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ABSTRACT

In many regions in the U.S., load management and peak demand issues are of greater importance to utility planners than are reductions in energy consumption. Proper daylight utilization in commercial buildings can substantially reduce peak demand and increase energy savings. However, to determine optimum design strategies for controlling electrical demand, it is first necessary to understand the often conflicting impacts of fenestration on lighting and cooling loads. We use an hour-by-hour energy simulation model (DOE-2.1B) to evaluate peak demand components and net effects in daylighted and nondaylighted buildings. More than 5000 parametric simulations were generated for prototypical office building modules containing both horizontal and vertical glazing, and located in 16 U.S. cities. From these simulations we draw conclusions about the effects of daylighting on peak demand for a range of climate types, orientations, fenestration areas, glazing shading coefficients and visible transmittances, U-values, lighting power densities, and lighting control strategies. Results for Los Angeles are briefly compared to results for the climatic extremes of Lake Charles, Louisiana (cooling-dominated), and Madison, Wisconsin (heating-dominated), and then discussed in detail. We also briefly describe studies in progress to measure peak load impacts of fenestration using an outdoor test facility and occupied buildings.

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BACKGROUND AND INTRODUCTION

Utility systems 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 to utilities of adding new generating capacity has escalated rapidly during the past few years. Utility rate structures for non-residential users frequently include high peak demand charges that reflect the cost of providing new peak generating capacity [1,2]. These high charges are an incentive for building owners to adopt design features that minimize a building's peak electrical demand.

Fenestration design in commercial buildings is a major determinant of total energy and peak electrical demand requirements for space conditioning. The impact of fenestration can be positive or negative depending on both architectural design decisions and building operation. Fortunately, those solutions offering substantial energy benefits also frequently offer improved thermal and visual comfort. Achieving these benefits requires an understanding of component energy impacts and interactions and a sensitivity to architectural design issues.

We have studied peak electrical demand, energy consumption, thermal performance, and lighting performance in detail using DOE-2.1B, a building energy simulation program, as the primary analysis tool, parametrically varying the important fenestration and electric lighting variables for 16 U. S. climates. DOE-2 is used because there are few measured performance data of sufficient detail on fenestration's net thermal performance and there is even less information on daylighting effects. Statistical analysis was used to establisn functional correlations from the results of an extensive number of DOE-2 runs. The analysis presented here focuses on the relationship between fenestration parameters and peak electrical demand with and without daylighting, and provides a detailed discussion of results from one of the 16 cities studied, Los Angeles.

To begin to understand peak demand savings, we investigate electric lighting reductions due to daylighting as well as thermal loads with and without daylighting. Daylighting effects from both vertical windows and horizontal skylights are considered. We developed two prototypical building modules, one with windows and one with skylights, for which fenestration and lighting characteristics are parametrically varied. Important peak demand and energy use patterns in these modules can be characterized on a per-unit floor-area basis and applied to other building configurations. So far, our work has focused on an office configuration; retail and apartment modules have also been designed and studied in a few climates. Initial results indicate that the primary differences between office and retail spaces are related to such factors as internal loads and operating schedules rather than fenestration, energy consumption trends are nonetheless different, and each occupancy

type requires a separate analysis. This paper is a synopsis of papers that describe this work in much more detail [3-6].

To study daylighting's effects on perimeter-zone vertical windows, we designed a representative five-zone commercial office module. This module (Fig. 1) consists of four identical perimeter zones, each 15 ft deep, surrounding a square common core zone. The ceiling and floor are modeled as adiabatic surfaces (no net heat transfer). The overall envelope thermal conductance value, U_o, is held constant in order to isolate solar gain and daylighting effects. Thus, when glazing area or U-value change, the wall U-value is adjusted to maintain a constant overall envelope conductance. After basic performance patterns were established, we varied the overall conductance over a representative range. Fenestration characteristics were varied by changing U-value, glazing area, visible transmittance/shading coefficient (with visible transmittance generally equal to two-thirds of shading coefficient), and exterior shading. A simple window management system is assumed in which occupant requirements for thermal and visual comfort result in the use of drapes or shades for any hour in which transmitted direct solar radiation exceeds 20 Btu/hr ft^2, or any hour in which window luminance produces a glare index greater than 20. Glare index is a measure of visual discomfort induced by the luminance of the window as viewed by an occupant. The interior shading device reduces solar heat gain by 40% and visible transmittance by 65%. For modeling vertical windows, identical fenestration consisting of continuous strip windows is used in the exterior wall of each perimeter zone. To study zone-by-zone effects, a separate, constant-volume, variable-temperature system with an economizer is used in each zone. Use of other systems, such as a multi-zone variable air volume system, could change results.

For the skylight module, the perimeter zones were eliminated and individual skylights were uniformly distributed over the core zone's roof, as indicated in Fig. 1. Exterior walls and the floor were modeled as adiabatic surfaces, which limits envelope energy flows to the roof and skylight system. The skylights modeled are diffusing white skylights typical of those commercially available. No window management was modeled as it is typically not found with skylights. Fenestration characteristics varied included roof U-value, skylight area, glazing shading coefficient and visible transmittance, and light well loss factor (the fraction of visible light transmitted by the glazing that enters the space, i.e., that not absorbed or reflected out by the light-well walls) [7].

For both module types, extensive sensitivity studies [8,9] were conducted to determine details of the final module design. Variables considered and not found to significantly affect daylighting's impact on annual peak demand and energy use trends included ceiling height, module size, and office equipment load. For most of our study, the minimum maintained illumination level was 50 footcandles (fc). The light-control reference point was placed at two-thirds of the perimeter zone depth for the five-zone module, and at the diagonal intersection of the four adjacent skylights in the center of the space.

Based on a maintained design illuminance of 50 fc, electric lighting power density was varied from 0.7 to 2.7 W/ft^2, resulting in lighting system "efficacies" of 71 to 19 lumens/watt, respectively. We use efficacy to represent the ratio of useful workplane illuminance divided by installed lighting power density. We examined the effects of stepped switching and continuous dimming in response to daylight. The continuous dimming system dims from 100% light output with 100% power to 0% light output with 10% residual power.

The DOE-2.1B building energy simulation program, used as the modeling tool, incorporates a daylighting model that calculates hourly interior daylight illuminance for each zone of a building based on architectural design and hourly weather data [10,11]. More than 5000 DOE-2 runs were performed in this study. Extensive analysis was completed for eight climates ranging from cooling-dominated (Lake Charles, Louisiana) to heating-dominated (Madison, Wisconsin). More limited analysis was completed for eight additional climates to provide sufficient data for climate generalization. Peak plant-level electricity demands for each module type were calculated by DOE-2 for each module configuration.

ANALYSIS OF RESULTS

The data from these numerous parametric runs demonstrate the complexity of daylighting energy analysis relative to our primary concerns--climate, orientation, and fenestration--along with other physical and operational building parameters. For buildings with vertical windows, using a single lumped parameter [the product of the floor-to-ceiling window-to-wall ratio (WWR) and the visible transmittance (VT)] to define daylighting performance simplifies the analysis and yields accurate results [12]. We call this new lumped parameter the effective aperture (A_{ew}).

A similar lumped parameter for skylights is constructed by including the visible light-well factor (WF) and substituting skylight-to-roof ratio (SRR) for WWR. This product, SRR x VT x WF, is the effective aperture (A_{es}) for skylights. Because the relationship between visible light transmitted through the skylight system and solar heat gain is not necessarily constant, we evaluated several SC values for each value of the effective aperture in daylighted cases. We define the ratio of the visible light transmitted by the skylight system to shading coefficient by K_e so that K_e = VT x WF/SC. This distinction is necessary since a change in the well factor will reduce the light flux transmitted to the space but may not change the solar gain.

In order to meet ASHRAE 90-type criteria, we require that the overall heat transfer coefficients are constant over the range of effective apertures studied. Thus, the relationship between increasing effective aperture and peak demand requirements is primarily a function of the light- and heat-admitting properties of the fenestration system.

Lighting Energy Savings

Before looking specifically at peak demand savings with daylighting, it is first instructive to analyze lighting energy savings with daylighting. The dimming system considered is continuously responsive to variations in daylight level and maximizes the benefit from low daylight levels. The simple, one-step (on/off) system reduces electric lighting power only when daylight exceeds the design illuminance requirement, and thus provides all required lighting; at zero electric light output there is zero power consumption. With a two-step system, half the electric lighting power is turned off when available daylight provides at least 50% of the required illuminance. Thus the step-switching system is most effective at high interior daylight levels, where it outperforms the continuous dimming system (which we modeled as having low-level parasitic power requirements); step switching is least effective where low daylight levels provide only a fraction of desired illuminance. Hourly average illuminance levels for a skylight effective aperture of 0.01 with a continuous dimming system are given in Table 1; the illuminance level setpoint is 50 fc.

The principal effect of daylighting is to reduce electric lighting use. As effective aperture increases, electrical consumption for lighting in all climates first drops off sharply and then levels off. For a given effective aperture, fractional savings depend on the design illuminance level and the lighting control strategy. Figure 2 illustrates the change in fractional lighting energy savings for the skylight module as a function of effective aperture for three design illuminance values with a continuous dimming system, and for one illuminance level with both a one-step and a two-step system. With the continuous dimming system, the savings for small aperture areas are not linear with respect to design illuminance level. For larger apertures, especially at lower design illuminance levels, the shape of the curves indicates that daylighting becomes saturated and further savings are impossible. Note that a minimum effective aperture is required before any energy savings accrue to the stepped systems. Performance of the one-step system consistently lags behind that of the two-step system, as expected.

The choice of lighting control strategy has several consequences. For small apertures at the same design illuminance level, the dimming control always outperforms the stepped system because, for many hours, the available daylight is below the control setpoint, allowing partial savings with the dimming system but none with the switched control. As the aperture increases, the difference between the two is reduced. Eventually the switched system outperforms the dimming system because of the dimming system's low-end operating characteristics. This pattern appears in all climates and orientations.

Electric Peak Savings with Daylighting

Daylighting's major effect is to reduce the amount of electric lighting required. This leads to cooling load reductions and heating load increases. We consider here only the case of an HVAC system with an electrically driven centrifugal chiller and a gas-fired boiler. This system typically has summer electric peaking; thus daylighting's total

effect on peak electrical demand will be a net reduction due to both lighting and cooling energy savings. The conclusions of this study are thus limited to summer peaking conditions. Patterns for the window module and the skylight module differ and are discussed separately.

Windows. Figure 3 shows that, in the five-zone office module, fenestration imposes substantial peak demand penalties unless daylighting is used. Without daylighting, peaks occur during sunny, hot afternoons at a time when the electric lighting is also at a maximum. When daylighting is used, peaks occur under similar conditions; however, electric lighting requirements are quickly reduced to their minimum at small effective apertures. This results in associated cooling savings as long as the effective aperture does not increase past the point (0.10-0.15) where added fenestration primarily provides excess solar gains. The peak demand in a daylighted building in Madison or Los Angeles with moderate-to-large effective apertures is 14-15% lower than the peak demand in a nondaylighted building with identical glazing when the electric lighting is 1.7 W/ft^2). Savings in Lake Charles are slightly less than in Madison and Los Angeles. This can be attributed to the combination of high latent load and high ambient temperatures at the time of the peak in Lake Charles. In all cases, daylighting can reduce the peak load to below that of an opaque wall, $(WWR)*(T_v) = 0.0$. For this building module, the perimeter-zone floor space is only 37% of the total. The fraction of total building peak demand saved will vary with the perimeter/core ratio.

A plot of required chiller size as a function of effective aperture is shown in Fig. 4. Chiller size increases continuously with effective aperture even in the daylighted cases. This pattern contrasts with the peak load patterns, which show an intermediate value of effective aperture for the minimum peak loads with daylighting. With daylighting at small apertures, chiller size increases less rapidly than without daylighting. Beyond an effective aperture of 0.15 the rate of increase is the same for both cases. These results emphasize the importance of controlling solar gain if daylighting is to be successfully utilized to control peak demand.

Peak electrical demand as a function of installed electric lighting power density for Los Angeles is shown in Fig. 5. Changes in installed lighting power are assumed to represent hardware changes that increase or decrease luminous efficacy. In all cases the illuminance design criterion remains 50 fc. For the nondaylighted cases, including a building having no windows, the relationship between peak demand and electric lighting power density is linear and the plots for different values of effective aperture are linear. However, for daylighted cases, the relationship between peak and lighting load is not linear. For the small effective aperture, 0.12, the peak demand with daylighting is always less than the peak with opaque wall for any choice of installed lighting power. However, with the larger effective aperture, 0.27, the peak with daylighting is only less than that with an opaque wall at lighting power densities greater than 1.2 W/ft^2. Higher solar gains with the larger effective aperture offset daylighting benefits up to 1.2 W/ft^2.

Skylight Peaks. Without daylighting, as in the five-zone module, peak electrical demand in the skylight module typically occurs during sunny summer afternoons when cooling and lighting loads are at their maximum. Thus, in the nondaylighted case, peak electrical demand increases with effective aperture in all climates. This is seen in Fig. 6, which assumes the following five conditions: (1) K_e = 1.0, (2) installed lighting power (L_w) = 1.7 W/ft^2, (3) design illuminance level = 50 fc, (4) continuous dimming lighting controls, and (5) ASHRAE-suggested overall roof U-values. These values fall in the middle of the range of parameters considered and are representative of current building practice. However, for a skylight module with daylighting, and with moderate and high lighting power densities, electrical peaks generally occur during warm overcast afternoons, when daylighting provides minimal lighting savings. At these times, cooling loads from equipment and people, solar gains introduced at earlier hours, and high ambient temperatures are at a maximum and combine with near-maximum lighting loads to produce the annual peak. Los Angeles is not as strongly influenced by solar gains as are Madison and Lake Charles. This is seen in the comparatively flatter slopes of the nondaylighted curves and the more gradual decrease in electrical peak as a function of effective aperture with daylighting. Peak electrical demand savings are different for each city because of weather conditions at the time of the peak.

In the previous paragraph, we assume that K_e = 1.0, which is equivalent to assuming that the product of visible transmittance and well factor is equal to shading coefficient. Glazing materials used in typical skylight systems usually have visible transmittance values between 0.7*SC and 1.0*SC. Skylights without light wells, by definition, have a WF of 1.0. However, well factors can decrease the amount of visible light entering a space to a small fraction of its original value, depending on light-well reflectance, well height, skylight length, and skylight width. A skylight system with a 3-ft by 3-ft skylight, a 1.5-ft-deep well, and a 70% well wall reflectance results in a WF of 0.7. Increasing the well depth to 3.5 ft lowers the WF to approximately 0.5 [7]. We assume that light losses in the well contribute to the solar gain in the conditioned space. This is probably a conservative assumption. A maintenance factor to account for dirt accumulation on a horizontal skylight would probably reduce VT and SC by approximately the same amount, so it would not alter K_e. Thus, under typical conditions, with a practical choice of available glazing materials with regard to visible transmittance, K_e will vary between a minimum of 0.5 and a maximum of 1.0. However, new spectrally selective glazing materials with enhanced visible transmittance are becoming available. We consider in this paper the case of skylight systems with a K_e of 1.5 to suggest the possible performance of future daylight-oriented glazing materials for skylight applications.

For the nondaylighted cases, at a given effective aperture, net solar gains increase as K_e decreases. In Los Angeles, this leads to an increase in the electrical peak (Fig. 7), as one might expect in any climate where the peak demand occurs during the cooling season. With daylighting, at a given effective aperture, the amount of visible light available to the space is the same for all K_e. Changing the K_e changes the solar thermal impact to the space. At small effective apertures,

daylighting has a large effect and cooling has a small effect. After daylighting saturates the space, the energy use or peak demand curves are dominated by solar gains. This is reflected in the similarity of the slopes of the daylighted and nondaylighted curves with effective apertures greater than 0.02. For low K_e values, there is a distinct minimum electrical peak demand. If one increases K_e one can use larger skylight areas without significantly increasing energy use or peak demand.

Changing the electric lighting power density (L_w) significantly affects the electrical peak. For Los Angeles, where daylighting's impact is greatest, Fig. 8 compares the base case (1.7 W/ft^2) to the limiting cases of 0.7 W/ft^2 and 2.7 W/ft^2. As L_w increases, lighting's proportionate share of the cooling peak and electrical peak rises, increasing potential savings from daylighting. Note that minimum electrical peak is still achieved at the lowest L_w level.

Daylighting in the skylight module can significantly decrease required chiller size, unlike the case of the five-zone perimeter module with windows (Fig. 9). Part of the difference between the skylight module and the five-zone module can be attributed to the fact that skylights provide savings over 100% of the skylight module floor area, while windows in the five-zone module can influence only 37% of the floor area. However, a more important factor is the manner in which daylight is distributed in each space. The more uniform distribution of daylight in the skylight model utilizes daylight with its intrinsically high luminous efficacy (90-130 lumens/watt) more advantageously than a sidelighted perimeter zone with a highly non-uniform light distribution and thus greatly reduced effective efficacy. As skylight effective apertures become large enough for saturation to occur (around 0.02), solar gains then dominate lighting savings, which leads to a steady rise in required chiller size. This is seen in the nearly identical slopes of the daylighted and nondaylighted curves at large effective apertures.

Figure 10 shows that with continuous dimming the lighting design illuminance criterion only slightly affects peak electrical demand, and primarily at small effective apertures. This might be expected since electrical peaks for cases with continuous dimming controls occur during periods of low daylight availability.

Stepped switching systems have an interesting effect on daylighting peak electrical savings (Fig. 10). As compared to the base case with continuous dimming, stepped systems provide considerably less peak electrical savings. With stepped systems (in the case of Los Angeles), peaks do not necessarily occur during overcast periods as with the continuous dimming systems. Depending on effective aperture and the number of steps, electrical peaks with step systems can occur over a range of conditions. The greater the number of steps and the larger the effective aperture, the more the peak behavior resembles that of a continuous dimming system. For the one-step (on/off) system, daylighting does not produce any peak savings for effective apertures smaller than 0.005. For the two-step system, daylighting savings first occur at an effective aperture of 0.0025.

SUMMARY AND CONCLUSIONS

Fenestration is a potentially important design and conservation strategy in nonresidential buildings. The importance of daylighting as a load management option is intimately related to the interplay of daylighting and solar control impacts. To maximize economic benefits, the impact of daylighting on peak electrical demand as well as on energy must be better understood. Results from an hour-by-hour simulation model that accounts for daylighting impacts help refine our understanding of this complex subject. An extensive set of parametric analyses for a simple office module in several climates suggests the following generalizations:

1. The concept of an effective aperture greatly simplifies the parametric analysis and evaluation of daylighting and fenestration systems with a minimal loss of accuracy.

2. Increasing fenestration area and/or transmittance to increase daylighting savings frequently reaches a point, depending on climate and, for windows, orientation, beyond which peak electrical demand increases due to greater cooling loads.

3. Control of solar gain is vital if daylighting strategies are to provide net peak savings.

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

5. The effective luminous efficacy of daylight will normally be higher in a properly designed, skylighted building than in comparable sidelighted perimeter zones. This conclusion could change if improved techniques for optical control of daylight distribution are developed.

6. Daylighted buildings may have lower total peak electrical demand, but may require larger cooling systems than nondaylighted buildings having smaller windows or skylights.

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

8. Most of the above conclusions are sensitive to climate, orientation, and other building modeling assumptions.

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

Additional study is needed to better understand performance results and to extend these results to a broader range of fenestration designs. Studies of roof monitors suggest that fenestration designs that are more sophisticated than simple horizontal skylights should further improve fenestration performance [13]. 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. [14]. We believe that the regression techniques we used [8] to simplify the representation of a large data set could also be used to convert our data set to a simple yet powerful design tool [15]. We are also working on experimental projects to obtain the quantitative data required to build confidence in the algorithms used in the simulation models [16], and have begun to collect detailed performance data in innovative daylighted buildings.

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Table 1. Skylight module: average illuminance (footcandles) at daylighting reference point.

Los Angeles: WWRxVTM=0.01; WWR=0.05; SC=VT=0.2; UO=0.09.

	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	0	14	28	38	44	44	38	28	14	4	0	0	0	0	0	0	0	26
FEB	0	0	0	0	0	0	0	0	20	36	52	56	58	52	42	24	10	0	0	0	0	0	0	0	36
MAR	0	0	0	0	0	0	0	0	38	56	66	74	76	70	58	40	18	4	0	0	0	0	0	0	50
APR	0	0	0	0	0	0	0	24	38	52	66	72	78	68	56	42	20	8	0	0	0	0	0	0	50
MAY	0	0	0	0	0	0	0	28	42	58	68	78	80	74	64	46	26	0	0	0	0	0	0	0	56
JUN	0	0	0	0	0	0	0	22	36	54	72	86	88	86	74	56	34	0	0	0	0	0	0	0	60
JUL	0	0	0	0	0	0	0	28	46	64	84	98	98	92	78	58	36	0	0	0	0	0	0	0	68
AUG	0	0	0	0	0	0	0	22	42	60	78	86	88	86	72	52	28	0	0	0	0	0	0	0	62
SEP	0	0	0	0	0	0	0	16	32	48	64	70	72	66	54	36	16	0	0	0	0	0	0	0	48
OCT	0	0	0	0	0	0	0	14	26	40	52	58	56	48	34	18	6	0	0	0	0	0	0	0	36
NOV	0	0	0	0	0	0	0	0	22	36	46	50	48	40	26	12	2	0	0	0	0	0	0	0	28
DEC	0	0	0	0	0	0	0	0	14	26	38	44	42	34	22	10	2	0	0	0	0	0	0	0	24
ANNUAL	0	0	0	0	0	0	0	22	32	46	60	68	68	62	50	34	16	2	0	0	0	0	0	0	46

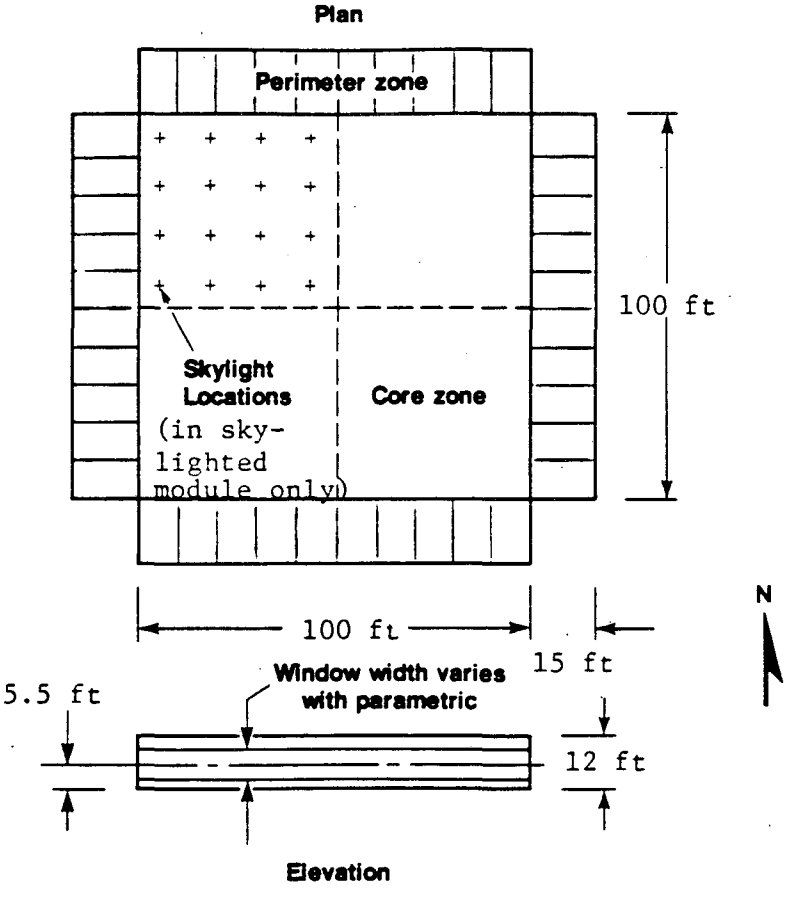

Figure 1. Building module description.

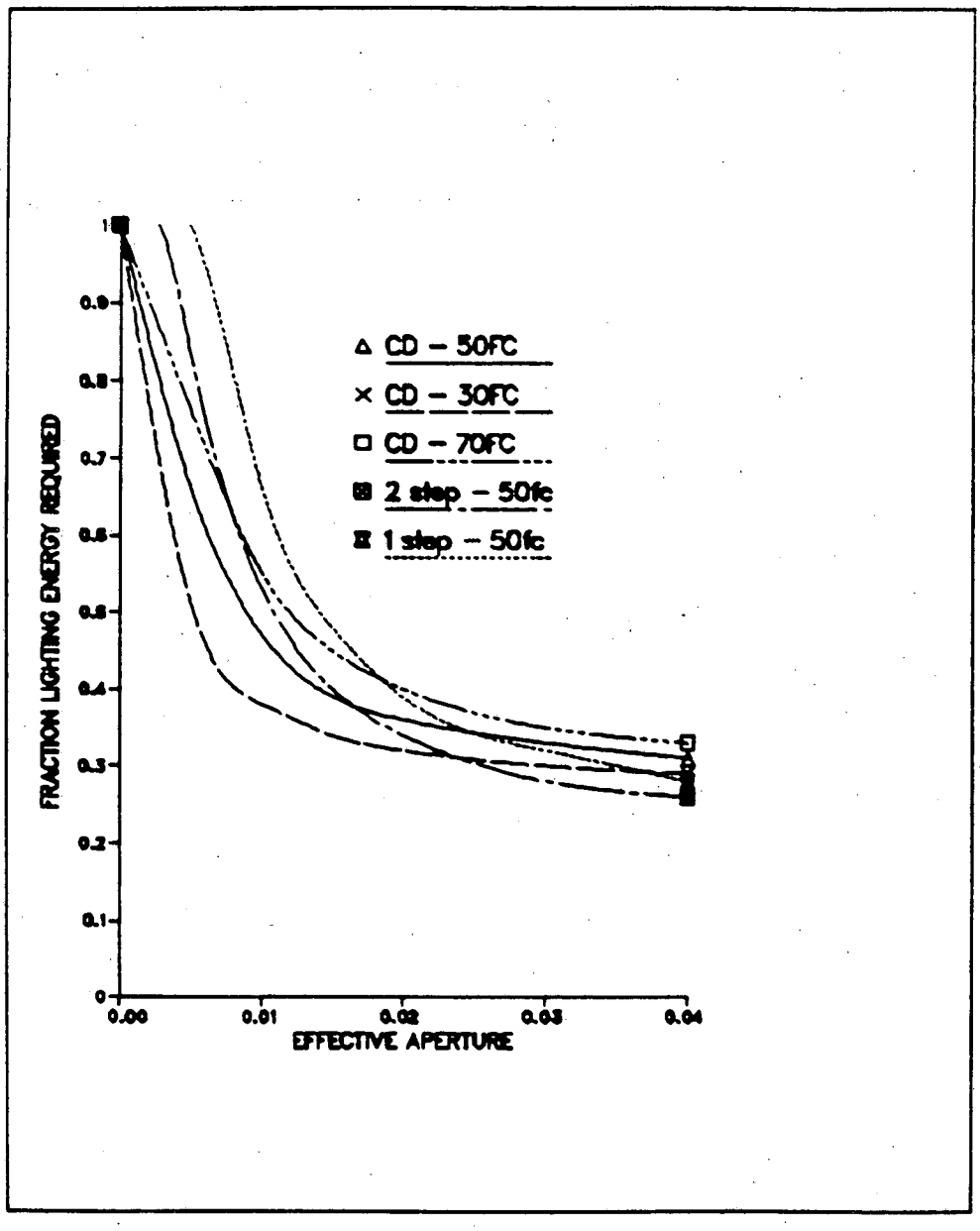

Figure 2. Lighting energy requirements with daylighting for skylight module in Los Angeles; comparison of lighting level and control.

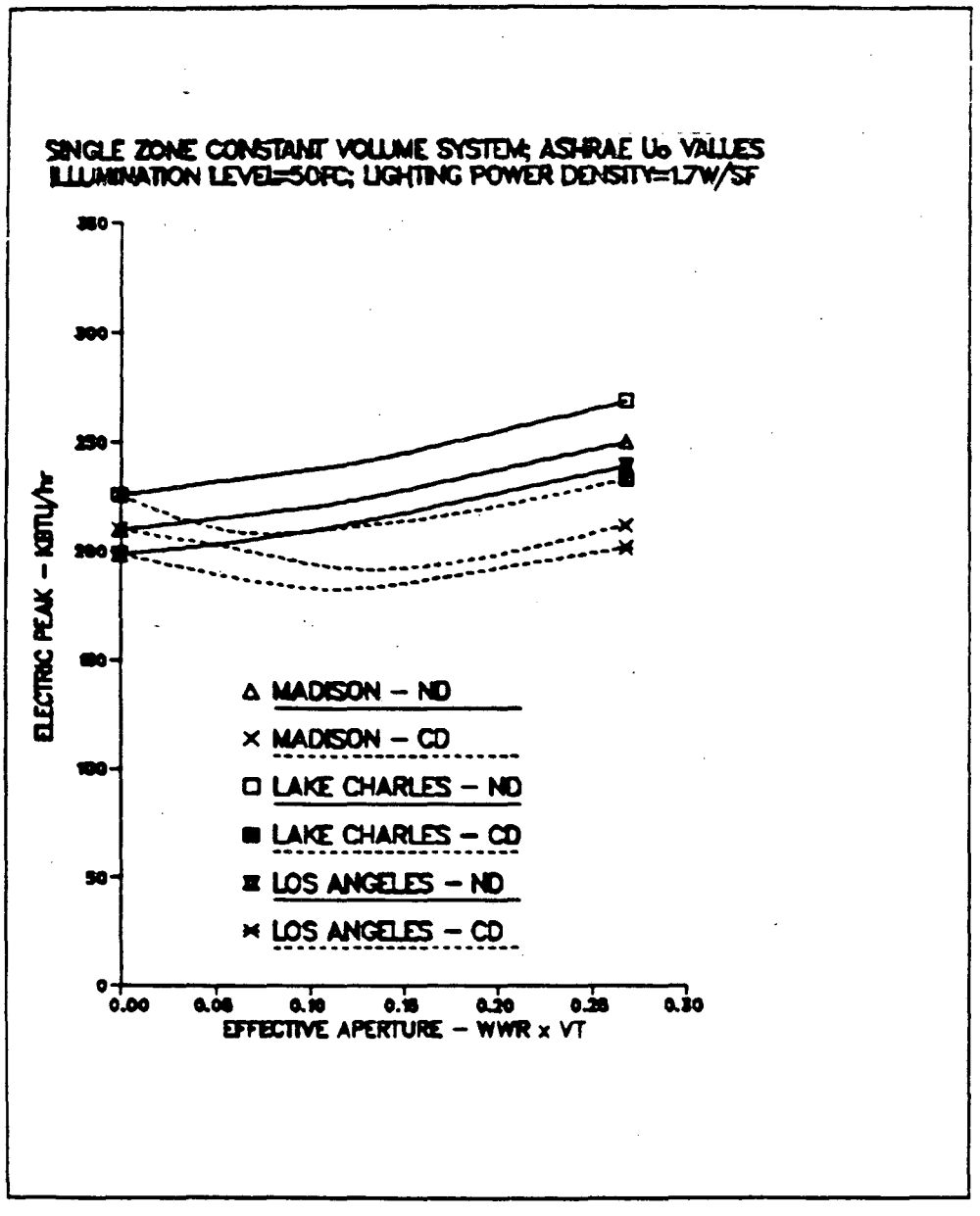

Figure 3. Peak electrical demand for window module; continuous dimming vs. no daylighting controls.

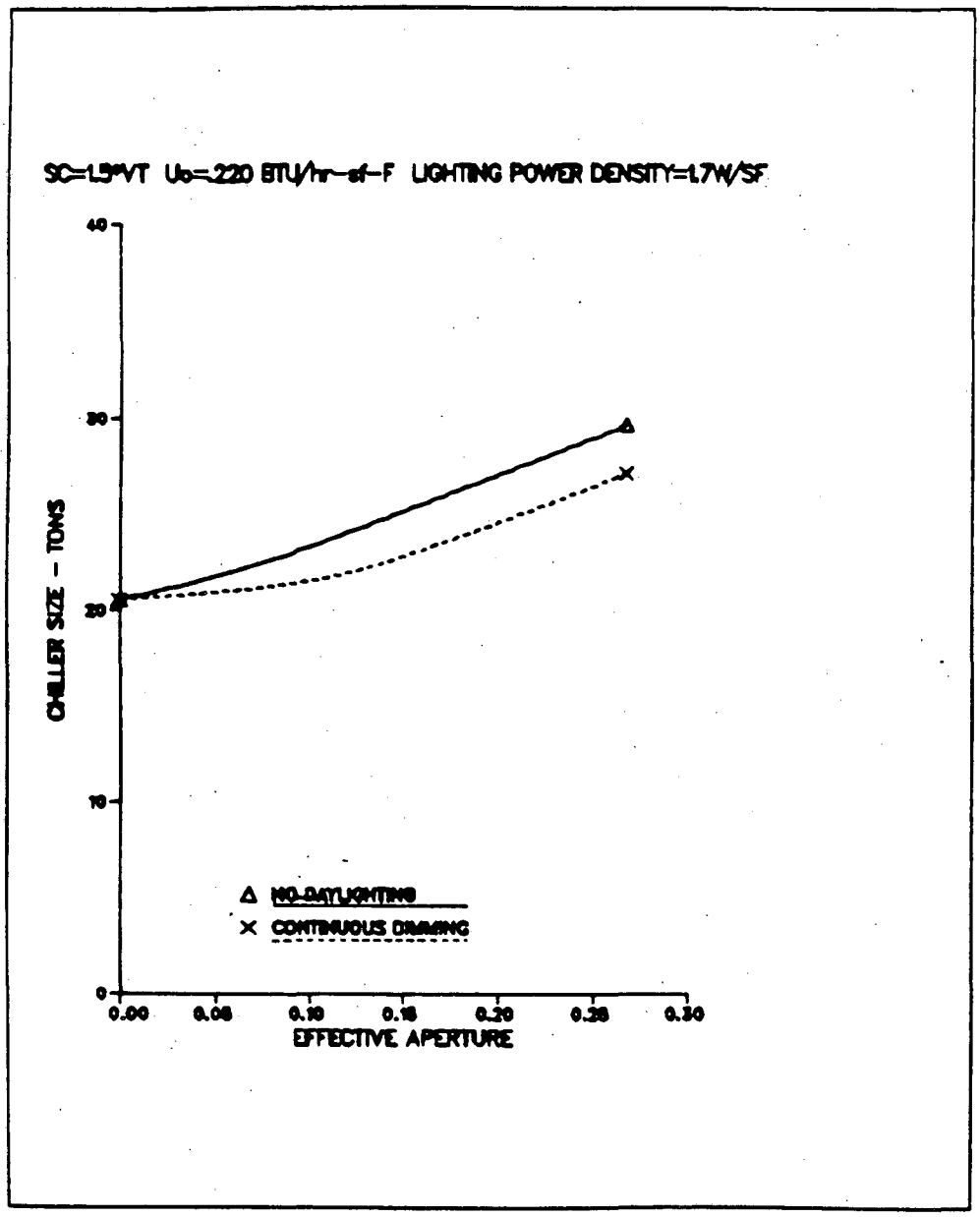

Figure 4. Chiller size as a function of effective aperture for office module with windows; continuous dimming vs. no daylighting controls.

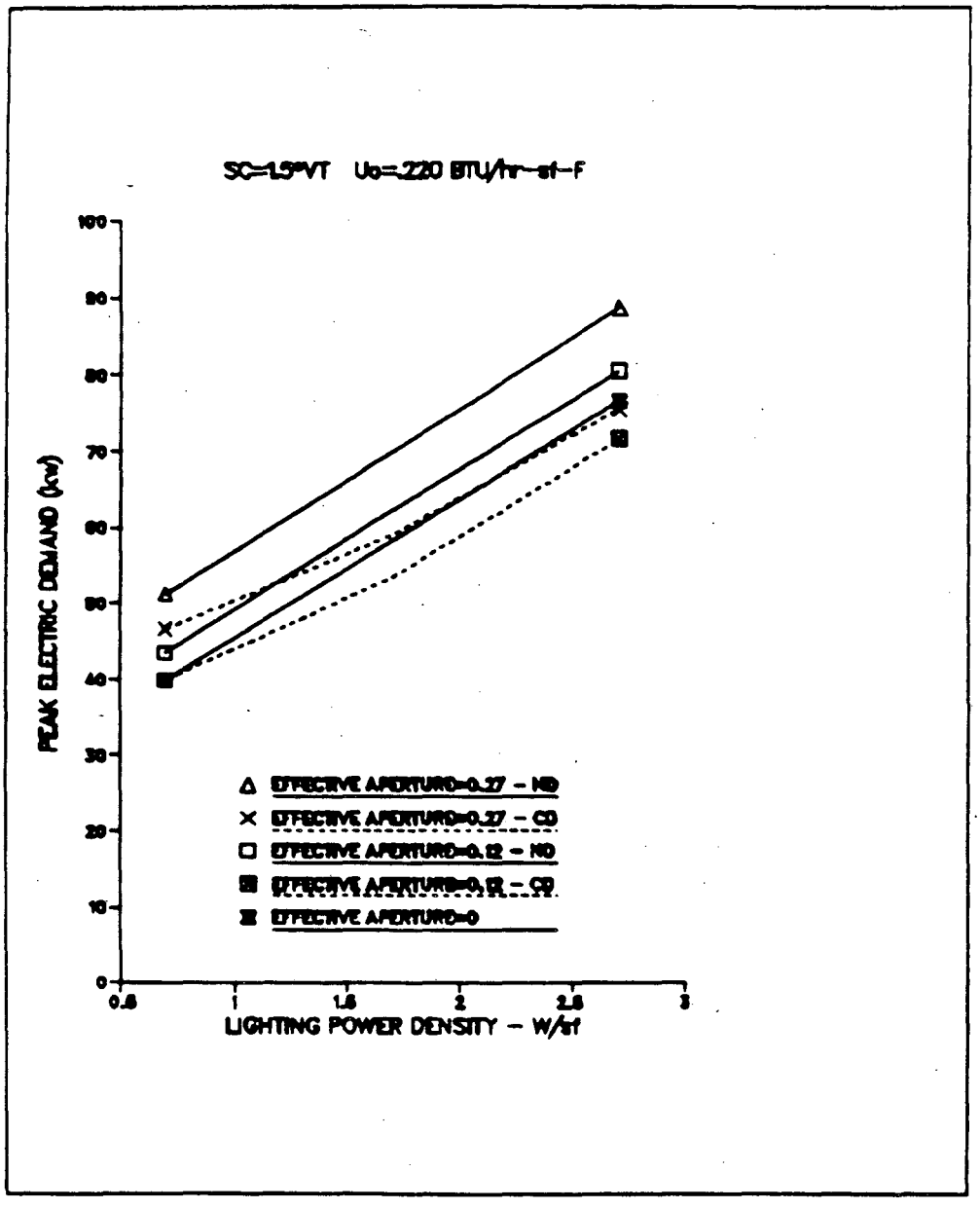

Figure 5. Peak electrical demand as a function of lighting power density: Los Angeles, office module with windows; continuous dimming vs. no daylighting controls.

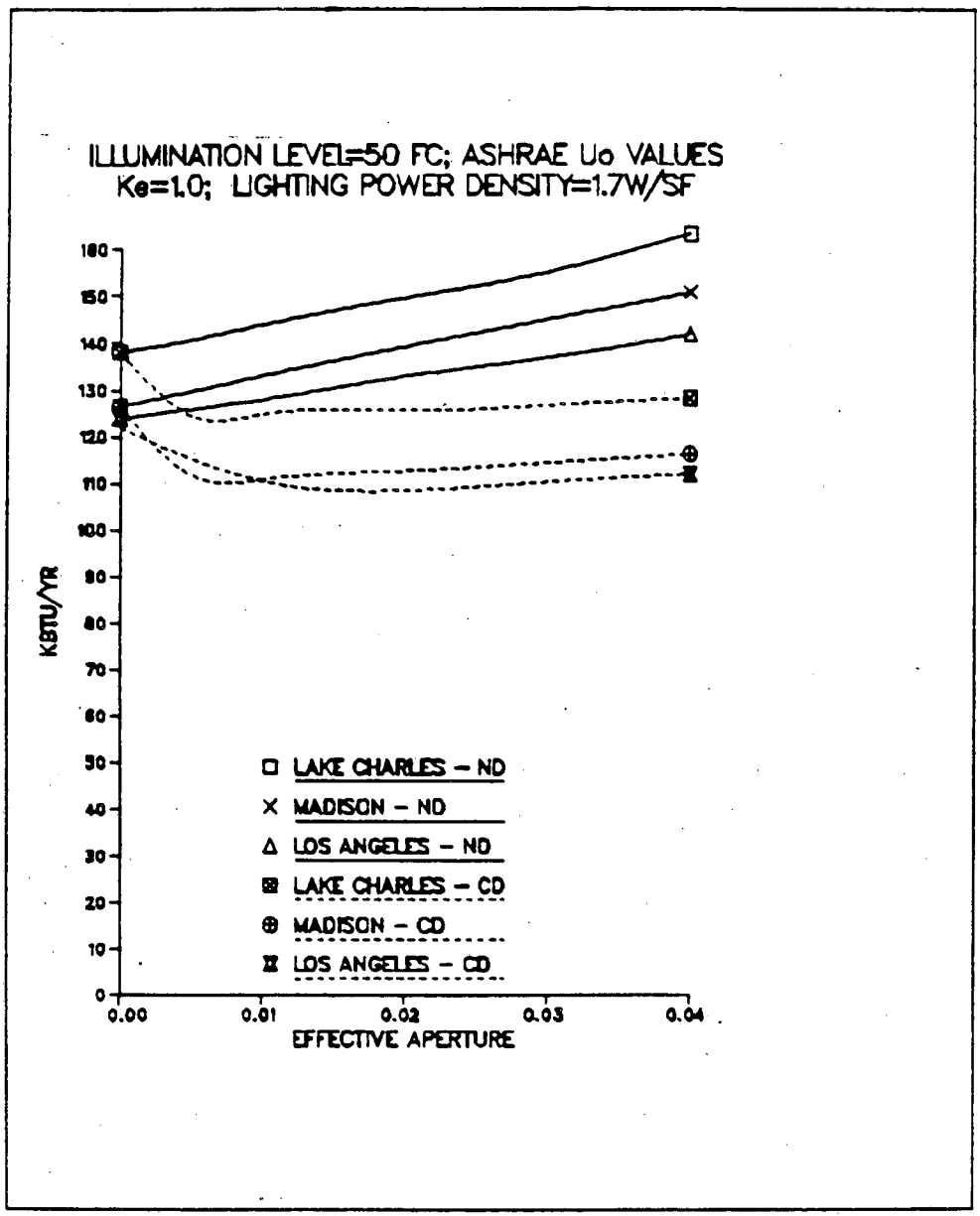

Figure 6. Peak electrical demand for skylight modules. Shows continuous dimming vs. no daylighting controls.

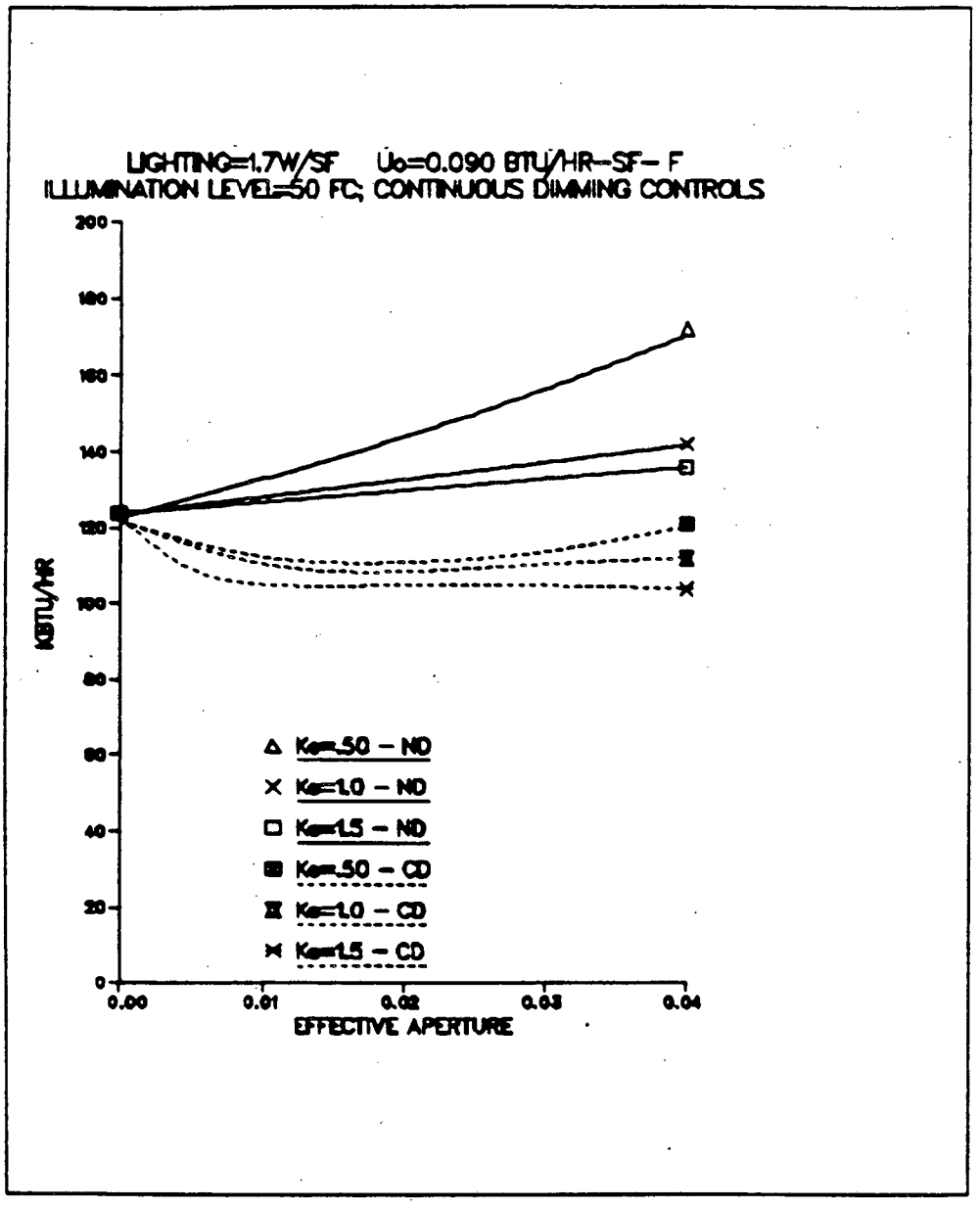

Figure 7. Peak electrical demand for skylight module in Los Angeles. Shows K_e variation with and without daylighting.

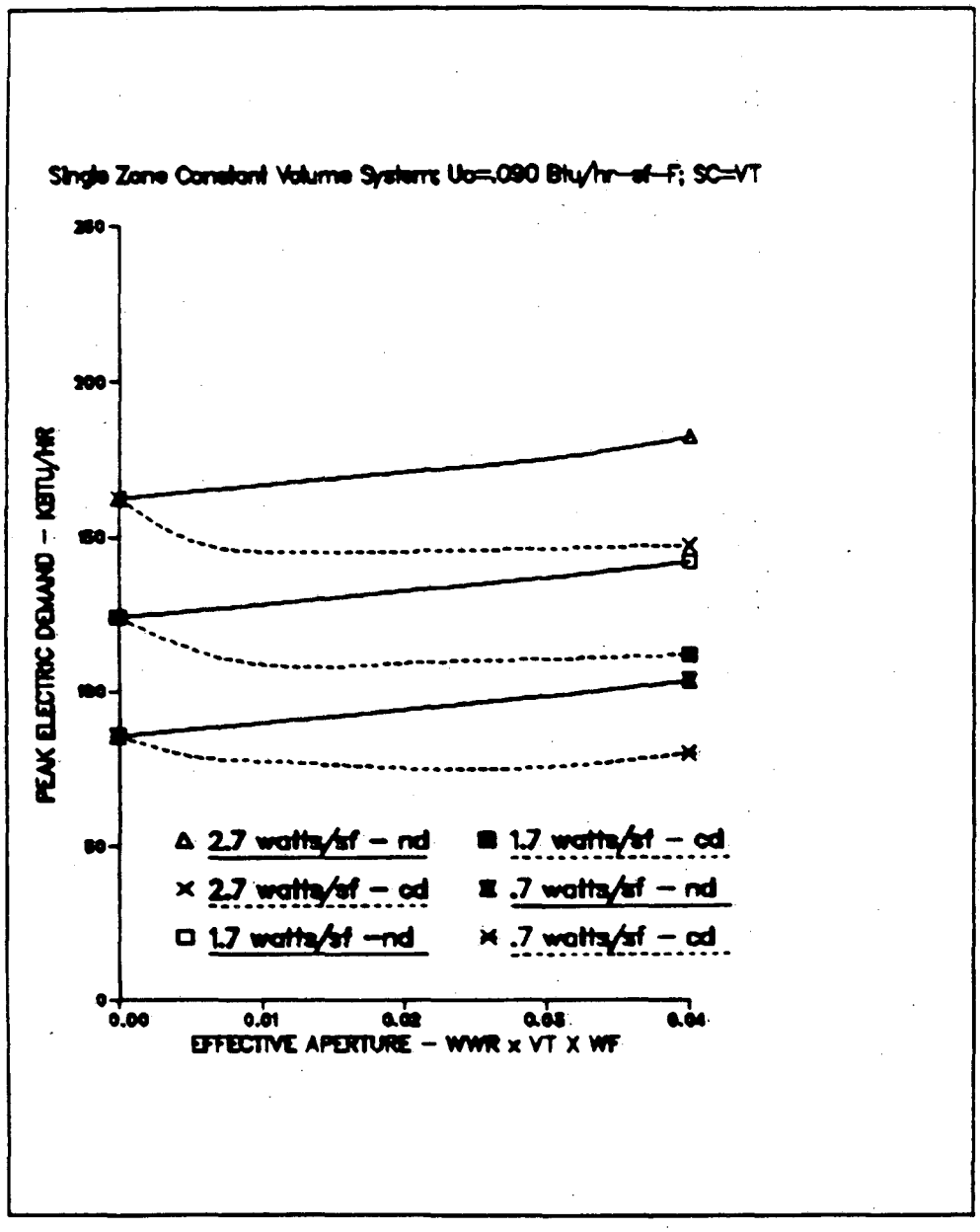

Figure 8. Peak electrical demand for skylight module in Los Angeles. Shows continuous dimming vs. no daylighting controls.

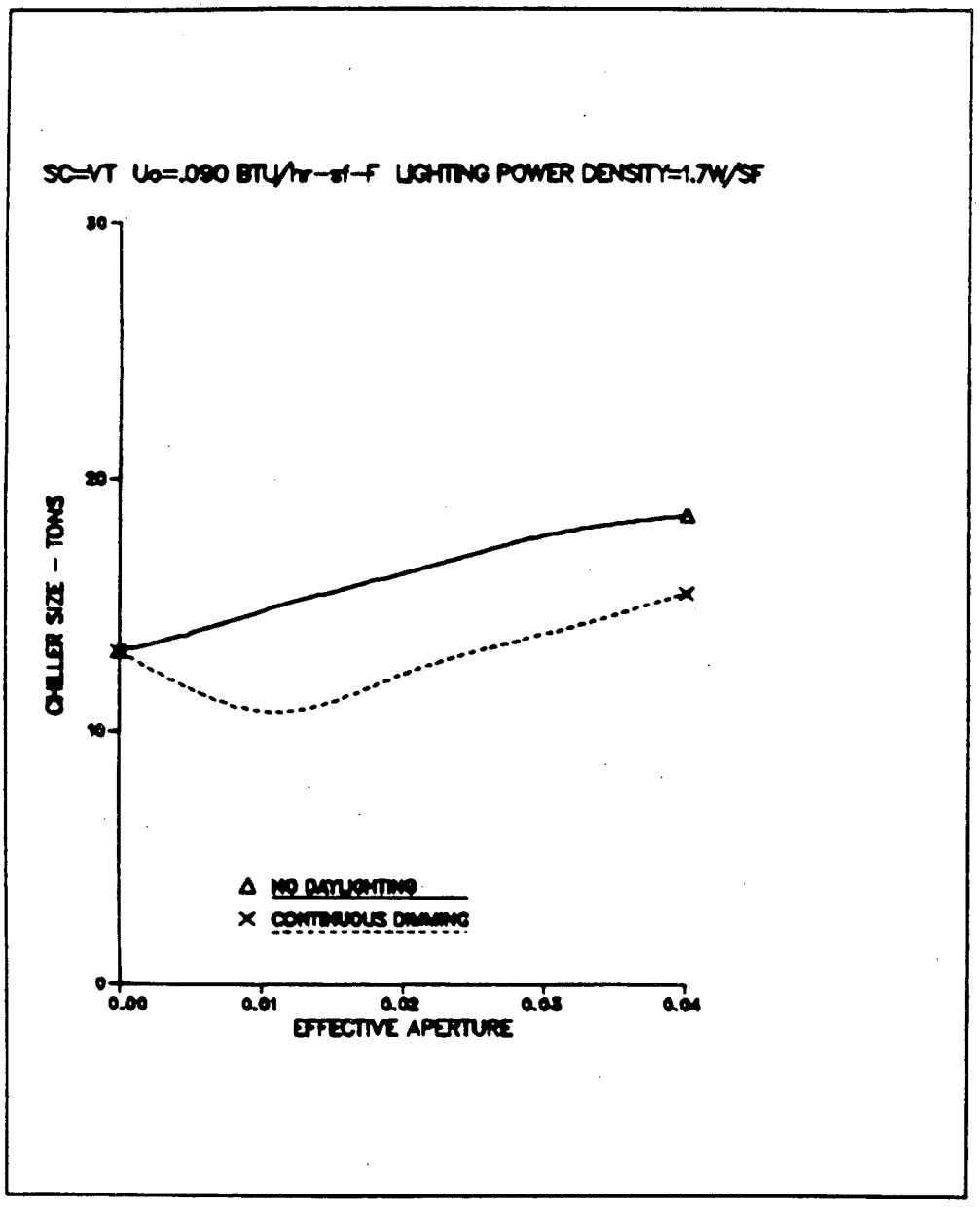

Figure 9. Chiller size as a function of effective aperture for skylight module in Los Angeles. Shows continuous dimming vs. no daylighting controls.

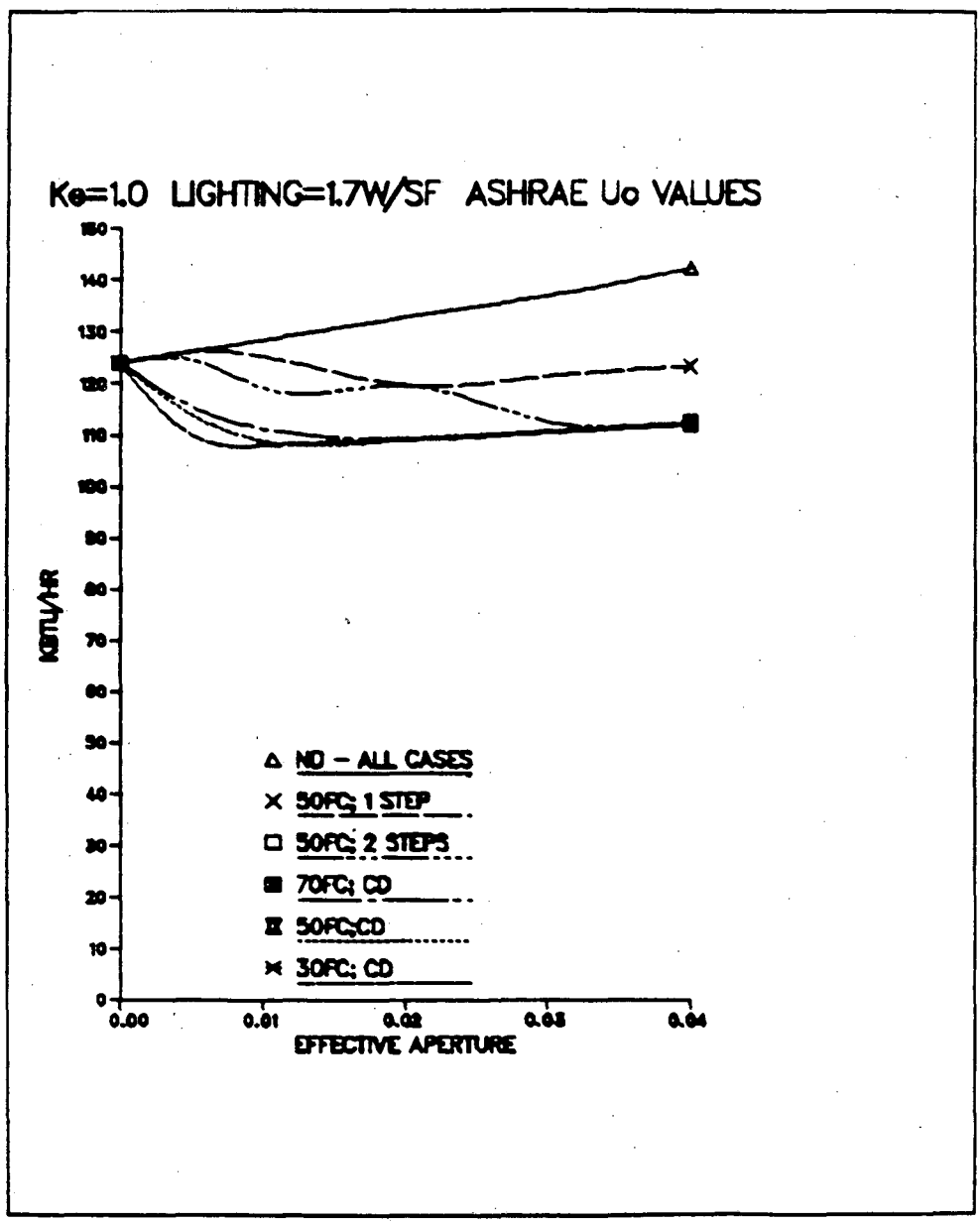

Figure 10. Peak electrical demand as a function of lighting load and control type for skylight module in Los Angeles.

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