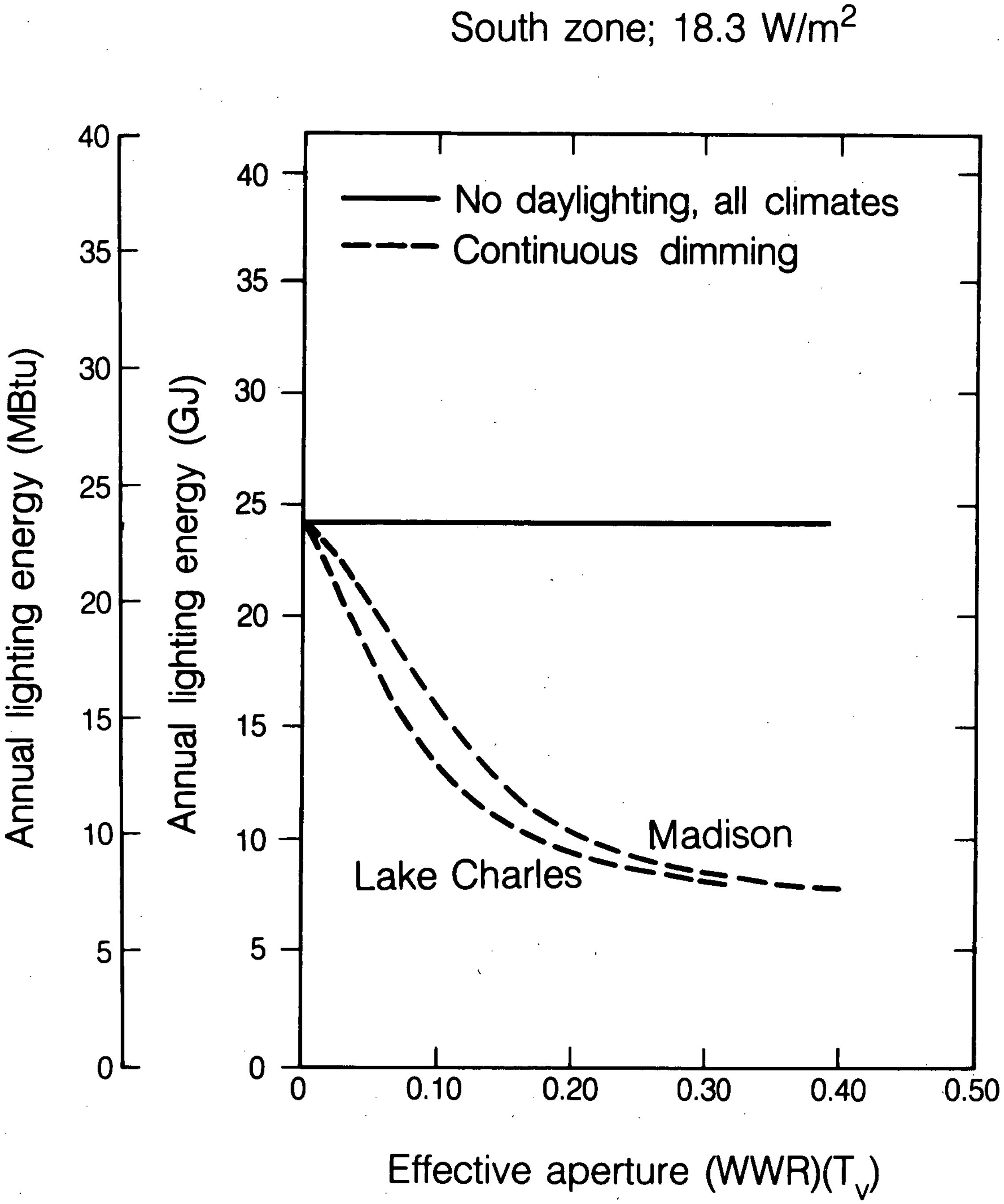
XBL 838-2960A

Fig. 1. Office building module.



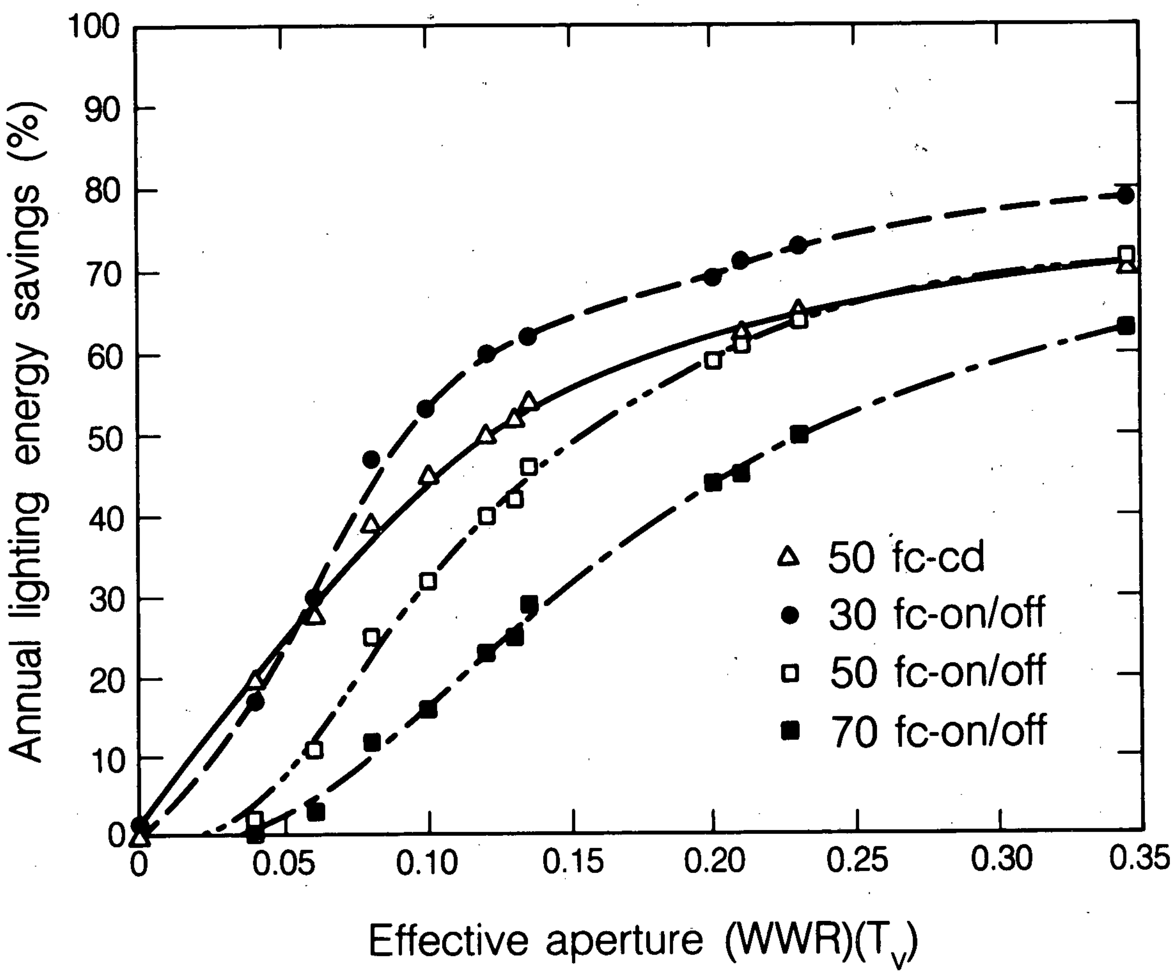
XBL 847-9802

Figure 2. Component energy comparison for Madison WI, 18.3 W/m^2 (1.7 W/ft^2).



XBL 847-9803

Fig. 3. Annual lighting energy as a function of effective aperture for Madison WI and Lake Charles LA, south zone, 18.3 W/m^2 (1.7 W/ft^2).

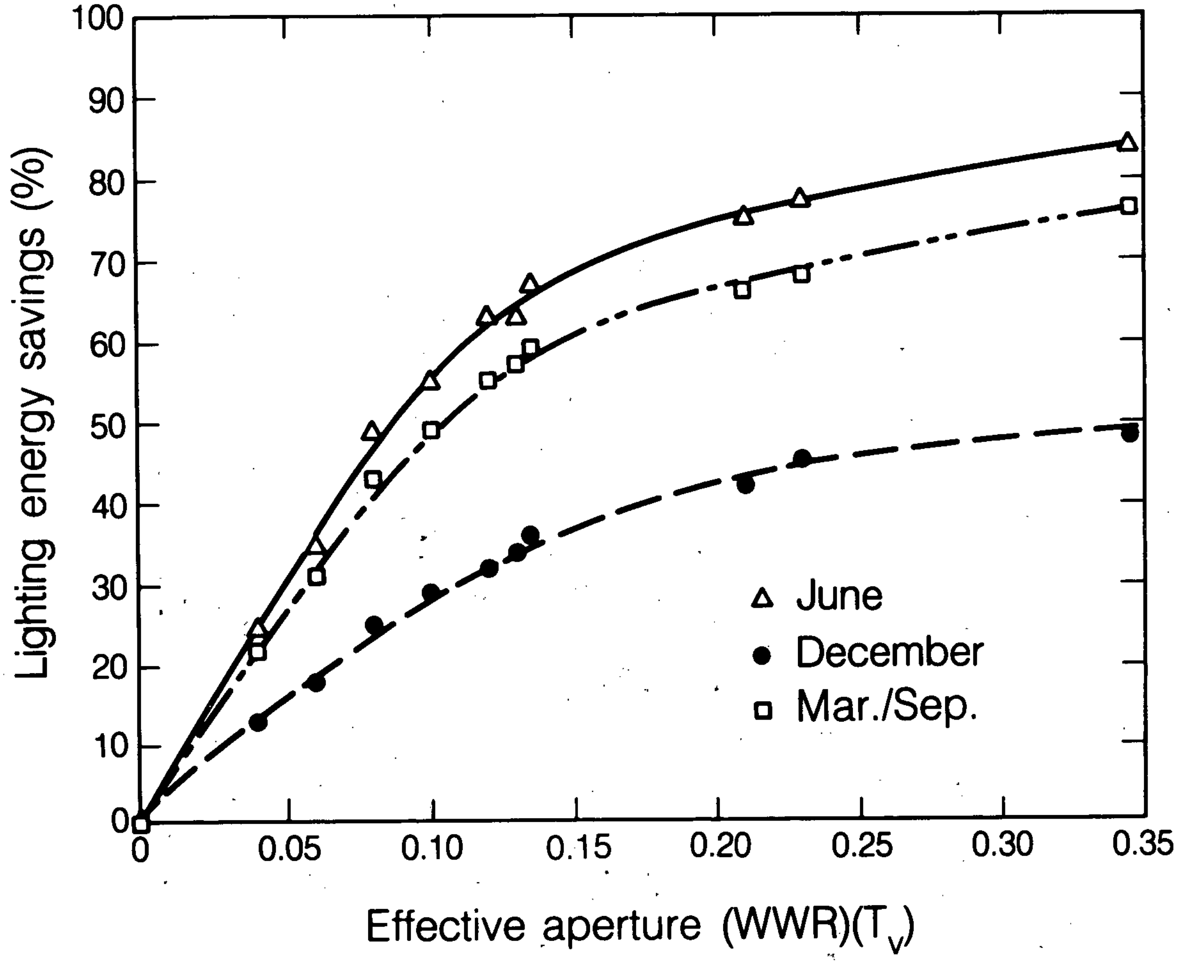


XBL 847-9804

Fig. 4. Annual percent lighting energy savings as a function of effective aperture comparing lighting control type and illuminance variations for Madison WI, south zone.

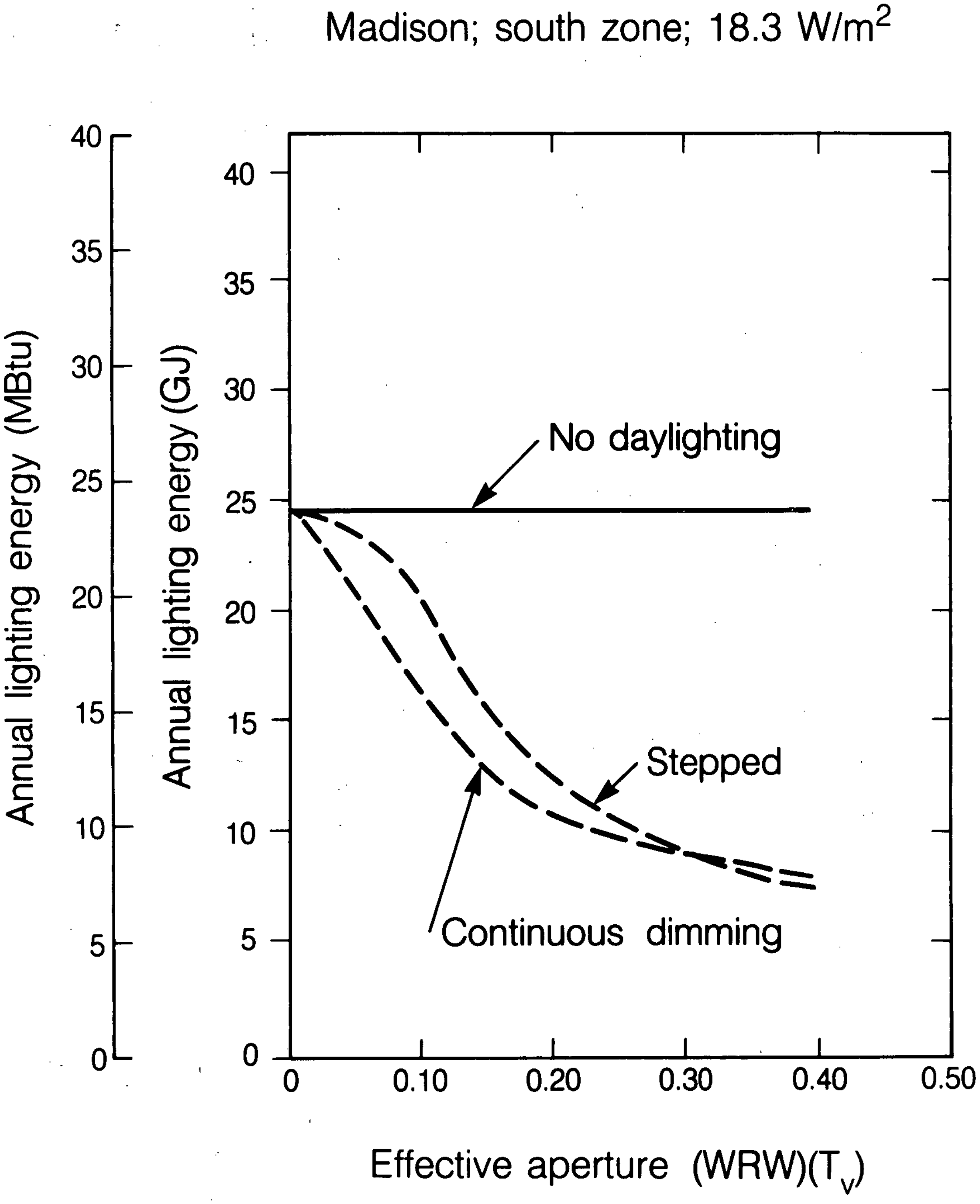
	HOUR OF DAY																								
MONTH	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	17	18	19	20	21	22	23	24	ALL HOURS
JAN	0	0	0	0	0	0	0	2	22	48	57	65	66	61	52	30	8	0	0	0	0	0	0	0	34
FEB	0	0	0	0	0	0	0	8	36	53	61	67	68	60	59	48	21	1	0	0	0	0	0	0	40
MAR	0	0	0	0	0	0	6	30	51	63	70	74	73	72	65	58	45	13	0	0	0	0	0	0	50
APR	0	0	0	0	0	4	31	60	51	60	71	79	78	70	60	52	58	28	2	0	0	0	0	0	53
MAY	0	0	0	0	0	18	44	65	75	65	68	75	70	63	65	76	61	36	10	0	0	0	0	0	58
JUN	0	0	0	0	1	20	40	58	77	65	67	74	69	69	69	84	66	43	18	1	0	0	0	0	60
JUL	0	0	0	0	0	14	36	62	78	68	66	71	67	61	71	85	72	45	19	1	0	0	0	0	60
AUG	0	0	0	0	0	5	34	68	64	69	73	79	84	75	72	73	71	36	5	0	0	0	0	0	61
SEP	0	0	0	0	0	0	22	56	58	67	78	82	82	77	71	62	56	12	0	0	0	0	0	0	57
OCT	0	0	0	0	0	0	7	35	52	59	67	64	68	67	57	44	25	0	0	0	0	0	0	0	45
NOV	0	0	0	0	0	0	0	13	31	48	58	62	54	51	40	22	2	0	0	0	0	0	0	0	31
DEC	0	0	0	0	0	0	0	3	23	42	57	58	58	57	49	29	0	0	0	0	0	0	0	0	32
ANNUAL	0	0	0	0	0	6	24	48	52	59	66	71	70	65	61	56	36	16	5	0	0	0	0	0	49

Figure 5. Percent lighting energy reduction by daylight for Madison WI, south zone. Effective aperture = 0.11.



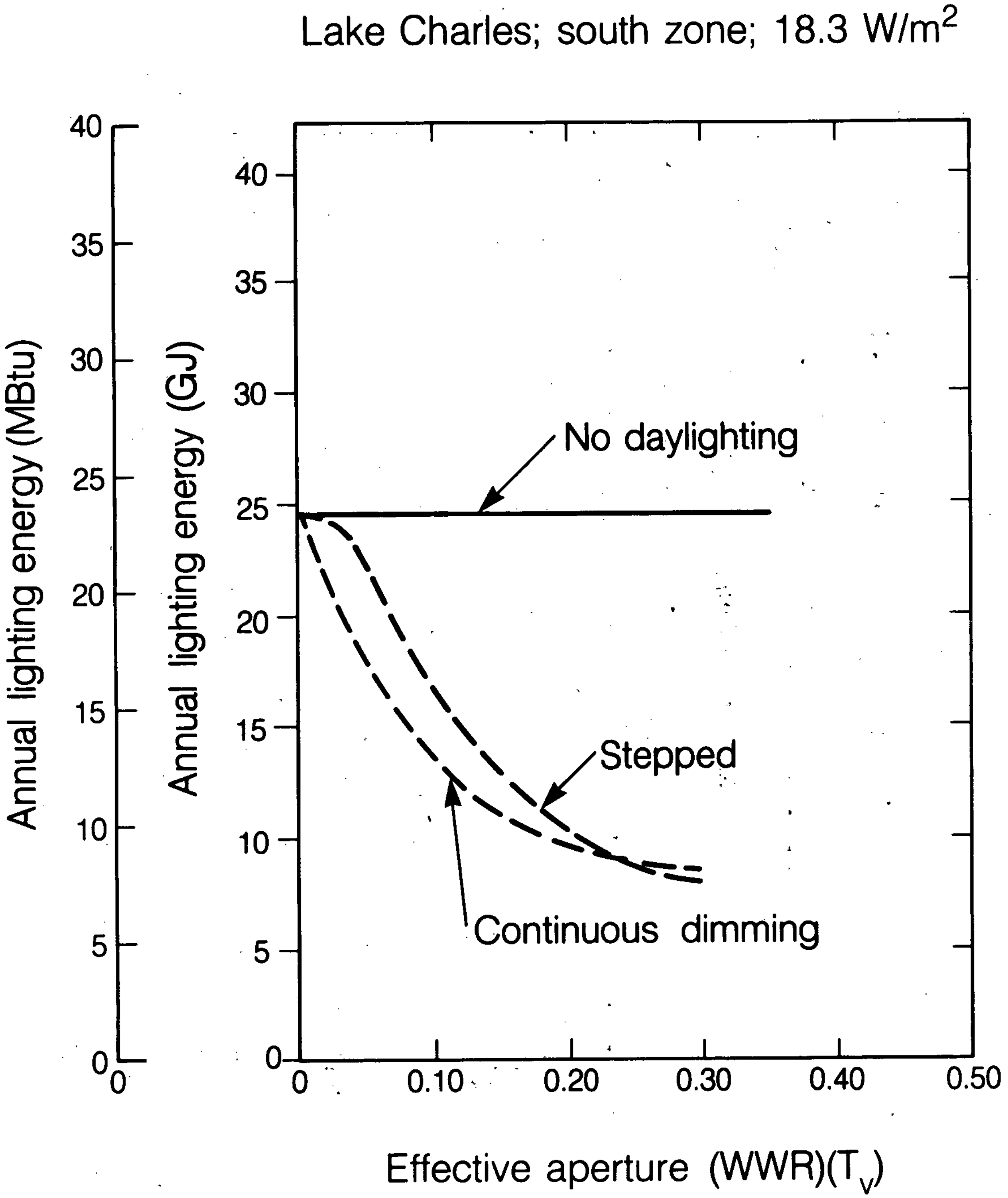
XBL 847-9805

Fig. 6. Seasonal variation of percent lighting energy savings as a function of effective aperture for Madison WI, south zone.



XBL 847-9806

Fig. 7. Annual lighting energy as a function of effective aperture for Madison WI, south zone, 18.3 W/m^2 (1.7 W/ft^2).



XBL 847-9807

Fig. 8. Annual lighting energy as a function of effective aperture for Lake Charles LA, south zone, 18.3 W/m^2 (1.7 W/ft^2).

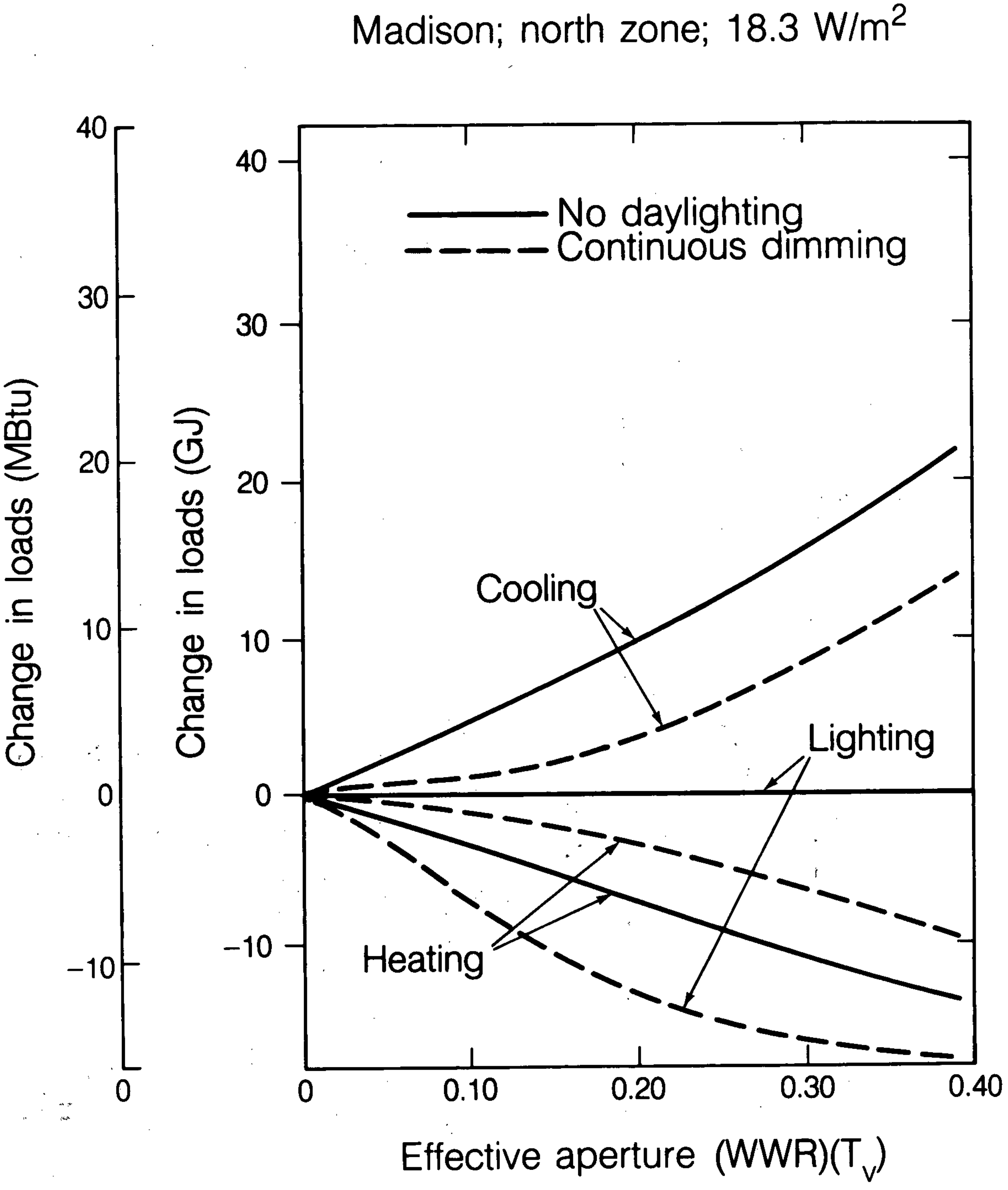
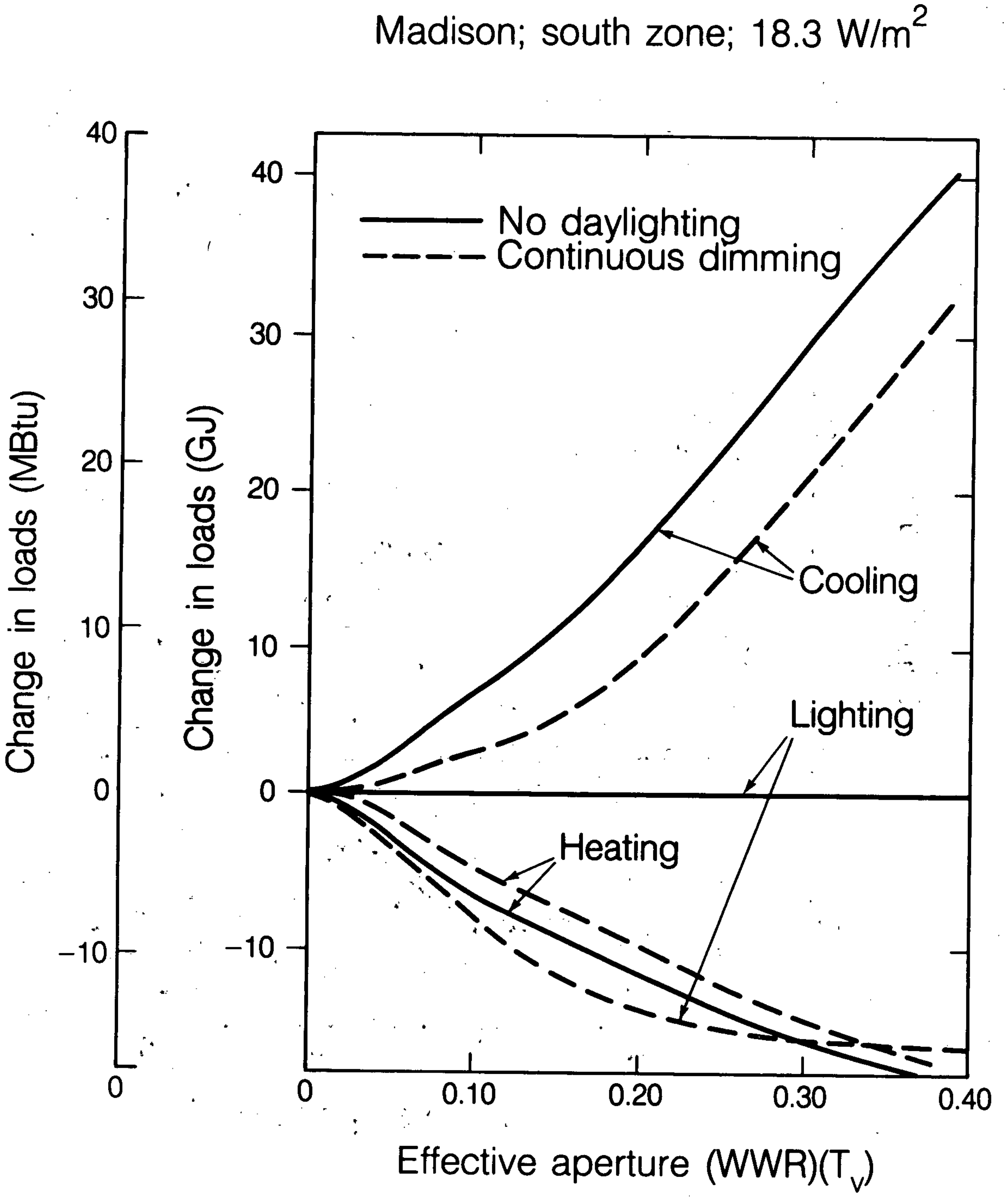
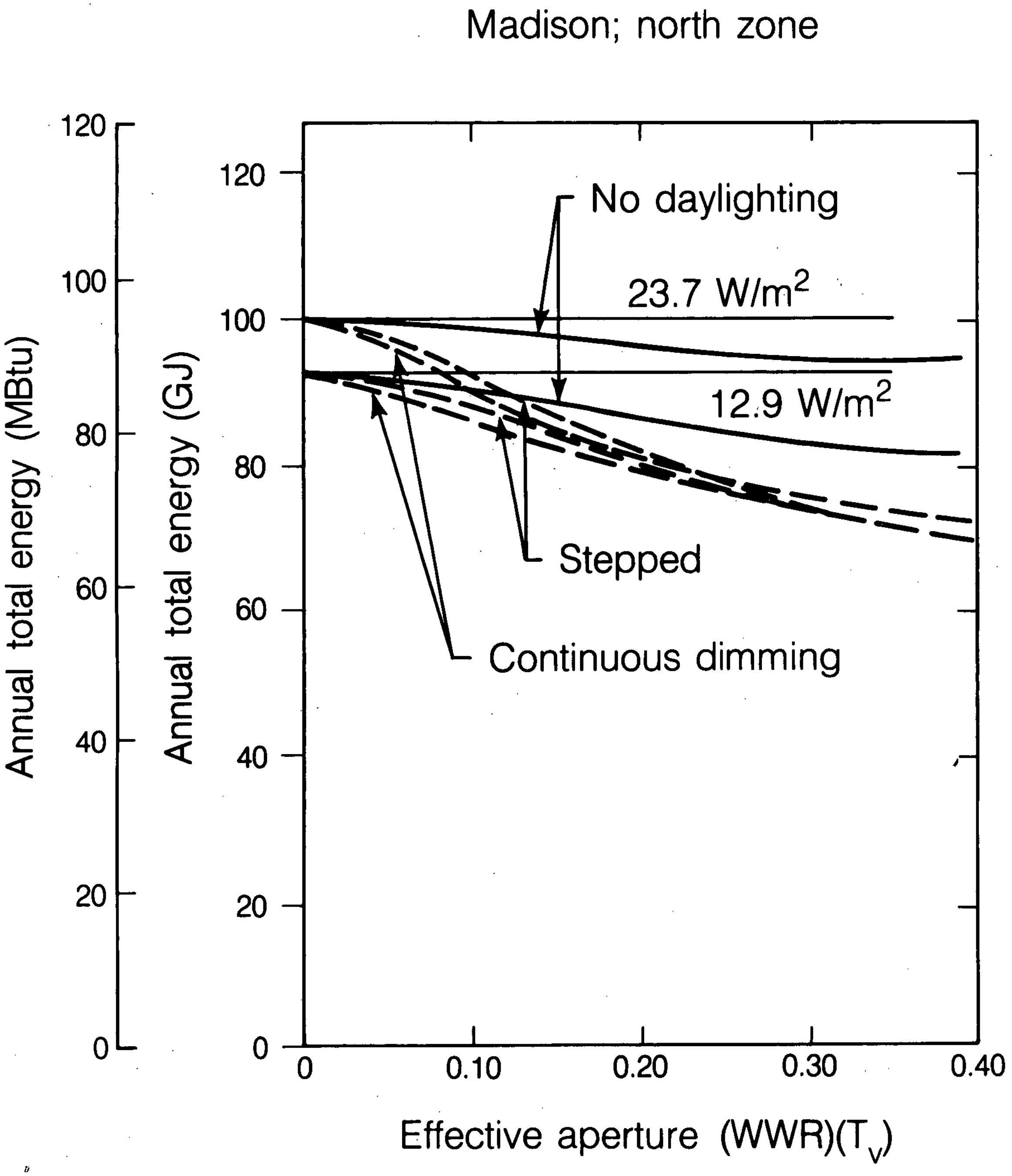


Fig. 9. Changes in annual zone load component energy quantities as a function of effective aperture for Madison WI, north zone, 18.3 W/m^2 (1.7 W/ft^2).



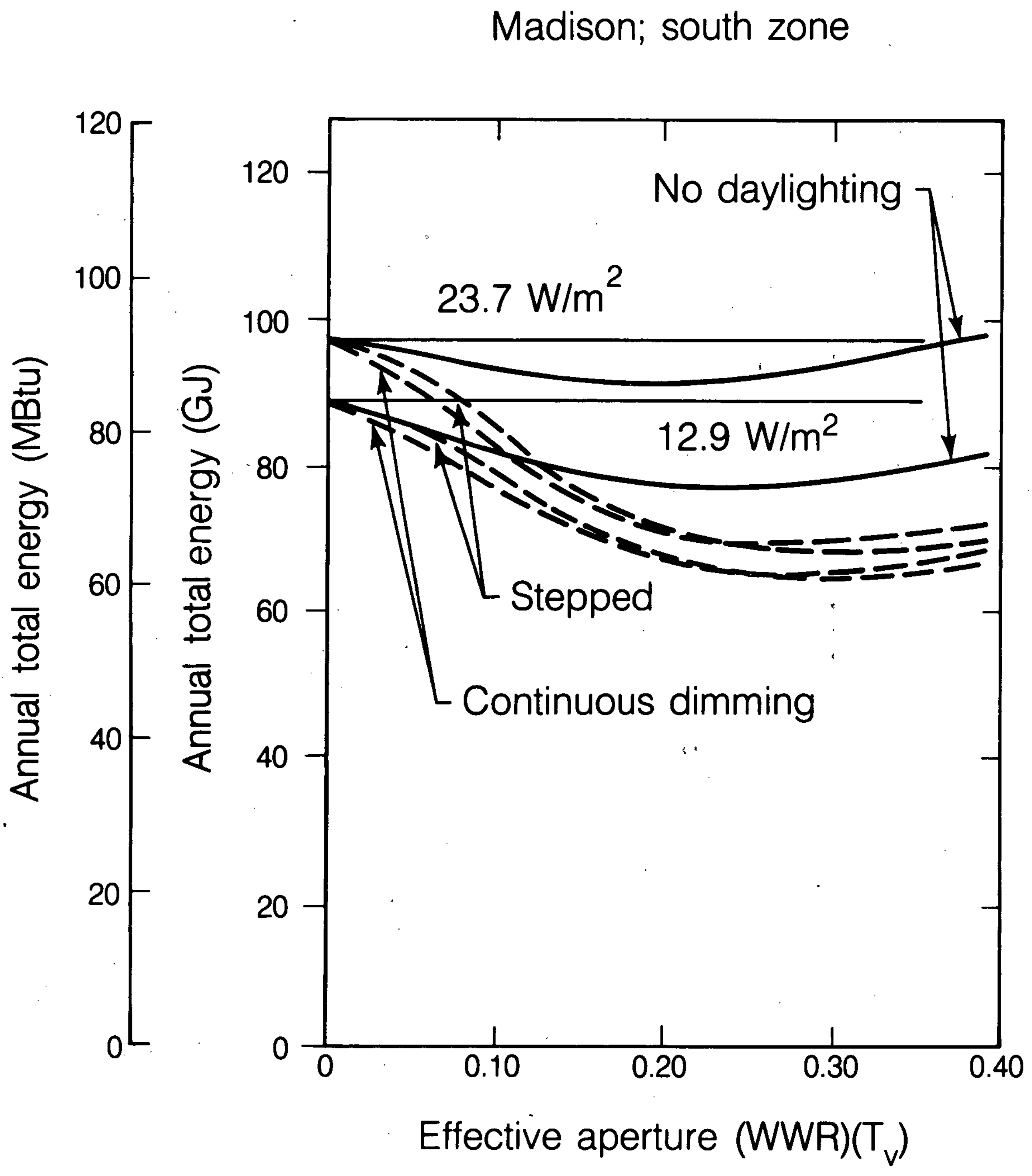
XBL 847-9809

Fig. 10. Changes in annual zone load component energy quantities as a function of effective aperture for Madison WI, south zone, 18.3 W/m^2 (1.7 W/m^2).



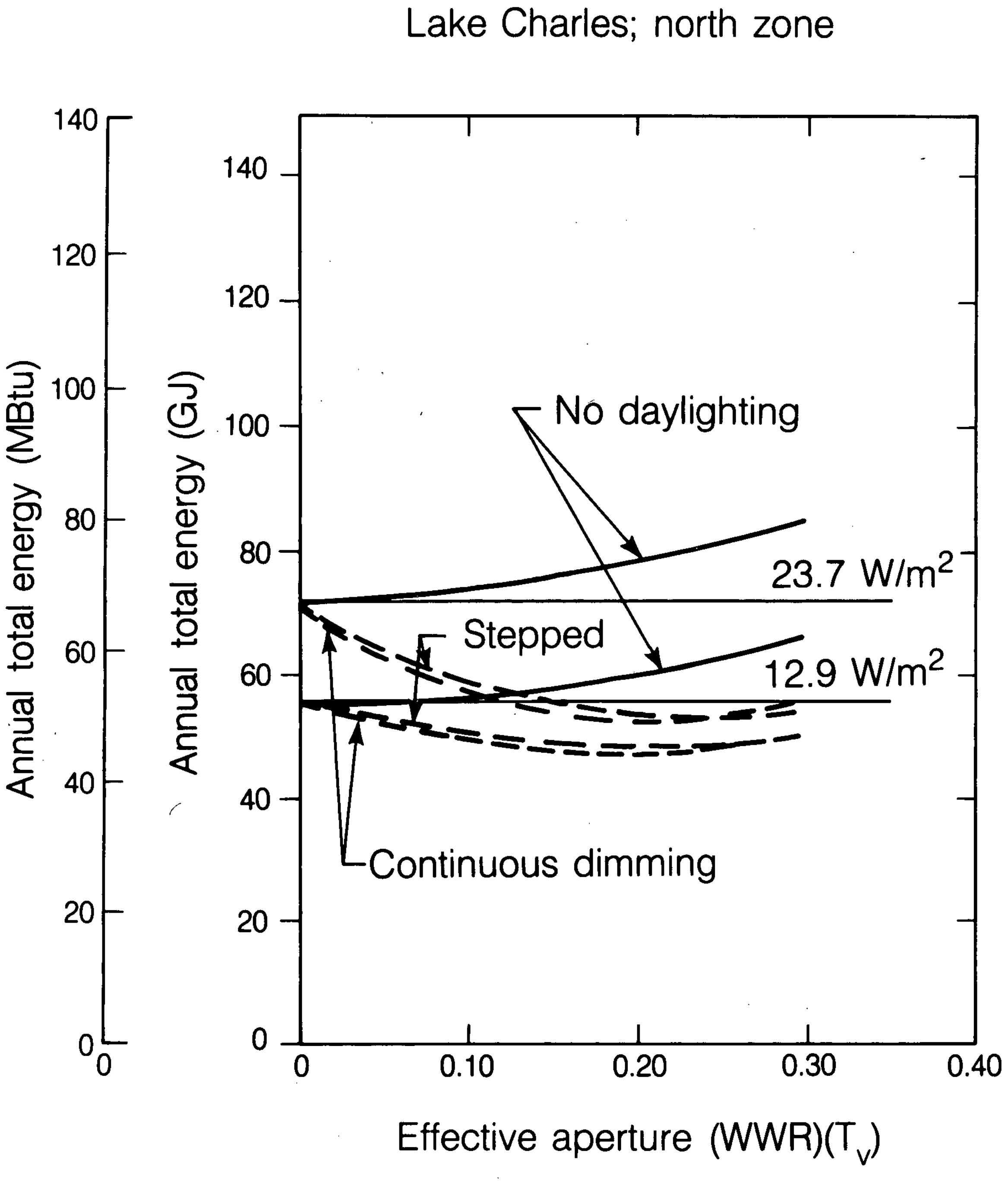
XBL 847-9810

Fig. 11. Annual total energy use as a function of effective aperture for Madison WI, north perimeter zone, 23.7 W/m^2 (2.2 W/ft^2) and 12.9 W/m^2 (1.2 W/ft^2).



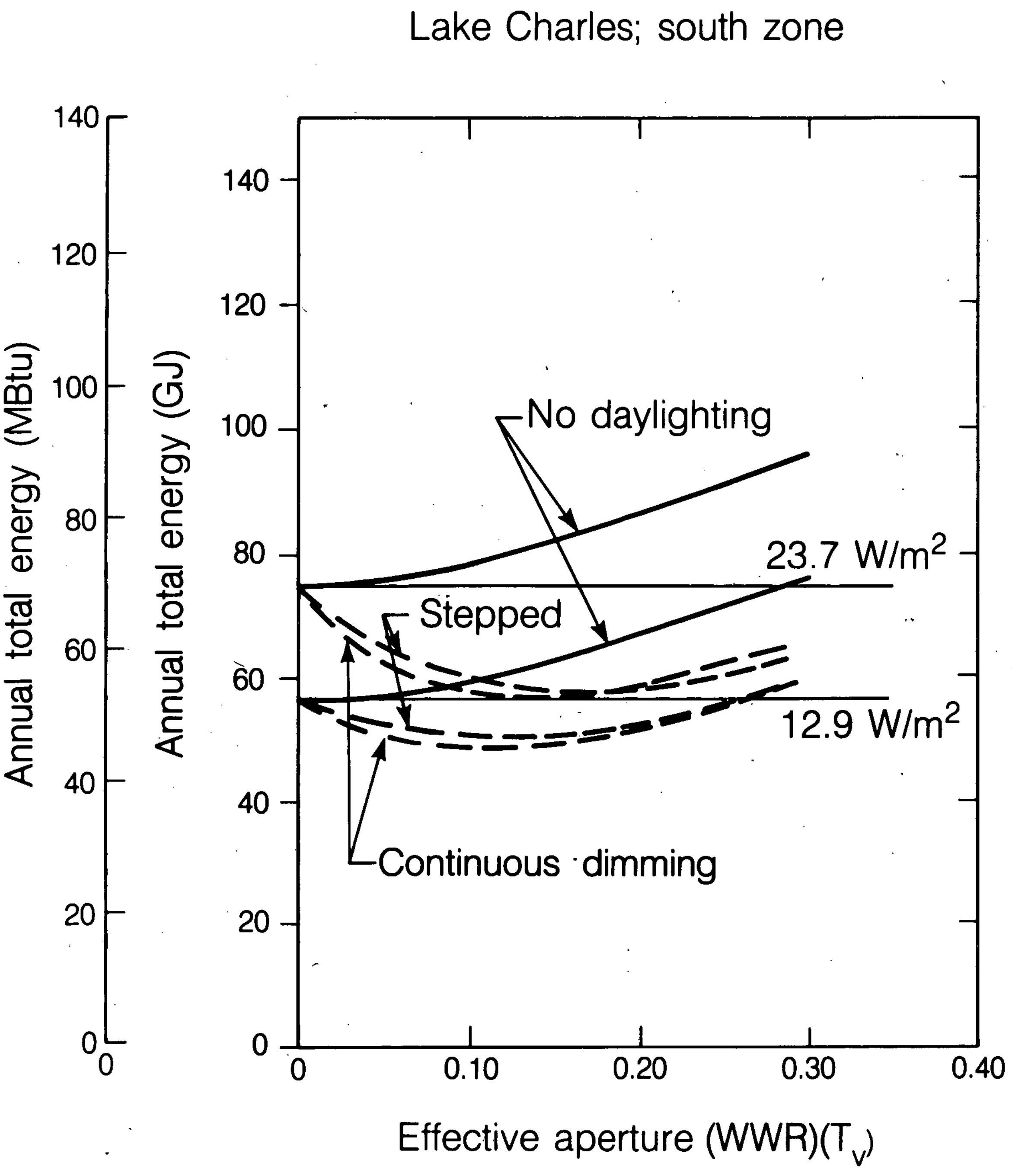
XBL 847-9811

Fig. 12. Annual total energy use as a function of effective aperture for Madison WI, south perimeter zone, 23.7 W/m^2 (2.2 W/ft^2) and 12.9 W/m^2 (1.2 W/ft^2).



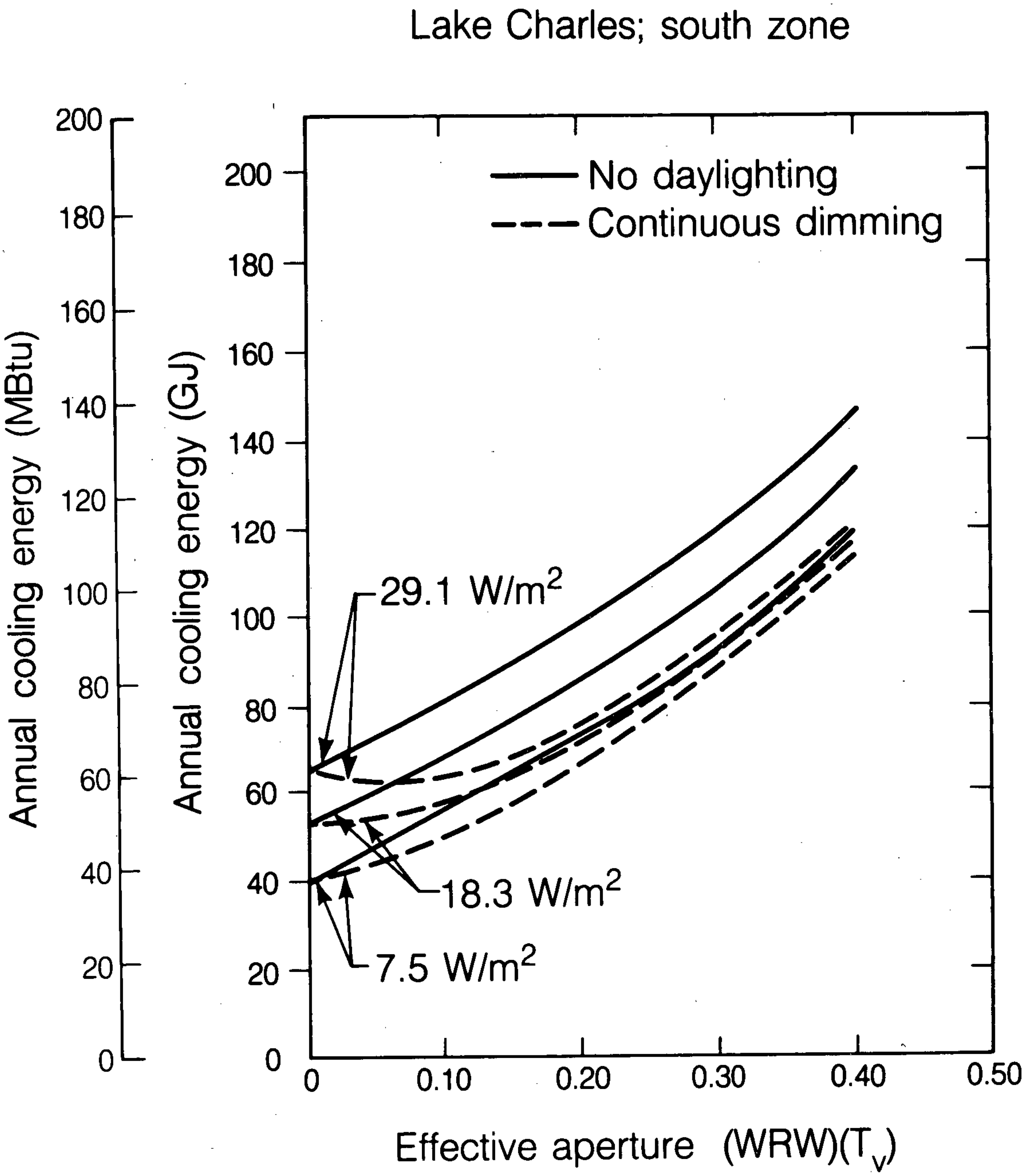
XBL 847-9813

Fig. 13. Annual total energy use as a function of effective aperture for Lake Charles LA, north zone; 23.7 W/m^2 (2.2 W/ft^2) and 12.9 W/m^2 (1.2 W/ft^2).



XBL 847-9812

Fig. 14. Annual total energy use as a function of effective aperture for Lake Charles LA, south zone, 23.7 W/m^2 (2.2 W/ft^2) and 12.9 W/m^2 (1.2 W/ft^2).



XBL 847-9820

Fig. 15. Cooling energy as a function of effective aperture for Lake Charles LA, south zone, 29.1 W/m^2 (2.7 W/ft^2), 18.3 W/m^2 (1.7 W/ft^2), and 7.5 W/m^2 (0.7 W/ft^2).

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