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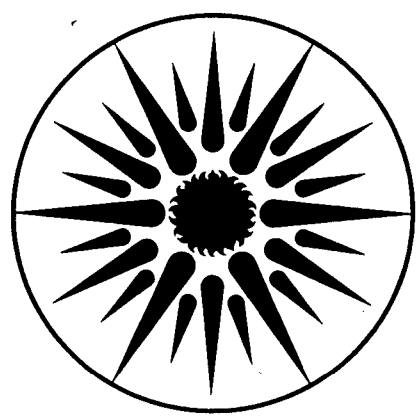
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THE EFFECT OF DAYLIGHTING STRATEGIES ON BUILDING
COOLING LOADS AND OVERALL ENERGY PERFORMANCE

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and S. Selkowitz

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AND OVERALL ENERGY PERFORMANCE

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ABSTRACT

It has been demonstrated that daylighting, by reducing electric lighting requirements, is one of the most effective energy-conservation strategies in office building envelope design. Additionally, because the luminous efficacy of daylight outdoors is higher than that of most electric lighting systems, it is frequently assumed that buildings designed for daylighting will have smaller cooling loads than similar buildings not designed for daylighting. This assumption is valid only within certain specific design limits. Outside these limits, daylighting may increase cooling loads, requiring larger chillers and associated cooling equipment, and may seriously compromise or even negate the economic benefits of reduced electric lighting use. In this paper we discuss these limits, the luminous efficacy of delivered daylight in sidelighted and toplighted spaces, methods of enhancing efficacy, and the resultant overall energy and economic impacts of daylighting design.

Using DOE-2.1C as the building simulation tool, our sensitivity studies examine the cooling load effects of daylighting as a function of the following design strategies: optical properties of fenestration; spatial distribution of luminous flux; use of fixed and operable solar control parameters; and electric lighting power density, flux distribution, and control systems. We identify combinations of these parameters that maximize daylighting efficacy and discuss their effects on net annual energy consumption, peak electrical demand, and chiller size. The energy performance of fenestration can be enhanced by using advanced optical materials that increase the efficacy of daylighting by selectively controlling daylight and solar transmission. We discuss the performance of these materials, which, although technically feasible, are not yet commercially available.

INTRODUCTION

The most significant influence on the energy performance of building envelopes is typically the fenestration system. In conventional building design, the high thermal conductivity of glazing systems increases heating loads, and the transmission of solar radiation increases cooling loads. The building community recognizes, however, that daylight used to replace electric lighting can offset negative thermal effects and yield net annual energy savings. Recent research has demonstrated that daylighting is an effective design strategy to reduce electric lighting requirements, conserve energy (Arasteh et al. 1984, 1985; Arumi 1977; Johnson et al. 1982, 1984, 1985; Sanchez and Rudoy 1981), and reduce peak electric demand (Choi et al. 1984; Selkowitz et al. 1983, 1984).

While the energy-conserving benefits of replacing electric lighting with daylighting are clearly understood, it is frequently assumed that daylighting also reduces cooling loads because the thermal energy per lumen of daylight is less than that of most electric light sources. A corollary assumption is that because daylight is free, replaces electric light, and is a "cooler" source, more daylight is always better and will always result in lower energy requirements and operating costs. However, daylighting can impose severe energy and cost penalties. These assumptions of daylighting energy benefits are valid only within

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certain specific design limits. Outside these limits, daylighting's energy benefits diminish and can become liabilities. The solar gains associated with excessive daylight levels result in cooling load penalties. If these loads are not controlled through proper design and system management, daylighting can become an energy liability. To realize the energy-conservation benefits of daylighting requires careful architectural design based on a successful integration of fenestration elements, lighting system, and architectural space, and proper management of electric lighting controls and solar shading controls. The objective of our research is to relate energy performance to the design details of the architectural and lighting elements in order to understand their interactions, influences, and practical limits.

Daylighting systems, just as electric lighting systems, must deliver light of adequate quality as well as quantity without producing glare or thermal discomfort. While this paper is confined to the energy-performance issues of daylighting, readers should keep in mind that lighting quality is the decisive criterion for the success of any lighting design. There will always be special cases where concern for lighting quality overrides, or even excludes, energy issues. Fortunately, properly designed daylighting offers both improved energy performance and lighting quality for most office spaces as well as schools, factories, warehouses, and other building types.

METHODOLOGY

In this paper we present the results of several parallel studies on the energy effects of daylighting. We assess fenestration effects in the context of whole-building energy use using the building energy simulation models DOE-2.1B and DOE-2.1C (LBL and LASL 1982; LBL 1983; Winkelmann and Selkowitz 1984). The many interactive parameters influencing energy use in buildings makes comprehensive parametric analysis a formidable task. In order to isolate and systematically study the impacts of daylighting on building energy performance, we have, through a series of sensitivity studies (Arasteh et al. 1985; Johnson et al. 1983), designed two standard building modules for parametric analysis by computer simulation. One module is used for vertical fenestration simulations and the other for skylight simulations. These studies were conducted to identify those design variables with the greatest potential energy impacts. These were then used as variable parameters in our detailed simulation studies, while all other design variables in the modules were held constant.

The physical configurations of these modules are shown in Figure 1. The vertical fenestration module, Figure 1a, consists of four identical perimeter zones, each 15 ft (4.9 m) deep and 100 ft (30.48 m) long, surrounding a common core. The ceiling, floor, and perimeter-zone end walls are modeled as adiabatic surfaces; thus envelope effects are constrained to the fenestrated walls. This allows fenestration thermal effects to be isolated and analyzed in the context of daylighting phenomena. The skylight module, Figure 1b, is similarly designed to isolate skylight thermal and daylighting effects. The module consists of a single zone, which is 100 ft (30.48 m) square. The exterior walls and the floor are modeled as adiabatic surfaces, constraining envelope effects to the skylighted roof.

In order to focus results on the solar gain and daylighting energy effects of fenestration, thermal conductivity of the wall and glass were adjusted as glass area was varied so that the overall conductance remained constant. With a fixed overall conductance and a fixed lighting power density, the window-to-wall ratio (WWR), visible transmittance (T_v), and shading coefficient (SC) were varied. This parametric variation of fenestration properties was repeated for other fixed values of overall conductance and lighting power density. Using regression analysis, quantitative correlations among all variables were developed from the combined results of these parametric sets (Johnson et al. 1983; Sullivan and Nozaki 1984).

In order to simplify analysis, the dimensionless product of WWR times T_v is used to describe the daylighting aperture and is called the "effective aperture." The ratio T_v/SC is useful in discussing the thermal impact of daylighting in relation to glazing material^v and is called K_e .

In previous studies, from which the present work has evolved, the influence of fenestration on net annual energy performance has been characterized in a general way (Arasteh et al. 1985; Choi et al. 1984; Johnson et al. 1982, 1983, 1984, 1985; Selkowitz et al. 1983, 1984). Figure 2 is a sample of these results. These curves, showing net annual energy consumption as a function of effective aperture for a south zone in Lake Charles (representative of a hot, humid climate), demonstrate typical trends that are important to understand in depth. In the nondaylighted case (solid line), energy consumption increases monotonically with effective

aperture. This is directly attributable to solar-gain-induced cooling loads. With daylighting (broken line), electric lighting consumption is reduced and net annual energy consumption for any effective aperture is substantially reduced. A distinct minimum appears in each of the daylight curves, and at larger effective apertures, energy use eventually increases at about the same rate as in the nondaylighted cases. Beyond a certain critical design point for minimum energy use, the constantly increasing cooling load begins to diminish daylighting's net benefits. Eventually the initial benefits may be negated, the daylighted design then requiring more energy than a design having little or no glazing and totally dependent on electric lighting. These trends, repeatedly demonstrated in other climates and orientations, make apparent the need to understand in detail the impacts of daylighting on cooling loads.

From the standpoint of effective energy utilization, and without regard to other important design issues, a lighting system should ideally provide no more light flux than necessary for the required illumination level at the task. This is true of electric lighting systems as well as daylighting systems. However, in many designs daylighting provides highly nonuniform flux distribution, especially in typical perimeter offices daylighted from only one side. Also, electric lighting is typically controlled uniformly over a large daylighted zone in response to the daylight level at a single point in the zone. Daylighting can be designed to provide much, or even all, of the required lighting, but because of nonuniform flux distribution and imperfect controls for both daylighting and electric lighting, illumination levels in parts of the space sometimes exceed requirements. The excess illumination imposes a cooling load with no additional lighting benefit.

In order to better understand the relationship between daylighting and cooling load, we have examined cooling load as a function of the following: daylight distribution, daylight levels, daylight or solar-control strategies, and electric lighting control strategies. Each of these factors independently influences the cooling load, and in real buildings they are interactive.

We examined daylight spatial distribution and illuminance level by varying the fenestration's location and effective aperture. Sidelighting from vertical fenestration and toplighting from skylights are compared. To bound the problem, a hypothetical case of perfectly uniform flux distribution is examined.

We examined solar control strategies by varying both type of control mechanism and control logic. These included varying K of the glazing, using simple window shades with on-off control, and using sophisticated mechanical or optical shading systems having continuously variable transmission and control logic responsive to radiation levels.

We modeled electric-lighting control strategies with on-off switching and with continuous dimming, both in response to the daylight illuminance level at a single control point. These control strategies are examined with one and two electric lighting zones in a single daylighted zone.

We examined DOE-2 simulation results from over fifteen climates but have concentrated on two extremes: heating-dominated Madison and cooling-dominated Lake Charles. In both climates the trends and the magnitude of daily cooling load effects are similar, but because of Madison's shorter cooling season its annual values are much lower. The focus of this paper is the cooling load impact of daylighting, and we therefore concentrate on Lake Charles results in our discussion.

DISCUSSION

Electric Lighting Requirements with Daylighting

General trends of electric lighting requirements with daylighting, or conversely, electric lighting savings, are shown in Figure 3. For all of the systems modeled, electric lighting requirements first drop off substantially as effective aperture increases and then asymptotically approach a minimum lighting power fraction. This minimum is not zero, because the lighting schedule modeled requires lighting during nondaylighted hours, and because the continuous dimming system is modeled with 10% power consumption at zero light output.

In all cases the electric lighting savings approach the knee of the curve at fairly small effective apertures. As the responsiveness of electric lighting control is improved, equal savings occur at smaller effective apertures. For example, simple one-step switching provides no savings until the effective aperture reaches approximately 0.1. This is because the electric lights switch off only when daylight provides the full design illuminance of 50 fc (538 lux). However, the continuous dimming system begins to provide savings as soon as daylight is introduced. At very large effective apertures, when the daylighting contribution is maximized, the on/off system outperforms the continuous dimming system because of its 10% power consumption at zero light output. The single lighting control zone used in most of these simulations is modeled with a single control sensor located 10 ft from the window in a 15-ft-deep office. Further electric lighting savings are possible by subdividing the space into multiple control zones.

Although minimum electric lighting power fractions are similar for vertical fenestration and skylights, electric lighting requirements with skylights drop off much more quickly as a function of effective aperture, and the knee of the curve occurs at a very small effective aperture, approximately 0.04. With evenly distributed skylights, properly spaced relative to ceiling heights, the daylight distribution in the space is substantially more uniform than in the sidelighted space with vertical fenestration.

Cooling Load as a Function of Lighting Source Luminous Efficacy

In order to examine the interaction between cooling load and lighting load, we compare the increase in cooling load due to daylight and electric light sources to a base-case building with no electric lights and no windows. The thermal impacts of the luminous efficacy of the sources are compared by varying the lighting power density of the electric light source and K_e of the glazing (the daylighting source). Figure 4 shows the daily cooling load increase from the base case as a function of the percentage of daily lighting requirement met by electric lights and by daylight on a clear day in March.

For the case of electric lighting only, the percentage of design illuminance met is varied from 0 to 100% at three lighting power densities. In each case, cooling load increases linearly with percent of lighting requirement met, and the rate of increase is a function of lighting power density.

For the daylighted cases there is no electric lighting, and lighting requirements outside of daylight hours cannot be met. Because the lighting schedule modeled requires lighting during nondaylight hours, daylighting, in these cases, never meets 100% of requirements.

Recalling that $K_e = T_v/SC$, the thermal energy content of the daylight introduced by the glazing is an inverse function of K_e . Thus increasing K_e is analogous to decreasing the lighting power density of the electric lighting. Three values of K_e are examined. The smallest value, 0.67, is typical of conventional gray- or bronze-tinted glass. The intermediate value, 1.1, is typical of blue-green glass and several recently introduced glasses with low-emissivity coatings. The largest value, 2.0, is approximately the theoretical limit at which only visible light is transmitted and all near-infrared is rejected.

In contrast to electric lighting, as the percentage of required lighting met by daylighting increases, the rate of change in cooling load increases, and as daylighting approaches its maximum contribution, the rate of change increases drastically. Each increment of effective aperture adds to cooling load but makes a successively smaller contribution to meeting lighting requirements. As indicated by the final nearly vertical rise, at the upper limit additional glazing makes little or no contribution to meeting lighting requirements but continues to add cooling load.

In the case of conventional gray- or bronze-tinted glass with $K_e = 0.67$, the cooling load of daylighting increases at approximately the same rate as for electric lighting with a power density of 1.7 W/ft² (18.3 W/m²) up to 20% of lighting requirements. The cooling rate then increases and at approximately 30% of lighting requirements the cooling load resulting from daylighting exceeds the cooling load of electric lighting at 2.7 W/ft² (29 W/m²).

Increasing K_e improves the daylighting efficiency of the glazing and diminishes cooling loads from daylighting. Blue-green glass with $K_e = 1.1$ outperforms electric lighting at 1.7 W/ft² (18.3 W/m²) up to about 70% of lighting requirements. A glazing material with $K_e = 2.0$ demonstrates that daylighting from moderately large apertures can be a cooler source than electric lighting at the very low power density of 0.7 W/ft² (7.5 W/m²).

The bounding case shown, in which $K_e = 2.0$ and the daylight flux is uniformly distributed throughout the space, demonstrates the theoretical potential of daylight. In this case the impact of daylighting on cooling loads is small, even negligible, throughout most of its useful range. The upper limit of this range is approximately 85%, which is essentially all of the lighting requirements during daylight hours. Beyond this point cooling load increases asymptotically, just as with the other glazing materials, because there are no further lighting benefits to be had. Thus for the case shown, a clear March day, glazing with ideal spectral transmittance properties for daylighting could provide lighting savings of 85% with less cooling load than any other options.

Time Dependence of Daylight

Daylight flux levels vary widely over time, from sunrise to sunset, from cloudy day to clear day, and from season to season. At any given moment the daylight flux incident on a vertical surface (e.g., a window) will vary with orientation. Daylight illuminance levels at midday vary from over 10,000 fc (107,639 lux) in bright sunlight to less than 50 fc (538 lux) under heavily overcast skies. With a single fixed daylight aperture, and without variable solar control, interior daylight levels will be either too high or too low much of the time. High levels will add cooling load; low levels will add electric lighting load.

An example of the variability over a 24-hour day of the solar heat gain through several fenestration options in a west zone is shown in Figure 5. The concurrent daylight levels at the control point are shown in Figure 6. This clear July day, showing the variability from diffuse early morning sky to direct afternoon sun, would be mirrored in the east zone. A similar range would occur in a south zone, but with seasonal variation. The fenestration systems modeled, all with $WWR = 0.3$, include three conventional types and two that have advanced glazing materials with optical switching properties. They are identified as follows:

PR - Passive response

Photochromic glass, responsive to solar radiation. Shading coefficient (SC) varies linearly from 0.8 to 0.2 as total solar radiation incident on the glass varies from 10 $\text{Btu/ft}^2 \cdot \text{hr}$ (31.5 W/m^2) to 100 $\text{Btu/ft}^2 \cdot \text{hr}$ (315 W/m^2). Visible transmittance is equal to shading coefficient ($K_e = 1.0$). There are no separate operable shades with the photochromic glass.

AC - Actively controlled

Electrochromic glass with T_v controlled to hold daylight levels to a maximum of 50 fc (538 lux) at the control point in the room. Maximum T_v is 0.8 and $K_e = 1.0$. There are no separate operable shades.

HT - High transmission

Conventional high-transmission glazing system with $SC = 0.8$ and $T_v = 0.78$. No operable shades.

HTS - High transmission with shade

Conventional high-transmission glazing with $SC = 0.8$ and $T_v = 0.78$. A window shade is deployed when direct-beam solar transmission exceeds $20 \text{ Btu/ft}^2 \cdot \text{hr}$ (63 W/m^2). The window shade reduces solar gain by 40% and visible light transmittance by 65%.

LT - Low transmission

Conventional low-transmission glass with $SC = 0.18$ and $T_v = 0.07$. No operable shades.

With high-transmission glass, daylight from a diffuse sky provides design lighting requirements most of the morning hours. During afternoon hours, with direct-beam solar as a source, even with shades pulled the daylighting level is about twice the required level, imposing additional cooling load with no additional lighting benefits. If afternoon solar control were to govern the daylighting level, morning daylighting levels would be too low and electric lighting would be required. Low-transmission glass minimizes solar heat gain but provides little usable daylight.

A fenestration control option that continuously modulates the daylighting aperture so that the daylight level at the control point never exceeds the design level is represented by AC. In this case, optically switching glazing was modeled with $K_e = 1.0$. A similarly controlled mechanical device, such as exterior venetian blinds, might be expected to perform similarly. This level of control, while allowing maximum lighting benefits with daylighting, is required to mitigate the afternoon solar gain while retaining required daylight levels in the morning, as shown in Figures 5 and 6.

Spatial Dependence of Daylight

Daylight flux distribution in a space varies with the size, shape, and location of daylight apertures in the space and the light-distributing characteristics of the aperture.

Sidelighting from vertical windows in offices is typically from a single direction and falls off rapidly as one moves away from the window. In order for daylighting to provide required lighting levels in the back of the space, daylighting levels next to the window will be far too high and the excess light will add cooling load. Evenly distributed, well-spaced skylights provide a multipoint lighting source, which can provide more uniform daylight distribution. It is thus useful to compare the cooling impacts of sidelighting and toplighting in order to understand the effects of daylight distribution on cooling loads.

Figure 7 compares the annual cooling load impacts of south vertical fenestration and skylights. The annual cooling energy required per square foot of daylighted space is shown as a function of the percentage of electric lighting energy replaced by daylight. The amount of useful daylight provided is a nonlinear function of effective aperture as was seen in Figure 3. As discussed previously, the maximum daylighting contribution is less than 100% because the lighting schedule requires light during nondaylight hours and the dimming system uses 10% residual power at zero light output. Therefore, in all cases there is a steep rise in cooling as the daylighting contribution approaches maximum.

As electric lighting is replaced with daylight from vertical fenestration, the annual cooling requirement goes down only for electric lighting power density of 2.7 W/ft^2 (29.1 W/m^2). For lower lighting power densities the cooling requirement increases as daylighting replaces electric lighting. Thus, the annual cooling load impact of daylight in this sidelighted configuration is only slightly less than that of electric lighting at 2.7 W/ft^2 (29.1 W/m^2) throughout the useful design range.

With skylights, cooling requirements diminish with increasing daylight for the two higher electric lighting power densities and increase slightly at the lowest power density. Not only does daylighting from skylights reduce cooling loads, but skylights yield electric lighting savings at effective apertures one-eighth to one-tenth as large as those needed for vertical fenestration to yield the same savings. The more uniform daylighting distribution of skylights provides the same lighting savings with smaller effective apertures and less total transmitted daylight and thus less solar gain. The curve for 0.7 W/ft^2 (7.5 W/m^2), with a slight positive slope, indicates that the cooling load from daylighting here is approximately equal to that of electric lighting at 0.7 W/ft^2 (7.5 W/m^2).

Chiller Size

The influence of daylighting on chiller size is similar to its influence on cooling load. Figure 8 shows chiller size as a function of effective aperture for the entire five-zone module, with perimeter-zone vertical fenestration having $K = 0.67$ and electric lighting power density of 1.7 W/ft^2 (18.3 W/m^2). This configuration, representing many typical office-building designs, does not maximize daylighting benefits.

Without daylighting, fenestration simply adds a cooling load, and chiller size is a monotonically increasing function. With daylighting, chiller size remains approximately the same as for an opaque wall (effective aperture of 0.0) up to an effective aperture of about 0.15. At larger effective apertures, chiller size is always smaller than the nondaylighted case with the same fenestration, but it increases with effective aperture at about the same rate as for the comparable nondaylighted case. However, the electric lighting energy savings from daylighting without managed window shades to control solar gain are quickly negated by cooling loads.

Peak Electrical Demand

Daylighting can be a significant factor in reducing peak electrical demand, particularly as a summer phenomenon of combined cooling load and electric lighting. While electric lighting can be reduced with daylighting, cooling requirements, as seen in the previous results, can either increase or decrease, depending on design. Maximum peak demand reductions will be obtained with daylighting design that optimizes the balance between electric lighting savings and cooling penalties.

In Figure 9 the peak electrical demand is shown for the same five-zone module representing typical office-building design. As effective aperture increases from zero, daylighting reduces peak demand to a minimum at about 0.1 effective aperture, with savings of 8.3% compared to the windowless building and 11.6% compared to the building with the same fenestration but without electric light dimming controls. In this example the perimeter zones comprise 37.5% of the total floor area. As the ratio of perimeter office zone to total floor area increases the relative peak demand savings will increase. At larger effective apertures, the additional savings in electric lighting become smaller while cooling requirements continue to increase, so the total peak demand rises from the minimum. However, with shades to manage solar gain, even at the largest effective aperture studied, peak demand with daylighting is about the same as that with an opaque wall.

Cost Implications

With proper design, daylighting will reduce peak cooling loads, peak electrical demand and building energy requirements, which in turn will affect both first cost and operating cost. Daylighting is frequently viewed as an added first cost (e.g., increased fenestration and lighting-control costs). However, reductions in chiller size may provide first-cost savings that can offset the costs of electric lighting controls, solar-control devices, and improved glazing products. For the results shown in Figure 8, at an effective aperture of 0.25, daylighting in the four perimeter zones, totaling 6000 ft² (557 m²), reduces chiller size by about 2.4 tons (8438 W). Assuming chiller and associated equipment costs to be \$2000/ton (\$0.56/W), total savings would be \$4800, which is equal to \$0.80/ft² (\$8.61/m²) of daylighted perimeter floor space.

Annual operating costs are influenced by the effectiveness of the daylighting design in relationship to the electric lighting system, the climate, and local utility rates. Annual electricity costs per square foot of daylighted space are shown in Figure 10. Two utility rate structures, one high and one low, are used to calculate annual costs with the same energy requirements. We use Houston's 1985 utility rates for the low cost scenario. With peak demand charges of \$0.55/kW and consumption charges of \$0.052/kWh, these rates are low for the southeast. For the upper bound of current cost, we use New York City rates, with peak demand charges of \$17/kW and consumption charges of \$0.07/kWh. This represents an upper limit of costs that might be anticipated for the present time and the near future.

As an example of annual electricity cost savings in a daylighted perimeter office with vertical fenestration, we examine the case of an effective aperture of 0.25, $K = 0.67$, and managed window shades. Using the low rate structure, with electric lighting at 2.7 W/ft² (29.1 W/m²), daylighting saves \$0.38/ft² (\$4.09/m²) of floor space, and the savings diminish to \$0.10/ft² (\$1.08/m²) at 0.7 W/ft² (7.5 W/m²). Using the high rate structure the savings are \$0.79/ft² (\$8.50/m²) and \$0.28/ft² (\$3.01/m²), respectively. For both rate structures savings are least at the low lighting power density. However, electric lighting systems providing 50 fc (538 lux) at 0.7 W/ft² (7.5 W/m²) would require more expensive, state-of-the-art lighting hardware.

Greater savings are possible with more sophisticated daylighting design. As one example, we show cost results for a sidelighted office glazed with an optically switching material, AC, which modulates the transmitted daylight and has $K = 1.0$. At WWR = 0.5 there is an additional savings of \$0.20/ft² at the low rate, and \$0.49/ft² at the high rate. When calculated on the basis of glazing, these savings amount to \$3.00/ft² (\$32.29/m²) and \$7.85/ft² (\$84.50/m²) of continuous window wall.

The traditional importance of windows in satisfying human needs need not be emphasized, and we can reasonably assume that office buildings will continue to have windows. Current office-building design practices must be reconciled with continually increasing energy costs. The results presented demonstrate that daylight always provides operating-cost savings if compared to a similar building without daylighting, that is, without electric lighting controls and solar controls to take advantage of daylight. Improved daylighting designs increase the savings, and improvements in electric lighting efficiency diminish the savings from daylighting. Comparing the relative cost effectiveness of more efficient electric lighting systems and daylighting designs is difficult because it requires accounting for non-energy benefits, such as occupants' well-being and productivity, associated with the design. To complement our simulation studies, we have collected case-study data on existing buildings. More data are required before we can make conclusions regarding these tradeoffs.

CONCLUSIONS

We have presented results from computer simulations parametrically examining daylighting's effects on electric lighting requirements, cooling loads, and peak electrical demand. We show that energy savings from daylighting can be compromised or even negated by improper design. Unfavorable solar optical properties of glazing materials, inadequate solar control to handle the range of daylight intensities, nonuniform daylight flux distribution, and excessively large effective apertures can impose cooling load penalties larger than electric lighting savings. Nevertheless, even in the context of conventional building design, daylighting can substantially reduce energy requirements and operating costs. Substantially greater savings are possible with more sophisticated architectural design having carefully sized and placed apertures and using high-performance glazing materials, solar control devices, and lighting control hardware.

The direct economic benefit of reduced operating costs from energy and peak demand savings are a function of utility rates. The energy savings are determined by the following physical characteristics:

1. The solar optical properties of the fenestration system as characterized by K_e . Typical tinted glazing has a $K_e = 0.67$ and the theoretical maximum value is approximately 2.0.
2. The dynamic range and responsiveness of the solar-control system relative to incident solar flux intensity.
3. The distribution of daylight flux in the space. Efficiency is greatest with uniform distribution.
4. The lighting schedule relative to hours of daylight. Savings are obviously greatest if lighting is only required during daylight hours.
5. The efficacy of the electric lighting system and its cooling-load impact relative to daylight.
6. The responsiveness of the electric lighting control system relative to distribution of daylight flux.

The factors used in simple payback analysis of daylighting designs are frequently limited to first costs of lighting controls and operating savings of electric lighting. A more rigorous approach would be life-cycle cost analysis including both first costs and operating costs of cooling, with first-cost trade-offs between cooling equipment and lighting control and solar control devices, demonstrating the viability of shifting some building capital investment from plant to envelope. More effective solar and daylighting control devices, such as exterior venetian blinds and ultimately new technology such as optical switching glazing, could then be considered to further improve the annual energy performance of the fenestration system.

The results presented in this paper, based on extensive computer simulations, indicate relative performance trends for various daylighting design strategies within the context of a specific set of building design conditions and parametric limits. Changes in operating conditions, parameters, or assumptions may lead to other conclusions.

In order to complement and validate computer simulation results, measured data from real buildings are needed, but at present few are available. Accurate measured data will soon be available from field tests with a new experimental test facility, the Mobile Window Thermal Test facility (Klems 1984). Results from this work will be used to validate existing computer algorithms and expand simulation capabilities. Extensive case studies of real buildings will be needed to complement measured data and particularly to examine building system interactions under real operating conditions.

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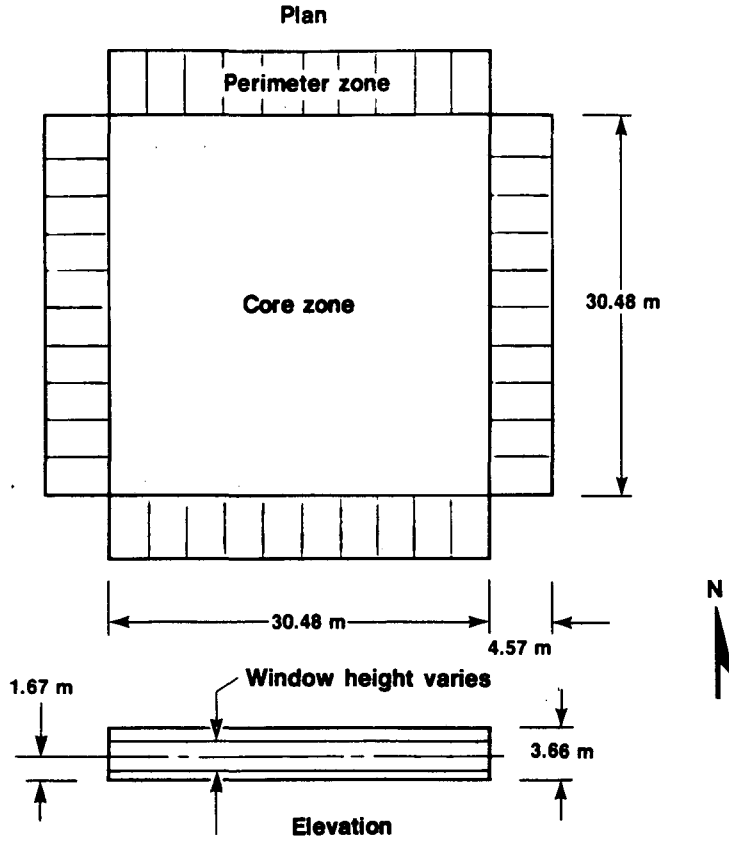


Figure 1a. Diagram of building model used for vertical fenestration simulations.

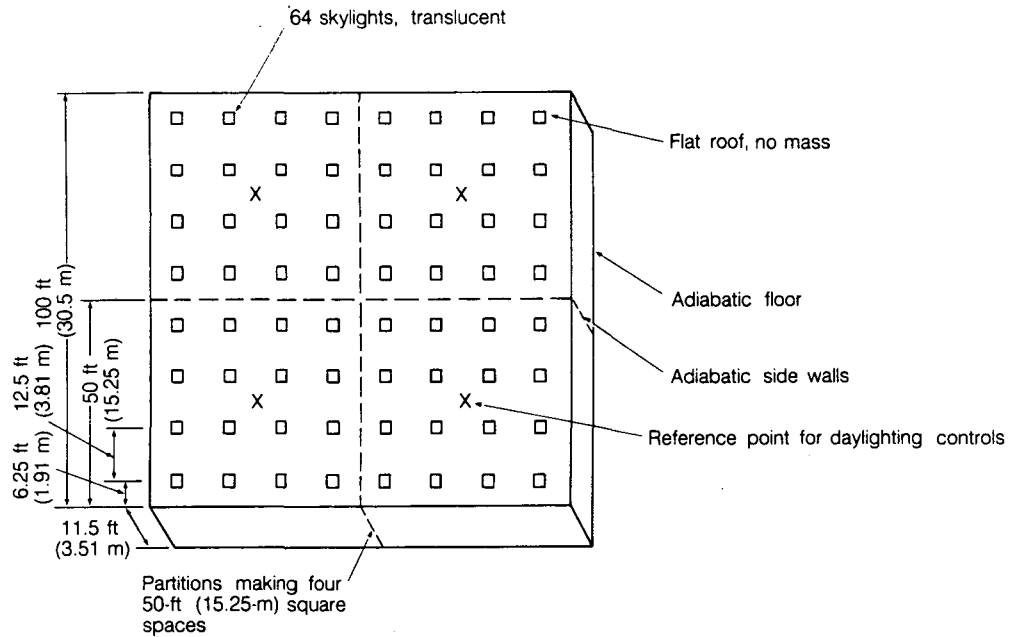


Figure 1b. Diagram of building model used for skylight simulations.

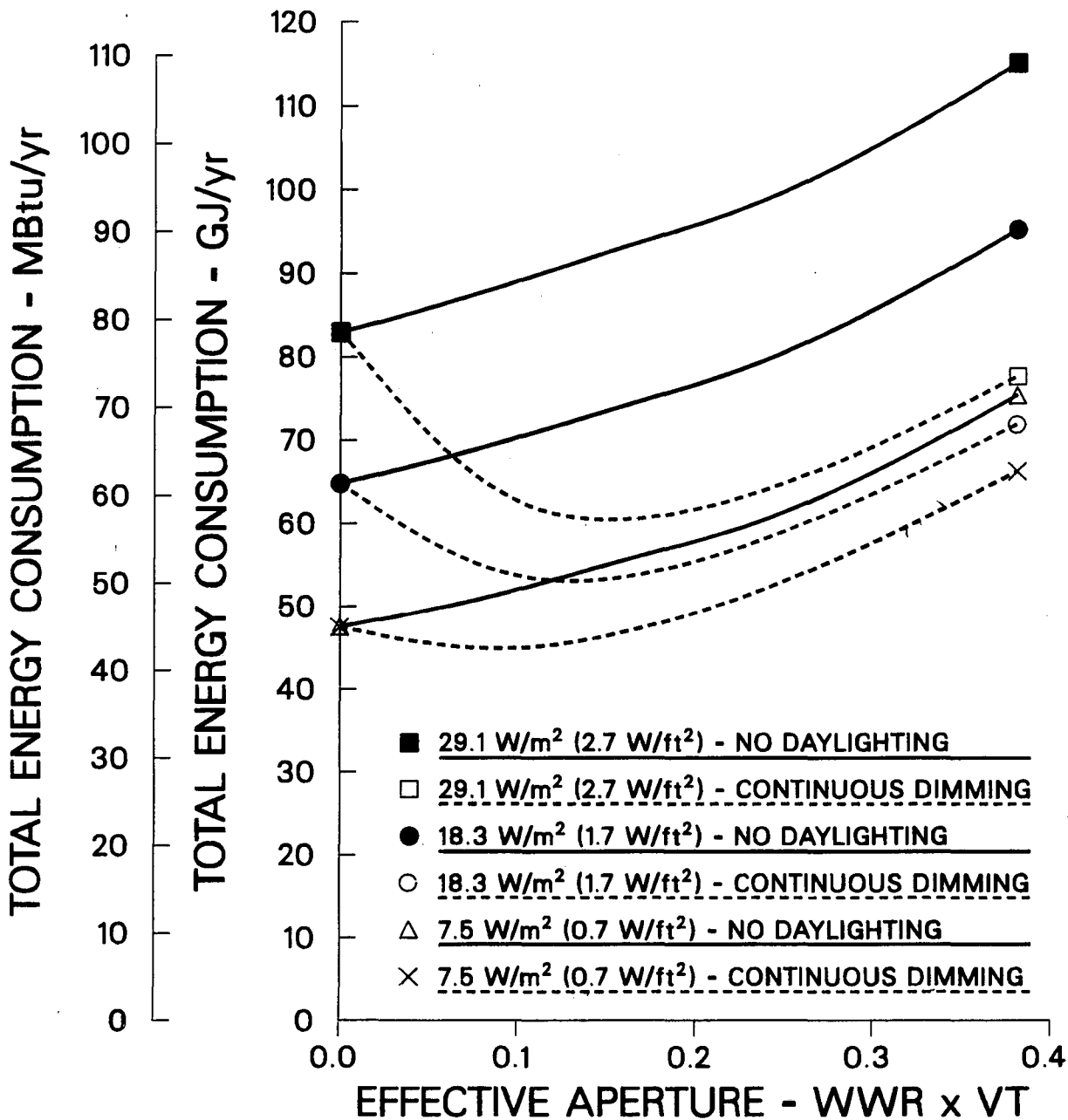


Figure 2. Net annual energy consumption in south zone as a function of effective aperture with and without daylighting. No daylighting (ND) has no reduction in electric lighting in response to daylight. Electric lights with daylighting have continuous dimming (CD).

- 1 STEP SWITCHING - 538 lux (50 fc) -----
- 2 STEP SWITCHING - 538 lux (50 fc) -----
- CONTINUOUS DIMMING - 538 lux (50 fc) -----
- △ CONTINUOUS DIMMING - 323 lux (30 fc) -----
- SKYLIGHTS - CONTINUOUS DIMMING - 538 lux (50 fc) -----

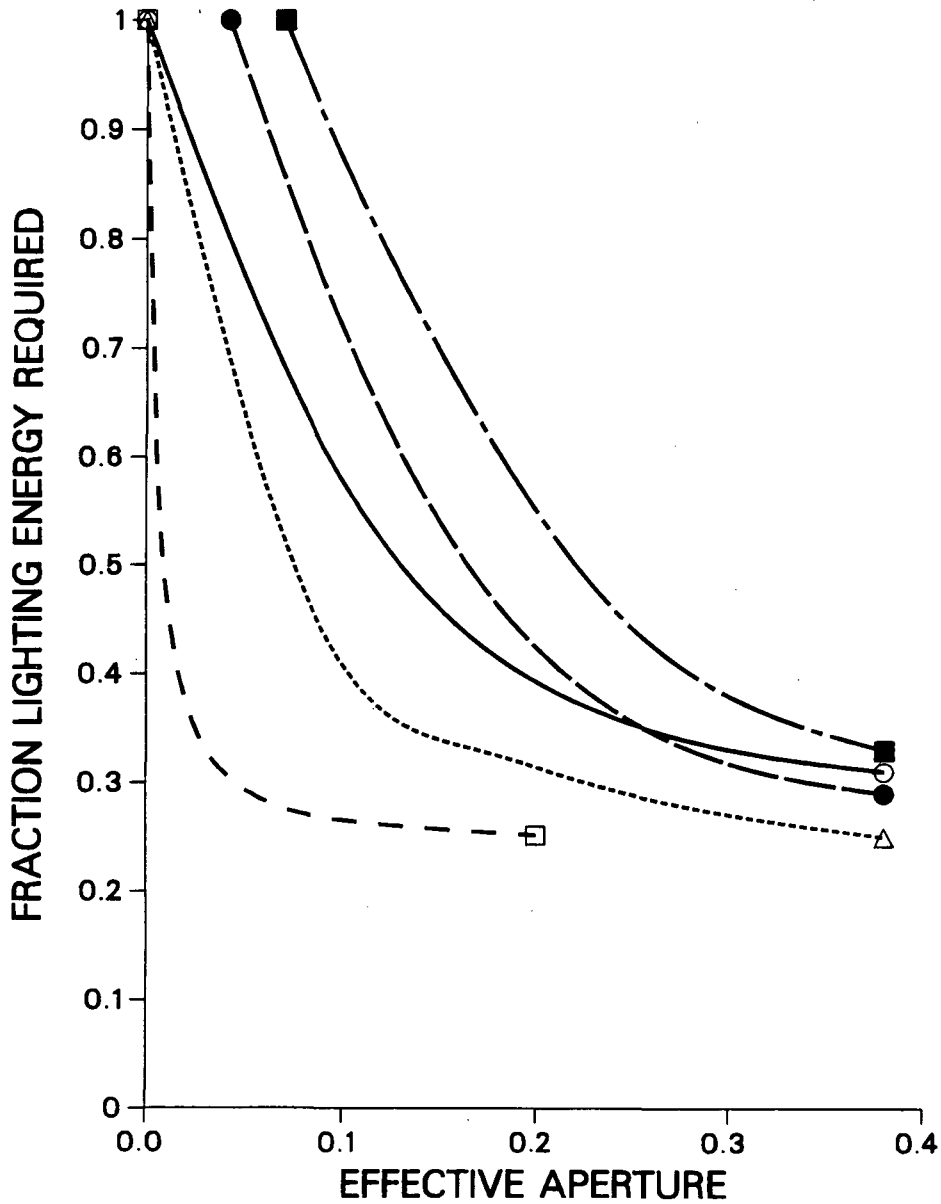


Figure 3. Electric lighting requirements with daylighting in a south zone as a function of effective aperture.

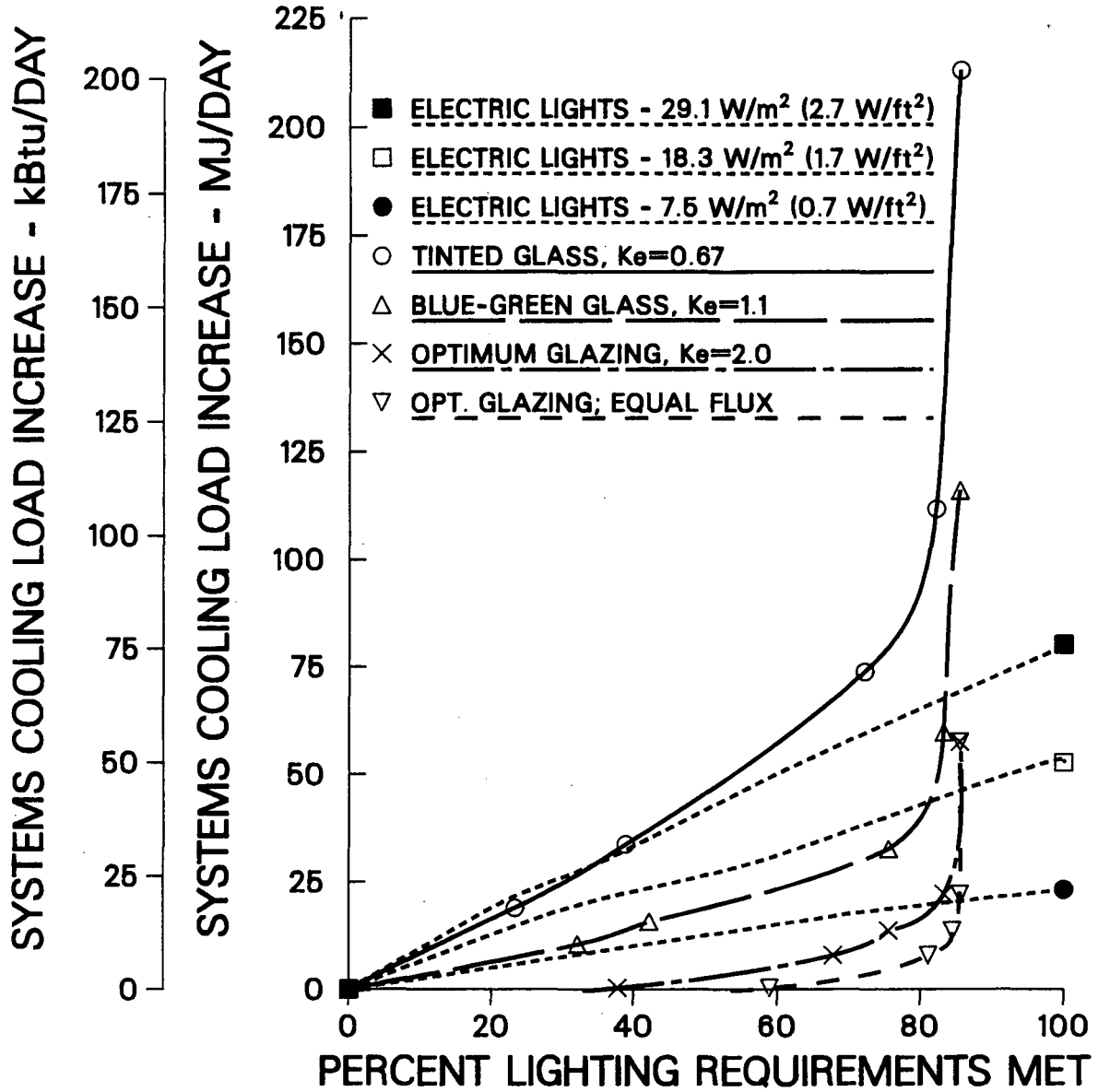


Figure 4. Increase in cooling requirements as a function of lighting requirements met using various sources in a south zone on a clear March day.

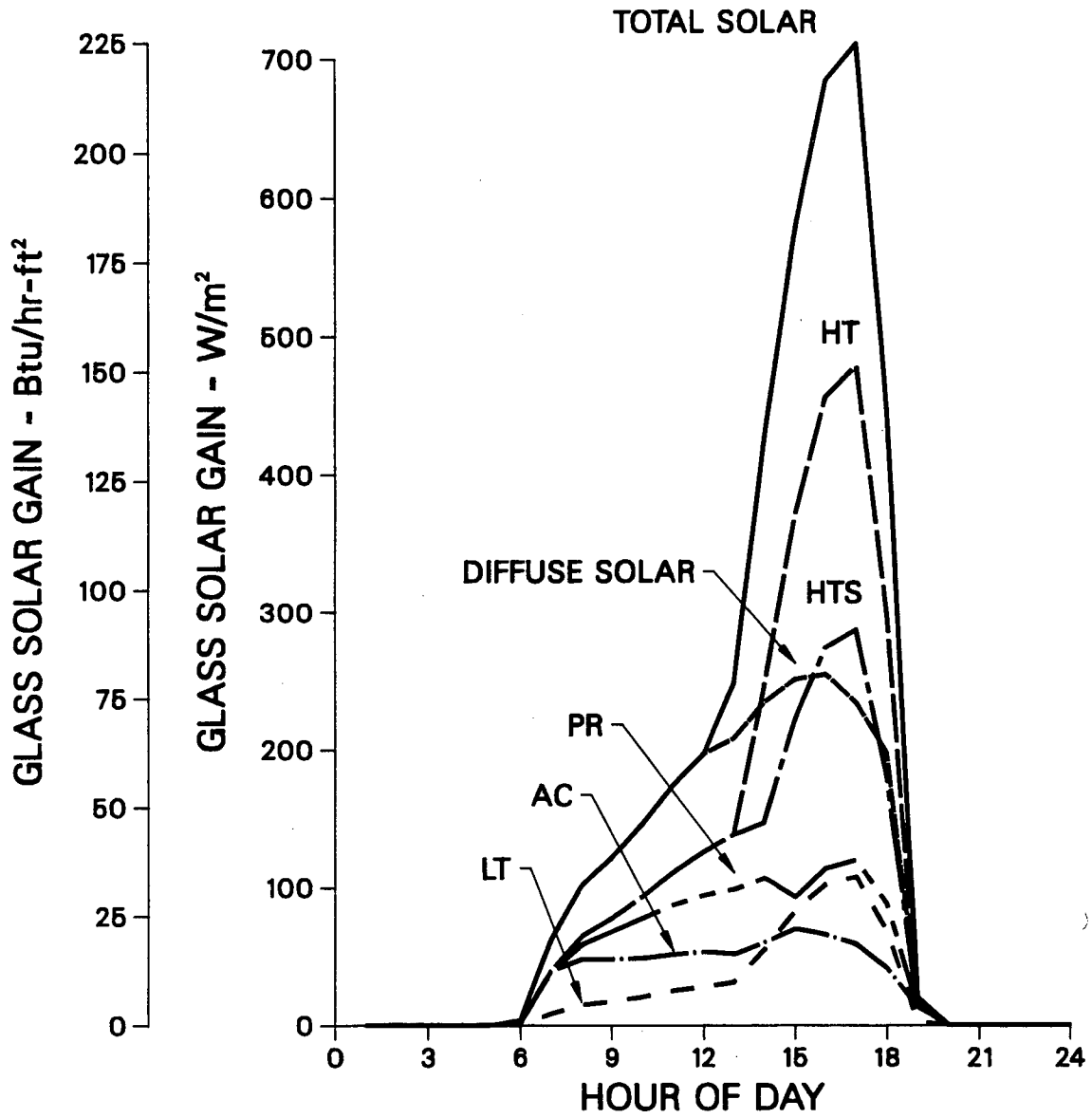


Figure 5. Hourly glass solar gain in a west zone on a clear July day.

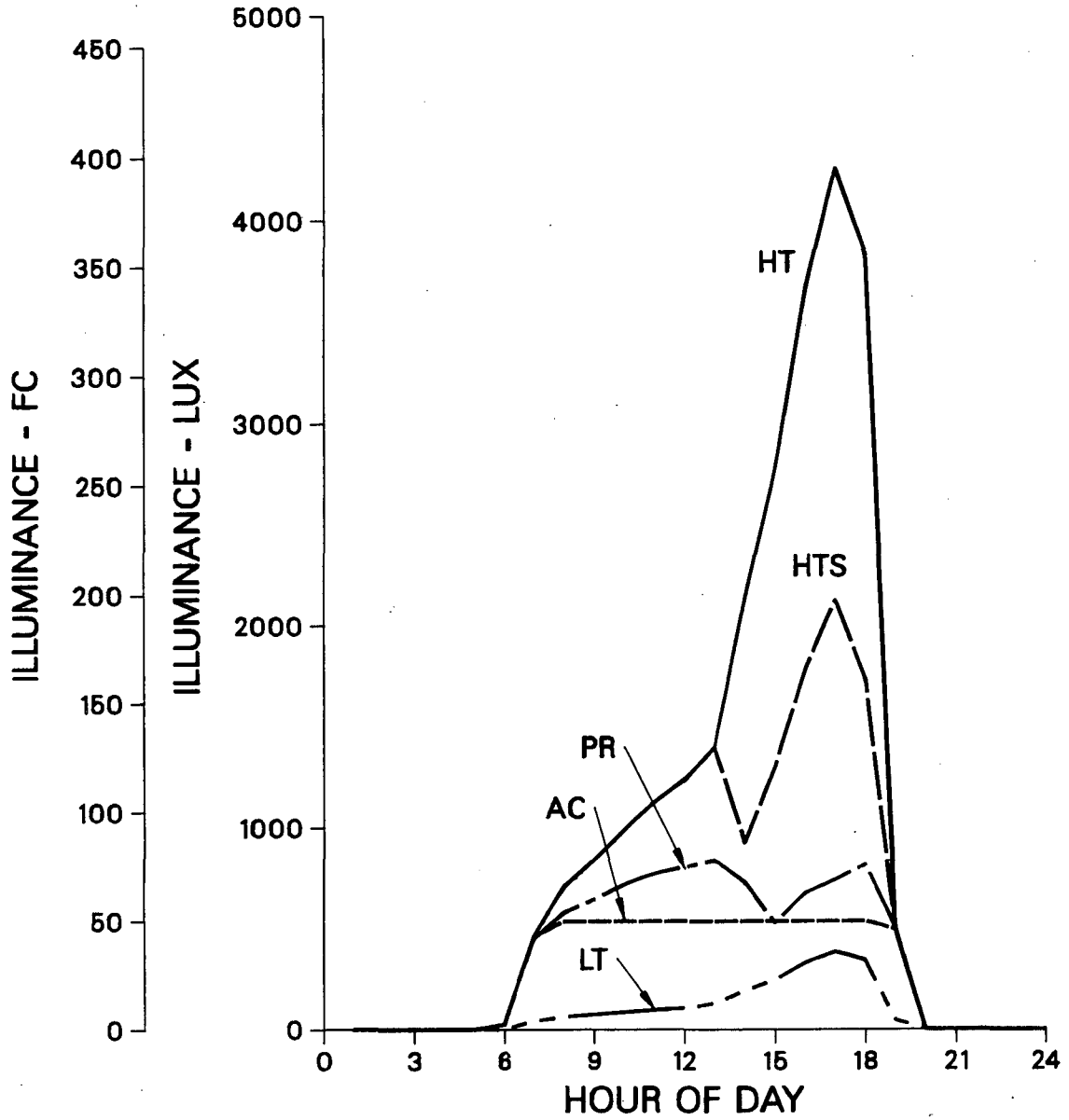


Figure 6. Hourly daylight illuminance level at the control point on a clear July day.

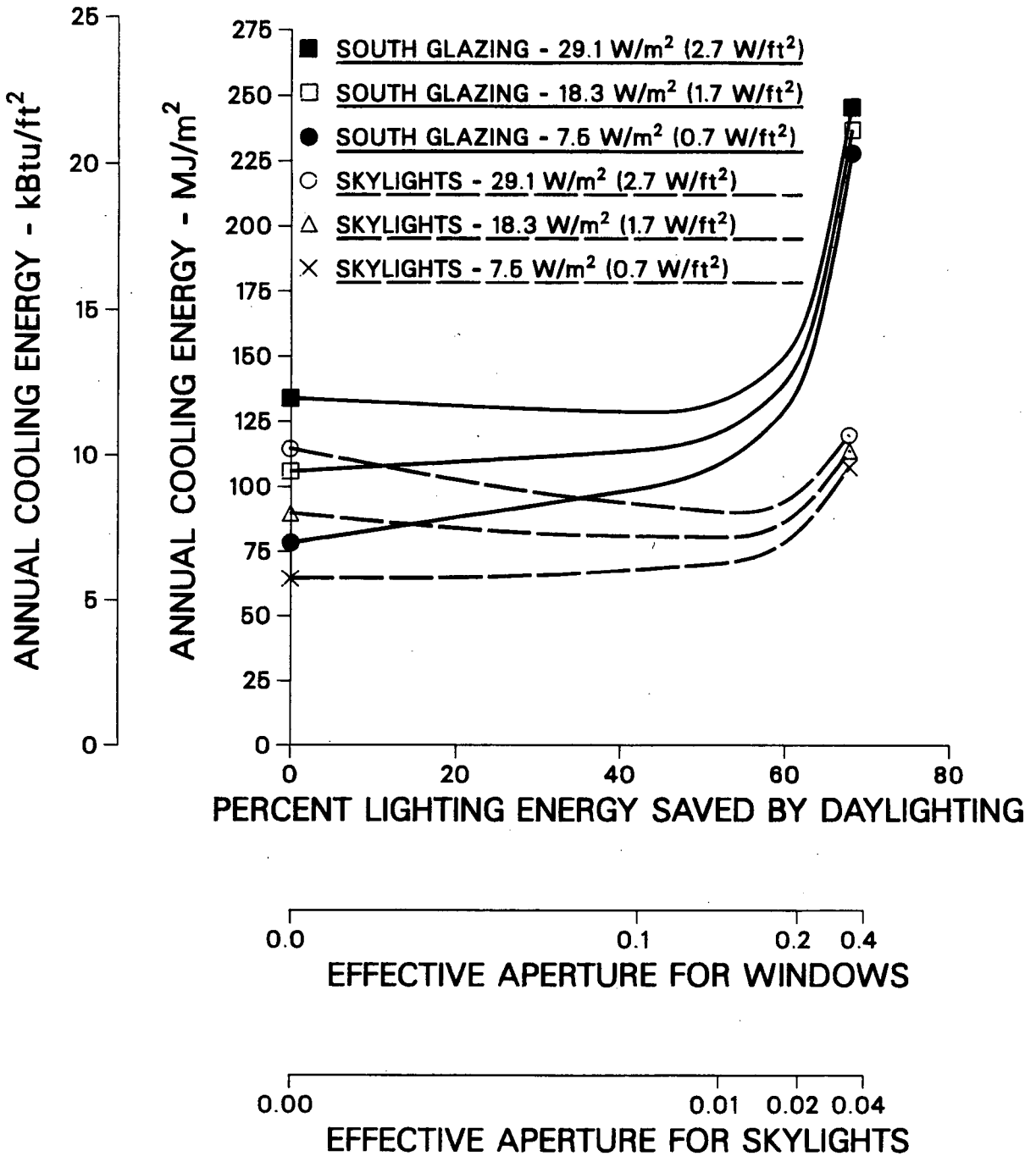


Figure 7. Annual cooling load as a function of electric lighting energy saved in a south zone and in a skylighted zone.

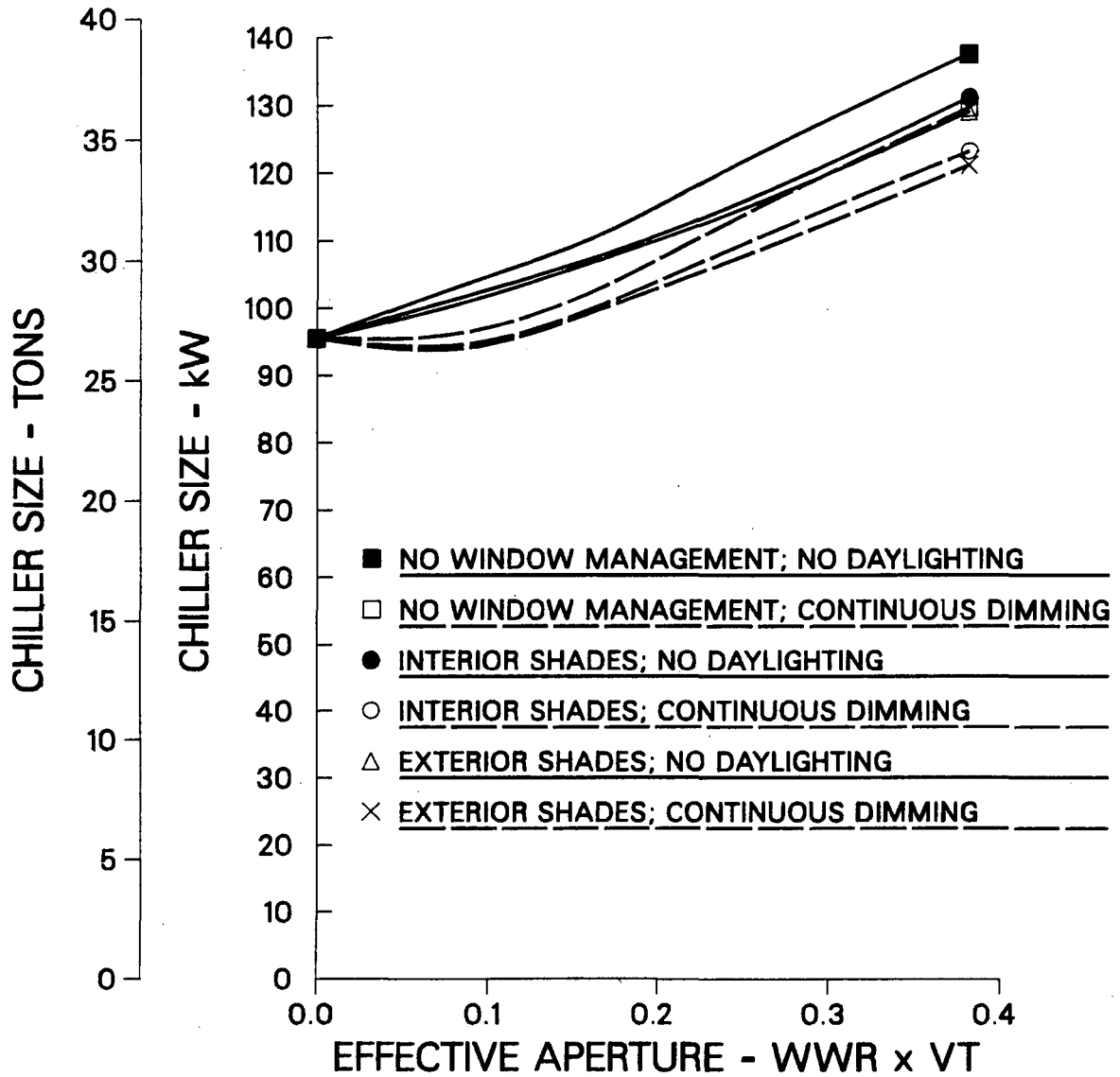


Figure 8. Chiller size for the five-zone module as a function of effective aperture. Electric lighting power density is 1.7 W/ft^2 (18.3 W/m^2).

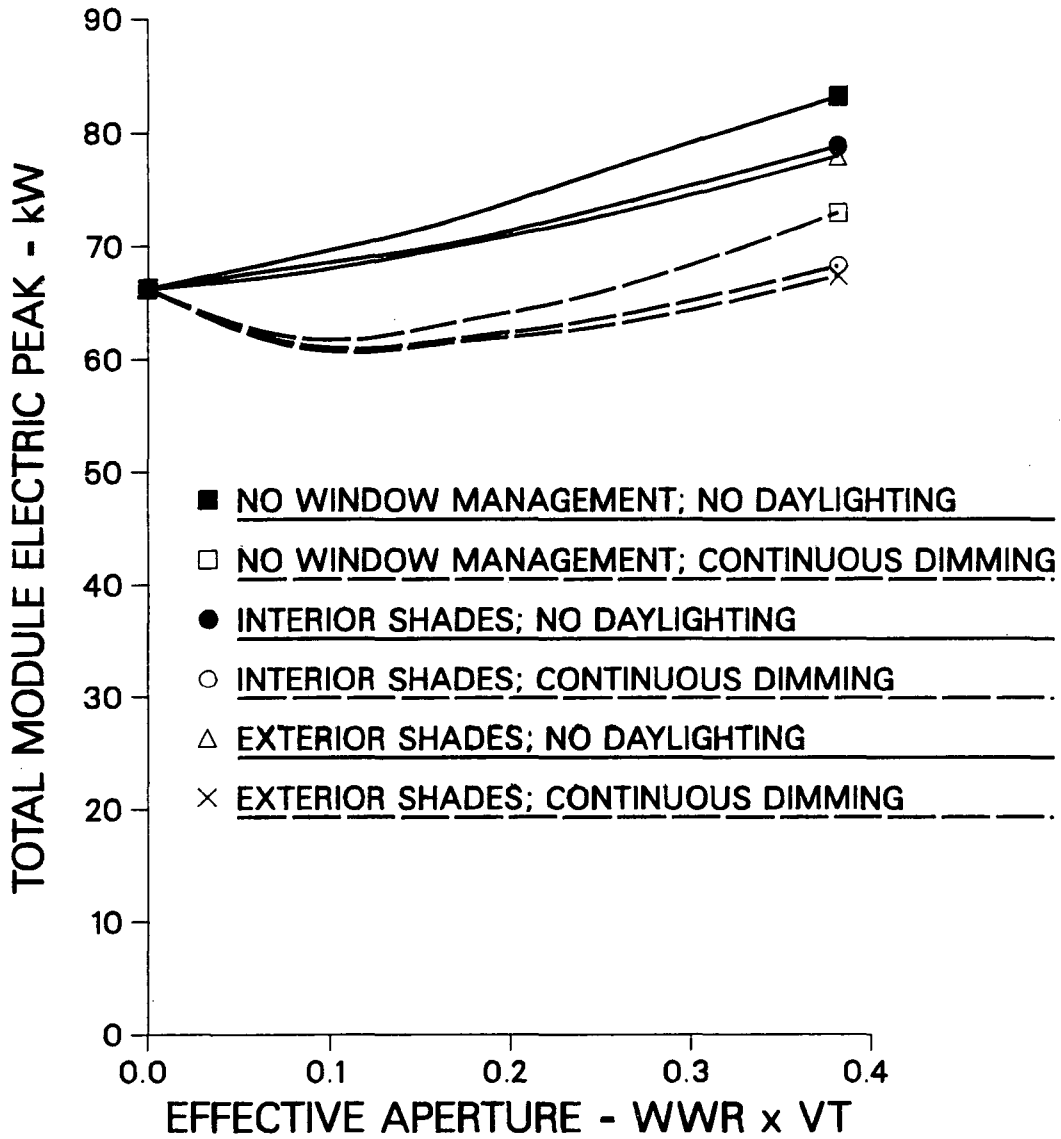


Figure 9. Peak electrical demand for the five-zone module as a function of effective aperture. Electric lighting power density is 1.7 W/ft² (18.3 W/m²). Electric lights are dimmed in response to daylight only in the perimeter zones which comprise 37.5% of total floor area.

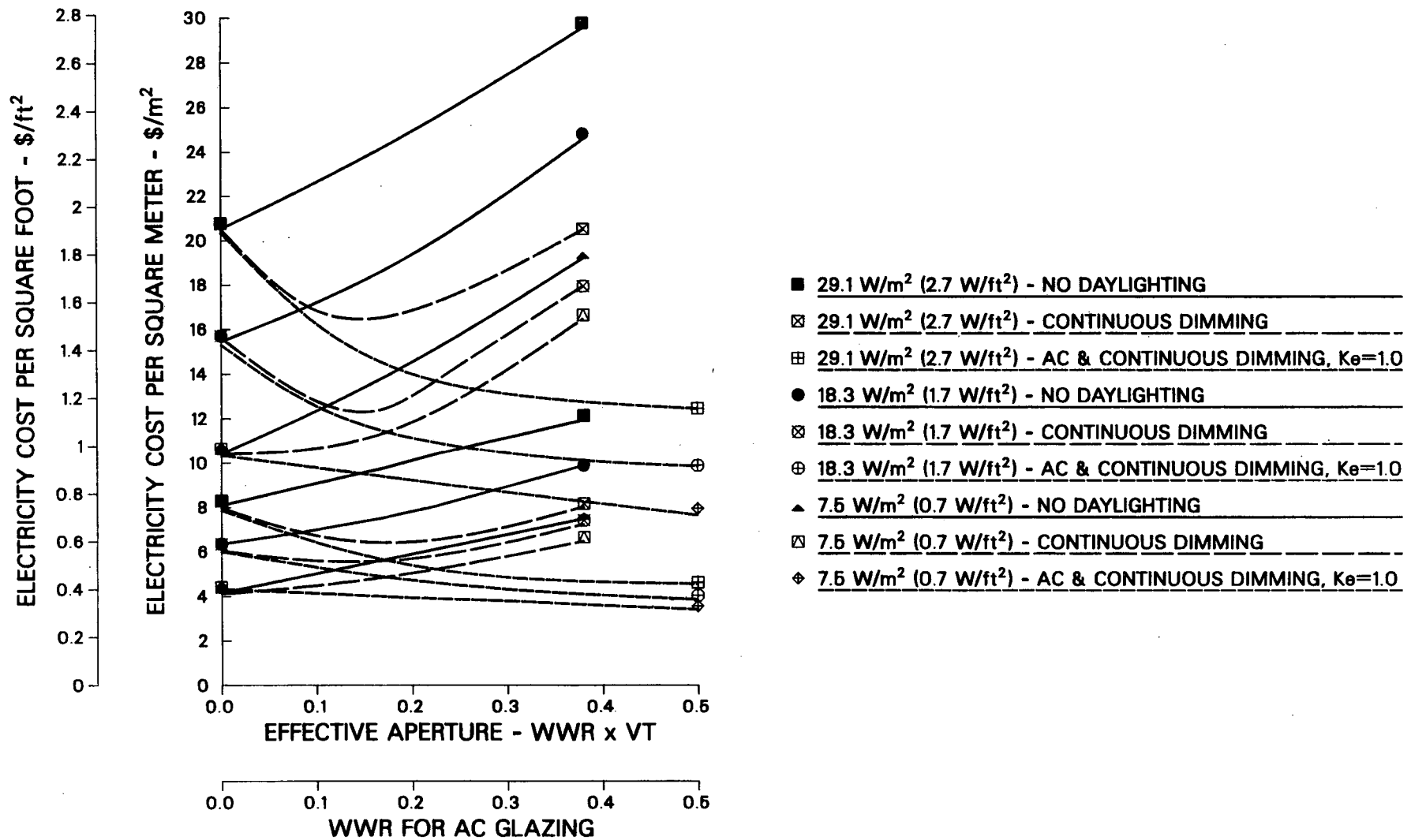


Figure 10. Annual electricity cost per square foot of daylighted perimeter zone space as a function of effective aperture for a high rate structure (New York City) and a low rate structure (Houston).

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