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ABSTRACT

This study systematically explores the energy effects of skylight systems in a prototypical office building module and examines the savings from daylighting. For specific climates, roof/skylight characteristics are identified that minimize total energy or peak electrical demand. Simplified techniques for energy performance calculation are also presented based on a multiple regression analysis of our data base so that one may easily evaluate daylighting's effects on total and component energy loads and electrical peaks. This provides additional insights into the influence of skylight parameters on energy consumption and electrical peaks. We use the DOE-2.1B energy analysis program with newly incorporated daylighting algorithms to determine hourly, monthly, and annual impacts of daylighting strategies on electrical lighting consumption, cooling, heating, fan power, peak electrical demands, and total energy use. A data base of more than 2000 parametric simulations for 14 U.S. climates has been generated. Parameters varied include skylight-to-roof ratio, shading coefficient, visible transmittance, skylight well light loss, electric lighting power density, roof heat transfer coefficient, and electric lighting control type.

INTRODUCTION

This study uses a powerful analytical model to calculate annual energy requirements over a wide range of skylight, electric lighting, and roof parameters. A typical skylighted floor of a commercial office building with and without daylighting controls is analyzed for 14 locations throughout the United States. The analytical tool used is DOE-2.1B, a state-of-the-art building energy simulation computer model. DOE-2 is used because a definitive performance data base on this subject does not exist. DOE-2's daylighting algorithms can determine hourly, monthly, and annual impacts of daylighting strategies on electricity consumption, cooling requirements, fan power, heating requirements, and, ultimately, total energy use. Selkowitz et al. (1982) and Arasteh et al. (1984) contain brief descriptions of the daylighting calculation procedure used in DOE-2.1B; more detail is presented in DOE-2 Supplement (1982) and Winkelmann (1983). McCluney (1983) and AAMA (1977), among others, have also investigated the daylighting and thermal impacts of skylights.

The results of this analysis have been developed into simple analytical expressions and graphic displays from which one can easily determine the effects of various combinations of skylight parameters other than those explicitly modeled in our study. We also suggest an approach that allows direct determination of skylight properties that minimize energy consumption and/or peak electrical load in a daylighted building in each climate.

BUILDING AND DATA BASE DESCRIPTION

The need to generate results generally applicable to a wide range of building types and configurations led to the development of a single prototypical building module 100 ft by 100 ft, (30.5 m by 30.5 m), in which the important energy use patterns can be characterized per unit floor area and then applied to other configurations. In this study, fenestration is limited to flat skylights uniformly distributed over the roof. To isolate the energy effects of the

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roof/skylight system, exterior walls and the floor are modeled as adiabatic (no heat transfer) surfaces. This limits envelope energy flows to the roof and skylight system. Building operating and occupancy schedules are based on standard hourly profiles. The space is conditioned by a single constant-volume, variable-temperature HVAC system operating with an economizer. Heating is furnished from a gas-fired boiler and cooling from an electrically operated centrifugal chiller. Choice of HVAC system can significantly affect absolute energy use, and the results discussed in this paper apply only to the system modeled. However, the general trends presented here as a function of fenestration parameters may also be applicable to other HVAC systems.

An extensive sensitivity study (Arasteh et al. 1984) was conducted with this one-zone module to determine details of the final module design and establish the variables and limits for parametric consideration. The following variables were considered in the sensitivity study: roof overall heat-transfer coefficient, roof absorptance, skylight area, skylight spacing, shading coefficient, visible transmittance, light-well factor (the fraction of visible light transmitted by the glazing that enters the space, i.e., that which is not absorbed or reflected out by the light well walls) (IES 1981), electric lighting power density, illumination level, daylighting control strategy, lighting control reference point, ceiling height, room size, and office equipment load. The primary variables affecting daylighting energy savings trends were found to be the roof overall heat-transfer coefficient, skylight area, shading coefficient, visible transmittance, well factor, and electric lighting power density. The influence of room size, ceiling height, skylight spacing, and equipment load were found to be minimal over the range of current design practice. For most of our study, the illumination level (50 fc or 538 lux), lighting control strategy (continuous dimming), and light control point (located at the diagonal intersection of four adjacent skylights in the center of the space) were selected as typical of office lighting requirements. Figure 1 details the final building module. Arasteh et al. (1984) and Johnson et al. (September 1983) describe the detailed results of the sensitivity study.

For buildings having vertical windows, it has been shown that the use of a single parameter (the product of the window-to-wall ratio [WWR] and the visible transmittance [VT]) to define daylighting performance simplifies the analysis and yields accurate results (Johnson et al. February 1983). We call this new lumped parameter the effective aperture. A similar lumped parameter can be created for skylights 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_e) for skylights.

Climatic data for 14 locations analyzed in this study are listed in Table 1. For the cases with no daylighting controls, we evaluated three values of electric lighting power densities (L_w), three roof overall U-values (U_o), and six values of effective aperture, resulting in 54 runs per climate. For the daylighted cases, because the relationship between visible transmittance and solar heat gain is not necessarily constant, we evaluated several SC values for each value of the effective aperture. 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. Table 2 shows the parametric variations of effective apertures for each climate for daylighted cases. The number of computer simulations per climate for a daylighted module with continuously dimming lighting systems was thus 207. The first six variations in Table 2 were also studied with no daylighting. Roof U-values were selected according to ANSI/ASHRAE/IES Standard 90 A-1980 and varied with climate (see Table 1).

Each DOE-2 computer simulation provides useful data on peak loads, component monthly loads, system design parameters, space temperature summaries, fan energy, equipment sizes, daylight factor summaries for each skylight, percentage lighting energy reduction due to daylight, and lighting levels available from daylight with corresponding frequencies of occurrence.

ANALYSIS OF RESULTS

We require that the overall roof heat transfer coefficients be constant over the range of effective apertures in order to meet ANSI/ASHRAE/IES 90-A type criteria. Thus, the relationship between increasing effective aperture and annual energy requirements is primarily a function of the light- and heat-admitting properties of the skylight system. For the nondaylighted cases—that is, for buildings without controls to reduce electric lighting output in response to daylight levels—Figure 2 shows that this relationship is nearly linear over a wide range of climatic types. In cool and cold climates (Seattle and Madison), increasing solar gains lead to a decrease in annual heating requirements, more than offsetting any rise in cooling energy. Thus, overall energy consumption drops slightly with increasing effective aperture. This trend is reversed in hot climates, like those in Lake Charles and El Paso, where, because of the minimal heating requirements, increasing solar gains only raise cooling loads. This effect is slightly more prominent in El Paso than in Lake Charles, as seen in the steeper slope of El Paso's annual energy line. In El Paso, cooling loads are dominated by solar gains, whereas in Lake Charles they are a mixture of solar gains and high latent loads. With daylight-responsive controls, annual energy requirements for all cities drop significantly.

Lighting Energy Reductions With Daylight Controls

Electric lighting energy consumption is the same for all climates in the nondaylighted case (16.4 kBtu/ft^2-yr [188.0 MJ/m^2-yr] for an installed lighting power of 1.7 W/ft^2 [18.3 W/m^2]). We normalize lighting energy consumption in the daylighted buildings to this value and plot against effective aperture in Figure 3. Daylighting results for all 14 climates demonstrate that the general character of the lighting energy savings curve is similar in all climates. At the limits of the study, Seattle, with extensive overcast periods, has the minimum daylight potential (61% savings) and El Paso, a very clear climate, the maximum (72% savings).

Daylighting savings increase almost linearly at first and then begin to level off quickly when the effective aperture increases beyond a certain point. At this point, the midday lighting requirements have been met during spring, summer, and fall, and additional glazing provides only limited benefits during the early morning and late afternoon (and some benefits in winter), but increases cooling loads induced by solar gains. For a continuous dimming system, Figure 4 shows monthly average percent lighting savings for each hour of the day for effective apertures of 0.01, 0.02, and 0.04 in El Paso. Hours where daylight has provided the maximum savings (90%)* are shaded. At an A_e of 0.01, this is just beginning to occur for scattered midday hours. At an A_e of 0.02, the times at which daylight savings are saturated have spread dramatically, averaging five hours a day for ten months. At an A_e of 0.04, the saturation effect begins slightly earlier in the morning and ends later in the afternoon; midday January hours also reach saturation levels. The value of effective aperture at which this saturation effect occurs varies among cities and depends on climate and latitude. The variation among cities is evident in Figure 3, in the differences in sharpness of change in slope of the savings vs. aperture curves, and the value of effective aperture at which the slope changes.

Annual Energy Consumption

The annual energy savings from daylighting are not only a function of differing reductions in lighting requirements, but also vary with climatic thermal and solar conditions, as seen in Figure 2. Note that this and subsequent figures are based on five assumptions: (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. The results of deviations from these assumptions are discussed at the end of this section. These values fall in the middle of the range of parametrics considered and are representative of current building practice.

In climates where cooling is not a major portion of the total load (i.e., Madison and Seattle), daylighting causes total energy use to drop continuously with effective aperture for the range considered in this study. However, in Lake Charles and El Paso, total energy use quickly reaches a minimum and then begins to increase slightly with increasing effective aperture. This minimum is more pronounced in El Paso, a hot climate slightly more sensitive to variations in effective aperture than Lake Charles because of its low fraction of cloud cover. In these two cases, total energy use is roughly constant between effective apertures of 0.01 and 0.03. From the data in this graph, one can calculate the range of maximum potential total energy savings. These values are governed by daylighting as well as thermal issues. The range of maximum savings from nondaylighted cases varies from 34% in El Paso (where daylighting performs best and there is a high cooling load) and 31% in Lake Charles (where cooling dominates) to 22% in Seattle (where the daylighting potential is lowest) and 21% in Madison (where heating dominates). In all cases, daylighting dramatically reduces

*We assume that, when the light output goes to zero, the continuous dimming system still using 10% of its base power. This "minimum power fraction" is typical of dimming systems. The relationship between light output and power input from this point to the fully "on" position is linear.

energy consumption compared to an opaque roof. Properly sized skylight systems can save energy; the potential economic benefits will depend on utility rates and hardware costs.

We now examine how daylighting affects thermal energy components for the limiting cases of maximum energy savings (El Paso) and minimum energy savings (Madison). In El Paso, as seen in Figure 5, daylighting significantly offsets electric lighting requirements, but high solar gains lead to an appreciable cooling load. A daylighted building will always have lower energy requirements than a nondaylighted building with the same effective aperture, since daylighting reduces the lighting load. An effective aperture of 0.02, which minimizes total energy use for the daylighted case, also saves up to 25% of cooling energy needs compared to the nondaylighted case. At this point, as a result of the diminished cooling load, total HVAC energy for fans and pumps drops by about 10% as compared to the case without daylight. In a daylighted building, cooling loads and associated HVAC loads drop as the effective aperture is increased from zero until the point at which the incremental cooling penalty of added solar gains outweighs the incremental benefits of providing daylight. This begins at very small effective apertures, e.g., 0.005, after which cooling loads rise as the aperture increases in size. These opposing trends (light reductions and thermal increases) lead to an effective aperture that minimizes annual energy requirements.

In Madison (Figure 6), the use of daylight also causes cooling to drop by 25%. However, this large percentage drop (10 MBtu [10.6 GJ]) does not make up for the 10% rise in heating energy (15 MBtu [15.8 GJ]) since heat formerly supplied by the electric lights must now be supplied by the HVAC system. Because of the minimal cooling load, total HVAC energy use does not change appreciably with either increasing aperture or daylighting. Thus, in heating-dominated climates, daylighting's primary effect is to reduce lighting energy. This is reflected in the daylighted case by the annual energy curve, which drops quickly to the effective aperture at which daylighting savings are saturated, after which its downward slope begins to level off and, eventually, rise.

Peak Electrical Demand

Without daylighting, peak electrical demand typically occurs during sunny summer afternoons when cooling and lighting loads are at their maximum values. Thus, in the nondaylighted case, peak electrical demand increases with effective aperture in all climatic types (see Figure 7, which assumes the five conditions previously stated for annual energy consumption). However, in a daylighted building, for moderate and high lighting power densities, electrical peaks generally occur during warm overcast afternoons, at a time 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. Peak electrical demand savings are different for each city because of ambient weather conditions at the time of the peak. At an effective aperture of 0.04, with an installed lighting power of 1.7 W/ft^2, savings in Seattle are highest (16 kW) because ambient temperature and humidity conditions at the time of the peak drop from hot and humid (without daylighting) to cool and dry (with daylighting). Because ambient conditions in Lake Charles at the time of the peak do not drop as significantly, the peak electrical demand savings are less (11 kW). While Lake Charles and El Paso have similar electric peaks for cases with no daylighting, electric peaks with daylighting are different. This is due to the large latent load portion of Lake Charles' cooling load, which is not affected by reductions in lighting heat gain, while the mostly sensible cooling load in El Paso is directly affected by electric lighting heat gain.

Effects of Variations in Base Case Assumptions

In the previous analysis, 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 (0.9-m by 0.9-m) skylight, a 1.5-ft (0.46-m) deep well, and a 70% well wall reflectance results in a WF of 0.7. Increasing the well depth to 3.5 ft (1.1 m) lowers the WF to approximately 0.5 (IES 1981). We assume that light losses in the light well contribute to the solar gain seen by 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, given a practical choice of the visible transmittance of available glazing materials, K_e will vary between a minimum of 0.5 and a maximum of 1.0. However, new spectrally selective glazing materials having enhanced visible transmittance are appearing on the market. We consider the case of skylight systems with a K_e of 1.5 in this paper to suggest the possible performance of future daylight-oriented glazing materials for skylight applications.

For the nondaylighted cases at a given effective aperture, as K_e decreases, net solar gains increase. In El Paso, this leads to an increase in the electrical peak (Figure 8), as one might expect in any climate where the peak demand occurs during the cooling season. With daylighting, at effective apertures not large enough for lighting saturation to occur, peak electrical demand does not vary significantly with K_e. After this point, the effect of increasing aperture is increased sensitivity to solar gains (i.e., decreasing K_e). At a given effective aperture, the amount of visible light available to the space is the same for all K_e. Changing K_e changes the solar thermal impact to the space. At small effective apertures, daylighting has a great effect and cooling has a small effect. After daylighting saturates the space, the peak curves are dominated by solar gains. This is reflected in the similarity of the slopes of the daylighted and nondaylighted curves after effective apertures of 0.02. Because El Paso is a cooling-dominated climate, total annual energy consumption also increases with diminishing K_e and behaves similarily to the electrical peak curves in Figure 8. For the case of El Paso where, for low K_e values, there are distinct minimums for both total energy consumption and annual electrical peak demand, electrical peak minimums occur at lower effective apertures than total energy minimums (not shown). However, by increasing K_e, one gains the option of using larger skylight areas without significantly increasing energy use and peak demand.

Changing the electric lighting power density (L_w) has a significant effect on both annual building energy use and electrical peak. As L_w increases, lighting's proportionate share of the cooling load (or cooling peak) and total energy use (or electrical peak) both rise substantially, increasing potential savings from daylighting. Minimum energy use is still achieved at the lowest L_w level. The fractional savings in annual energy consumption from daylighting are approximately equal to the fractional savings for peak electrical demand at low L_w levels, 0.7 W/ft^2 (7.5 W/m^2). However, at high L_w levels, 2.7 W/ft^2 (29.1 W/m^2), daylighting produces a higher fractional savings for electrical peaks. This is attributable to the fact that, in a daylighted building with high L_w levels, peak electrical demand generally occurs during cloudy conditions, when lighting is the overriding component of the peak demand.

Different illumination criteria and lighting control systems also affect annual energy use. Figure 9 shows the same graph of normalized annual lighting energy requirements with daylighting in Los Angeles as shown in Figure 3; also included are illumination level and lighting control variations. These parameters have an effect as significant as that due to climatic extremes. With a dimming system set to 30 fc and 70 fc, lighting energy requirements follow trends similar to those of the 50-fc case. As expected, selection of a lower lighting design criterion increases the fractional savings from daylighting. Conversely, as the lighting design criterion increases to 70 fc, the fractional energy savings decrease.

For the 50-fc lighting level, lighting energy savings from stepped switching follow a different trend than with continuous dimming. At small effective apertures (< 0.01), savings with the dimming system are substantially greater than those for step switching; however, beyond an effective aperture of about 0.02, savings from step switching equal or exceed those from continuous dimming. This effect at larger apertures is due to the minimum power fraction required of the dimming system. When daylight illuminance exceeds the daylight setpoint, stepped switching systems are turned off and use no power. Note that a minimum effective aperture is required before any energy savings accrue to the stepped systems. Performance of the one-step (on/off) system consistently lags behind that of the two-step (100%-50%-off) system, as expected.

As seen in Figures 5 and 6, with daylighting, the decrease in lighting energy with increasing effective aperture is reflected in the graph of total annual energy. Similarly, the effects of varying illumination levels and lighting control variation seen in Figure 9 are also directly reflected in annual energy use graphs (not shown). These graphs follow similar but less pronounced trends. For annual energy use, the greatest difference in daylighting savings for spaces with different required lighting levels and control types occurs at small effective apertures. For larger apertures, the daylight benefits have increased to near their maximum levels and the differences between them are small.

Figure 10 shows that the lighting design criterion only slightly affects electrical peak energy savings from daylighting. This might be expected, since electrical peaks for cases with continuous dimming daylighting controls occur during periods of low daylight availability.

Stepped switching systems have an interesting effect on daylighting peak electrical savings (Figure 10). As compared to continuous dimming systems, 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 was the case 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 a continuous dimming system and not a nondaylighted system. For the one-step (on/off) system, daylighting does not produce any peak savings for effective apertures less than 0.005. For the two-step system, daylighting savings first occur at a smaller effective aperture, 0.0025.

The effects of overall roof U-value variations on daylighting energy savings are minimal. Only in cases of severe heating requirements and exceptionally high U-values will roof U-value produce a noticable change in daylighting's impact on annual energy requirements.

SIMPLIFIED PERFORMANCE CALCULATIONS

The large number of parametric runs made in this study produced a data base suitable for statistical analysis. An analytical expression was developed correlating energy consumption and electrical peak demand to the relevant design variables. A series of multiple regressions were undertaken to define coefficients for selected configuration variables. This regression technique compresses the very large data base into a manageable form that allows energy use patterns to be further analyzed conveniently. It also permits us to analyze, with confidence, parametric values that were not specifically studied as long as these values are within the range of parametric variation and the functions are known to vary continuously.

For hourly simulation of daylighted buildings, under the conditions chosen, the DOE-2 simulations represent state of the art in predicting energy use. Parameter values not specifically considered in the analysis but within the limits of the data base were calculated using the regression results, and compared with actual DOE-2 results. The regression procedure resulted in acceptable accuracy. The conditions used in our test module are representative of building practice; it is unlikely, however, that many buildings will be designed in exactly this manner. Therefore, the energy values defined by the regression procedure and given here should not be assumed to predict absolute energy use. Rather, they are best utilized to predict trends (i.e., minimum energy use) in energy performance and to compare the differences between design alternatives.

Distinct regression expressions for total electricity consumption (cooling, lighting, fans, and equipment), peak electricity consumption, and fuel energy (heating) consumption were generated. Because we chose a form for these expressions that is the same for all three quantities, the total energy (fuel + electricity) consumption can be found by adding total electricity and fuel energy regression coefficients. The daylighting impacts are modeled as an adjustment factor to the lighting terms. The resulting regression expression is of the form:

$$Q = b_{i1} U_o A + b_{i2} A_g SC + b_{i3} k_d A L_w + b_{i4} A \qquad (1)$$

where

b_i's = regression coefficients (Table 3)
i = 1 : total electricity
2 : peak electric
3 : fuel energy

U_o = exterior roof overall U-value (Btu/hr·ft^2·F)
(1 Btu/hr·ft^2·F = 5.678 W/m^2·C)

A_g = skylight area (ft^2)
(1 ft^2 = 0.0929 m^2)

A = floor (roof) area (ft^2)

L_w = lighting power density (W/ft^2)
(1 W/ft^2 = 10.76 W/m^2)

k_d = adjustment factor due to daylighting (Figure 3).

Each term of the above regression expression was chosen to contain the energy effects from a particular building performance component. The first term accounts for conductive heat transfer with the environment, the second for solar gains, the third for lighting, and the fourth for energy use not directly related to fenestration but generally a function of floor area (equipment loads, infiltration, and HVAC energy). Multiple regression is an analytical technique for determining the best mathematical fit to the independent variables input. Each term of the regression equation, however, cannot always stand alone and completely describe one component of the energy issue with a high degree of accuracy. In particular, the fourth term may account for some of the effects attributable to other terms.

An analysis of the regression terms shows that they are reasonably physically consistent with the performance of actual buildings. When climatic variables are not a factor, the regression coefficients are fairly constant over the range of climatic types, i.e., b_3 and b_4 for electrical peak and electricity consumption. Because b_4 accounts for infiltration and HVAC loads (which vary with climate) as well as equipment, it varies slightly more than b_3. In climates where heating is significant, the conduction coefficient for the fuel equations, b_1, increases. The regression coefficients for the solar gain and lighting terms in the fuel equation are both negative because they lower the heating load. For the electrical energy and peak terms, b_2 rises as the cooling demand rises with increasing solar gain. Thus, by comparing coefficients, one can predict which loads are significant or insignificant. A more detailed description of the regression procedure is given in Sullivan et al. (1983).

Table 3 presents the regression coefficients and relevant statistical variables to indicate the reliability of the fit. Generally, the r^2 values (square of the correlation between the predicted value and the actual value; an r^2 of 1.0 represents a perfect correlation) are above 0.99, with the exception of the fuel energy, for which they are above 0.92. Slightly better fits can be achieved with more complex equations for Q_f, involving second-order terms. However, this added complexity reduces the value of the simplified formats.

Daylighting Adjustment Factor

The daylighting adjustment factor to the lighting term accounts for the fraction of the original lighting energy (or electrical peak) displaced by daylighting. It is a function of effective aperture and is represented by:

$$k_d = 1-C_1[1-\exp(-C_2A_e)] \quad (2)$$

where

C's = regression coefficients (Table 4).

This equation can be used to determine the impact of daylighting on all energy and peak quantities analyzed. It assumes that energy quantity (electricity consumption, electrical peak, and fuel energy) savings with daylighting are equal to the fractional lighting energy savings (represented by $1-k_d$) multiplied by the lighting component of the regression equation ($b_3 \cdot A \cdot L_w$). This simplification was found to provide reasonable comparative results between DOE-2-generated points and those predicted by the regression equation. Coefficients are presented in Table 4 for the daylighted case with lighting criteria of 50 fc and continuously dimming controls. We are developing more accurate daylighting adjustment factors based on the actual savings for daylighted and nondaylighted cases for each quantity studied.

Most of our results in this paper are plotted as functions of effective aperture for a single value of electric lighting power density, a single value of overall roof heat-transfer coefficient, and a fixed relationship between VT and SC. However, using the regression expression, energy analyses can also be carried out for roofs where the U-values of the opaque portion and the transparent portion each remain constant (thus the overall roof U-value increases with skylight area). However, for this case, results must be plotted against skylight-to-roof ratio (SRR) or net visible transmittance (VT x WF), and then a VT x WF (or SRR) must be selected.

Climate-Generalized Results

The effect of daylighting on lighting savings (i.e., daylighting adjustment factor) is climate-related and primarily a function of incident solar radiation. The first of the two daylighting adjustment factor coefficients, C_1, measures the maximum possible lighting fraction with daylighting; while the second coefficient, C_2, measures how quickly the lighting energy requirement curve drops before it begins to level out. Figures 11 and 12 show these coefficients plotted versus K_t (Beckman et al. 1977), the ratio of monthly average daily total radiation to extraterrestrial daily insolation (given in Table 1). Because daylight factors are influenced by other factors such as latitude, atmospheric turbidity, and atmospheric moisture, C_1 and C_2 cannot be expressed as a simple function of K_t (or other similar parameters such as cloud cover or percent sunshine) with a high level of accuracy. However, from a practical point of view, where a very accurate k_d is not required, using the curves or formulas presented in Figures 11 and 12 to calculate K_d for other climates will result in a reasonable estimate of annual lighting energy savings.

Optimum Effective Apertures

To find the value of the effective aperture where the energy quantity is lowest, one can take the derivative of Equation 1 with respect to effective aperture and set it equal to 0. This yields:

$$(A_e)_{min} = -[\ln (b_2/K_e b_3 C_1 C_2 L_w)]/C_2 \qquad 0 \leq A_e \leq 0.04. \tag{3}$$

The values of effective aperture that minimize total energy use and electrical peak as a function of K_e and L_w are plotted for El Paso in Figure 13. These graphs offer detailed information on the relationship of optimal aperture values to thermal and daylighting properties of skylights and to electric lighting parameters. A striking result, which is readily apparent, is the difference between optimal aperture that minimizes energy consumption and that which minimizes peak electrical load. The optimum for minimizing energy costs will be highly dependent on local utility rate structures.

Using Equation 3 or Figure 13 to determine optimal sizes is convenient and may be appropriate for preliminary investigations. However, because of skylight aesthetics, economics, or design criteria, it may be useful or important to examine the nature of the curve around the minimum energy point. In many cases the minimum is not a sharply defined point, and considerable design latitude may exist on either side of the minimum value without serious compromise to energy performance. For example, using Equation 3, the minimum total energy use for El Paso occurs for an aperture of 0.013. However, between effective apertures of 0.01 and 0.03, energy use is roughly constant. Future work will further explore these relationships and examine the sensitivity of selecting optimal aperture values for various independent design parameters. More sophisticated regression expressions for daylighting savings now under study will also add to the accuracy of this procedure.

CONCLUSIONS

Several conclusions as to the daylighting potential from skylights can be drawn from the work presented in this paper. The concept of an effective aperture (incorporating skylight roof coverage, visible transmittance, and light well factor) simplifies daylighting analyses without compromising accuracy. Optimum skylight effective apertures for simple horizontal skylights range between 0.02 and 0.03, depending on climate. The effect of climatic differences on lighting energy savings from daylighting is moderate (approximately $\pm$ 20%) and is associated primarily with differences in daylight availability due to cloud cover and, to a lesser extent, latitude. In cooling-dominated climates, daylighting can also significantly lower cooling requirements; while in heating-dominated climates, heating needs will rise modestly. Where cooling loads dominate, total energy use will rise if the effective aperture increases significantly beyond the optimal value. Daylighting can provide large reductions in peak electrical demand; however, electrical peaks will rise if the effective aperture increases beyond an optimal point.

Within the parameters specified for the basic building module, the analytical methods presented in this paper indicate the magnitude of energy savings achievable with skylights as well as the relative savings among different daylighting design options. The initial sensitivity studies discussed in Arasteh et al. (1984) indicate which building parameters can vary without significantly affecting end-use patterns. For example, all other conditions being equal, small changes in ceiling height should not result in noticable differences in end-use energy patterns. However, using clear instead of diffusing skylights or greatly increasing or decreasing the spacing between skylights will affect the accuracy and validity of the results. A potential user of this data must, when interpreting the results, keep in mind the assumptions upon which the regression analysis was based.

The impact of daylighting will be different if rooflighting systems other than flat glazing in a horizontal roof are considered. We are extending our studies to examine the effects of domed skylights, skylights in sloped roofs, and roof monitors. Based on other studies (Treado et al. 1983; Fontoynont 1983), we expect these results to follow similar fundamental trends although the details may vary.

As one might expect, HVAC system design and operation greatly affect total energy consumption in the building, specifically the response to the load changes brought about by daylighting. Future research will investigate these effects in more detail by examining HVAC systems other than the one modeled in this study.

Our building module is useful for characterizing energy performance for an office space. A similar study has been started for a retail space. Initial results indicate that, although the primary differences between office and retail spaces (e.g., internal loads and operating schedules) are not related to fenestration, energy consumption trends are different and each module type requires a separate set of regression coefficients. Warehouses are another generic type of space suitable for daylighting from skylights. Warehouses would be more suitable for stepped switching and lower lighting levels; therefore, their energy performance trends may vary significantly from those presented in this paper.

The analytical results presented here should give the reader a better understanding of the parameters affecting energy and peak electric savings from daylight in skylighted buildings. However, measured data from operating skylighted buildings are not available to compare to calculated results. Until such data become available, results of this and any other simulation-based study must be interpreted and utilized with appropriate caution.

Finally, we note that many building design decisions are made on a cost basis. Design parameters that minimize total energy use may not minimize total utility costs because of the high variability of fuel and electricity prices. Depending on the complexity of local utility rate structures, the fuel and electricity consumption values provided by the regression procedure may allow one to easily approximate energy costs for current or future energy cost scenarios.

ACKNOWLEDGEMENT

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TABLE 1

Climatic Data

City	Latitude	K_t^*	ASHRAE Standard 90 U_o; $Btu/hr \cdot ft^2 \cdot F$	$(W/m^2 \cdot C)$
El Paso, TX	31°	0.27	0.098	(0.556)
Los Angeles, CA	34°	0.38	0.100	(0.568)
Lake Charles, LA	30°	0.45	0.100	(0.568)
Madison, WI	43°	0.47	0.055	(0.312)
Washington, D.C.	38°	0.51	0.090	(0.511)
New York, NY	40°	0.52	0.084	(0.477)
Seattle, WA	47°	0.54	0.088	(0.500)
Albuquerque, NM	35°	0.27	0.089	(0.505)
Boise, ID	43°	0.41	0.075	(0.426)
Dallas, TX	32°	0.44	0.100	(0.568)
Las Vegas, NV	36°	0.28	0.098	(0.556)
Medford, OR	42°	0.45	0.082	(0.466)
Omaha, NE	41°	0.43	0.067	(0.380)
Nashville, TN	39°	0.49	0.097	(0.551)

$^*K_t$ = the ratio of monthly average daily total radiation to extraterrestrial daily insulation (Beckman et al., 1977).

TABLE 2

DOE 2.1B Parametric Variations for Daylighted Cases for each Climate (14), Lighting Power Density (3), and Roof U_o Value (3).

A_e	SRR	SC	K_e
0.00	0.0	0.0	-
0.005	.05	0.1	1.00
0.005	.05	0.2	0.50
0.005	.05	0.4	0.25
0.005	.05	0.6	0.17
0.005	.05	0.8	0.13
0.01	.05	0.2	1.00
0.01	.05	0.4	0.50
0.01	.05	0.6	0.33
0.01	.05	0.8	0.25
0.015	.05	0.2	1.50
0.015	.05	0.4	0.75
0.015	.05	0.6	0.50
0.015	.05	0.8	0.38
0.02	.05	0.2	2.00
0.02	.05	0.4	1.00
0.02	.05	0.6	0.67
0.02	.05	0.8	0.50
0.03	.05	0.4	1.50
0.03	.05	0.6	1.00
0.03	.05	0.8	0.75
0.04	.05	0.6	1.33
0.04	.05	0.8	1.00

TABLE 3

SKYLIGHT MODULE REGRESSION COEFFICIENTS*

	Lake Charles LA	Seattle WA	Madison WI	New York NY	Los Angeles CA	Washington DC	El Paso TX	Medford OR	Dallas TX	Boise ID	Las Vegas NV	Albuquerque NM	Omaha NE	Nashville TN
ELECTRICAL PEAK														
b_1	17.34	5.633	6.249	7.546	9.625	13.47	24.42	11.17	14.28	14.43	26.08	19.49	24.62	11.63
b_2	64.08	59.58	60.52	50.94	47.24	61.11	79.42	58.68	66.04	57.27	76.98	70.08	53.92	62.24
b_3	3.936	3.830	3.925	3.880	3.873	3.945	3.899	3.869	3.860	3.820	3.846	3.834	3.812	3.950
b_4	5.353	4.710	5.689	5.620	4.928	5.530	4.088	5.212	5.665	4.619	4.449	4.334	5.186	5.556
Mean	150.4	128.0	137.9	137.9	132.8	145.2	147.0	139.1	147.8	135.2	148.8	139.8	150.2	145.0
r^2	0.9990	0.9999	0.9999	0.9998	0.9995	0.9993	0.9981	0.9984	0.9987	0.9990	0.9979	0.9977	0.9997	0.9983
σ	1.137	0.4177	0.4010	0.4292	0.7268	0.9448	1.583	1.366	1.250	1.065	1.618	1.660	0.5273	1.455
ELECTRICAL CONSUMPTION														
b_1	27.47	16.50	25.64	20.14	11.44	24.48	46.42	24.93	24.15	27.39	51.00	42.28	44.85	21.11
b_2	125.4	23.08	43.34	48.25	76.55	79.66	174.7	78.24	120.5	76.95	175.5	136.9	51.30	98.84
b_3	11.43	9.731	10.08	10.31	10.82	10.57	11.26	10.27	11.10	10.24	11.17	10.81	10.12	10.87
b_4	11.47	12.11	13.02	13.01	10.62	11.88	8.548	10.57	11.86	11.06	9.429	9.221	13.25	12.08
Mean	360.7	306.3	324.4	332.2	314.6	336.3	356.9	318.3	351.9	325.0	364.7	341.2	357.3	343.5
r^2	0.9980	0.9995	0.9995	0.9994	0.9989	0.9979	0.9962	0.9966	0.9979	0.9969	0.9968	0.9954	0.9996	0.9974
σ	4.398	1.847	1.988	2.176	3.079	4.159	6.214	5.121	4.616	4.905	5.595	6.469	1.808	4.754
FUEL CONSUMPTION														
b_1	25.04	92.83	151.3	83.65	16.20	76.66	37.66	59.57	41.08	106.3	34.27	69.84	110.0	45.09
b_2	-25.53	-45.66	-64.39	-49.33	-18.84	-50.57	-50.90	-50.73	-38.43	-73.67	-50.75	-78.01	-57.67	-49.32
b_3	-0.6237	-2.023	-2.395	-2.038	-0.4090	-1.740	-0.8619	-1.619	-1.004	-2.230	-0.8238	-1.390	-2.433	-1.508
b_4	1.927	5.540	12.88	14.33	0.4945	7.083	2.741	3.959	3.975	6.931	2.883	4.405	12.51	7.208
Mean	31.33	101.5	166.6	176.1	10.52	107.3	43.90	61.37	56.07	122.4	39.42	74.99	181.1	81.84
r^2	0.9806	0.9667	.09778	0.976	0.9480	0.9770	0.9732	0.9193	0.9838	0.9810	0.9787	0.983	0.9824	0.9258
σ	1.460	5.991	5.258	4.654	1.511	4.250	2.624	6.897	2.011	5.254	2.102	3.413	5.215	5.564

*Note: For Table 3 the following units are used:

Peak Electrical Demand:	Btu/hr (1 Btu/hr = 0.293 W)
Electricity and Fuel:	KBtu (1 KBtu = 1.055 MJ)
U_o:	$Btu/hr \cdot ft^2 \cdot F$ ($1\ Btu/hr \cdot ft^2 \cdot F = 5.678\ W/m^2\text{-}C$)
A_g, A:	ft^2 ($1\ ft^2 = 0.0929\ m^2$)
L_w:	W/ft^2 ($1\ W/ft^2 = 10.76\ W/m^2$)

TABLE 4

Daylighting Adjustment Factors
50 fc; Continuous Dimming Controls

$$K_d = 1 - C_1(1 - \exp(C_2 \times A_e))$$

	C_1	C_2	R^2
El Paso, TX	0.717	168.1	0.998
Seattle, WA	0.625	85.5	0.999
Madison, WI	0.674	94.7	0.999
Lake Charles, LA	0.676	148.2	0.998
Washington, D.C.	0.660	106.3	0.999
New York, NY	0.636	93.4	0.999
Los Angeles, CA	0.687	142.0	0.999
Boise, ID	0.676	126.3	0.996
Medford, OR	0.640	122.5	0.998
Albuquerque, NM	0.683	167.7	0.999
Nashville, TN	0.617	120.0	0.999
Omaha, NE	0.678	112.9	0.999
Dallas, TX	0.680	130.3	0.999
Las Vegas, NV	0.673	180.7	0.999

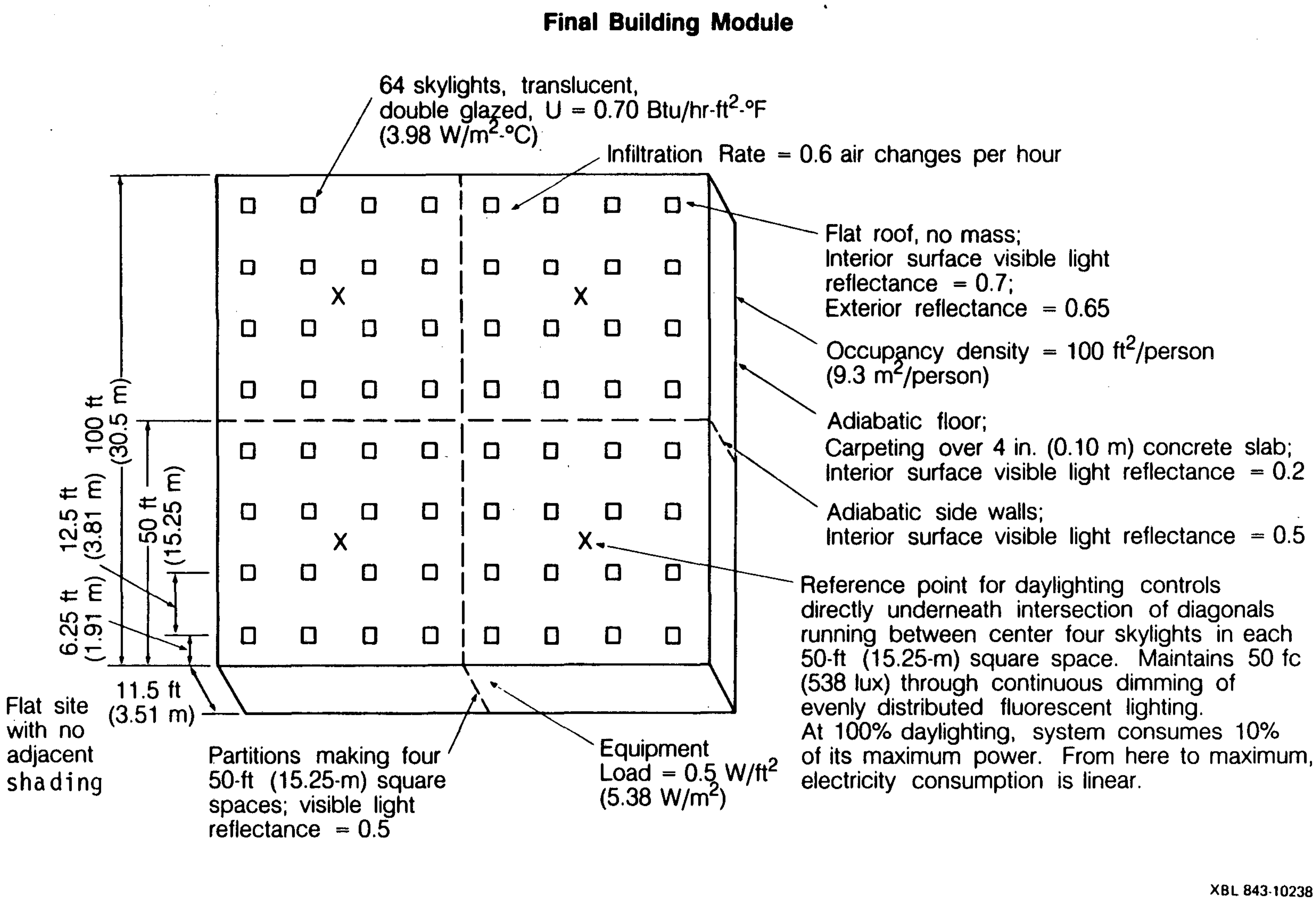

Figure 1: Skylighted building module modeled on DOE-2.

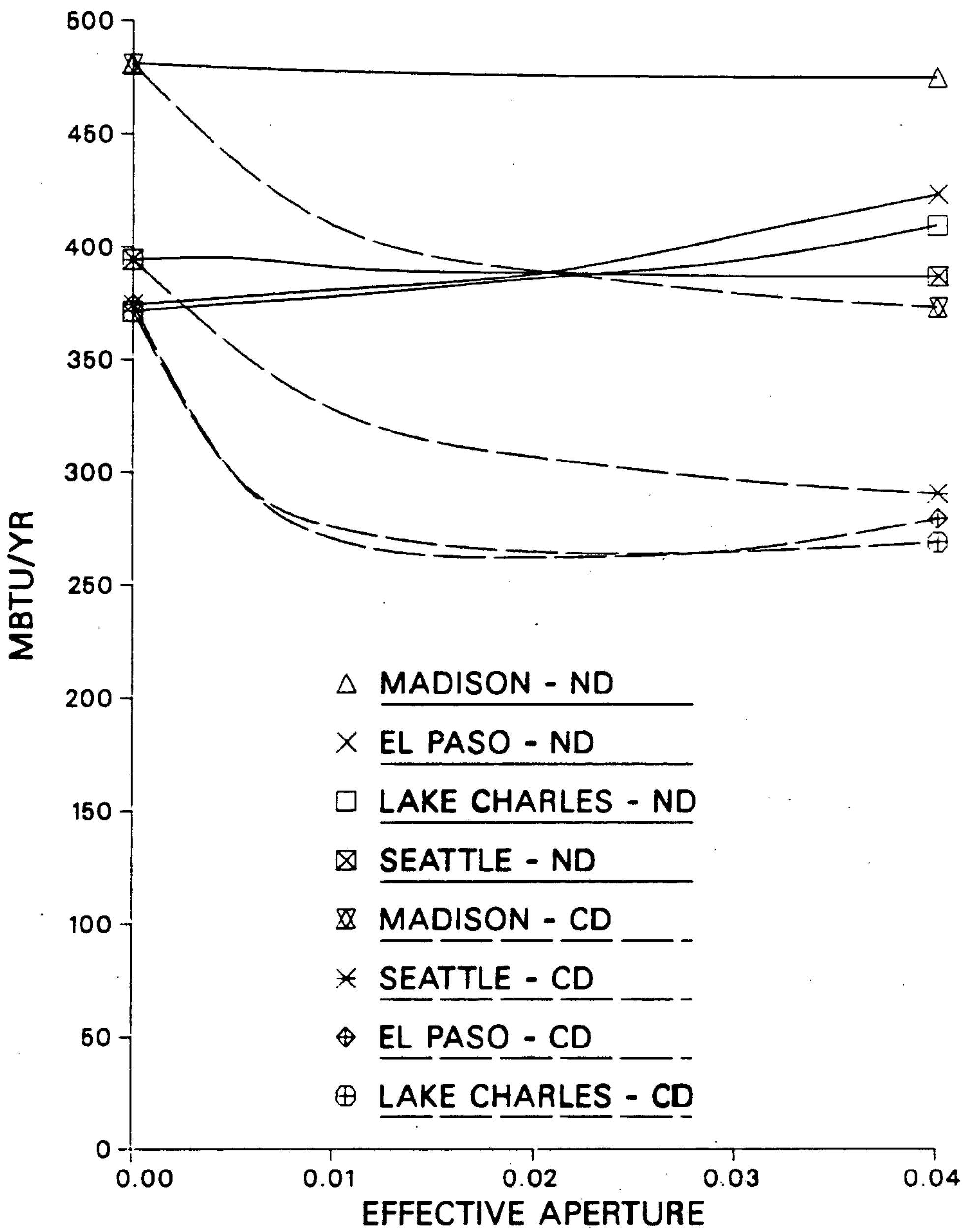

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Figure 2: Total annual skylight module plant energy as a function of effective aperture; no daylighting (ND) and continuous dimming (CD) controls for an illumination level of 50 fc, K_e = 1.0, a lighting power density of 1.7 W/ft^2, and ASHRAE Standard 90 A-1980 roof U-values.

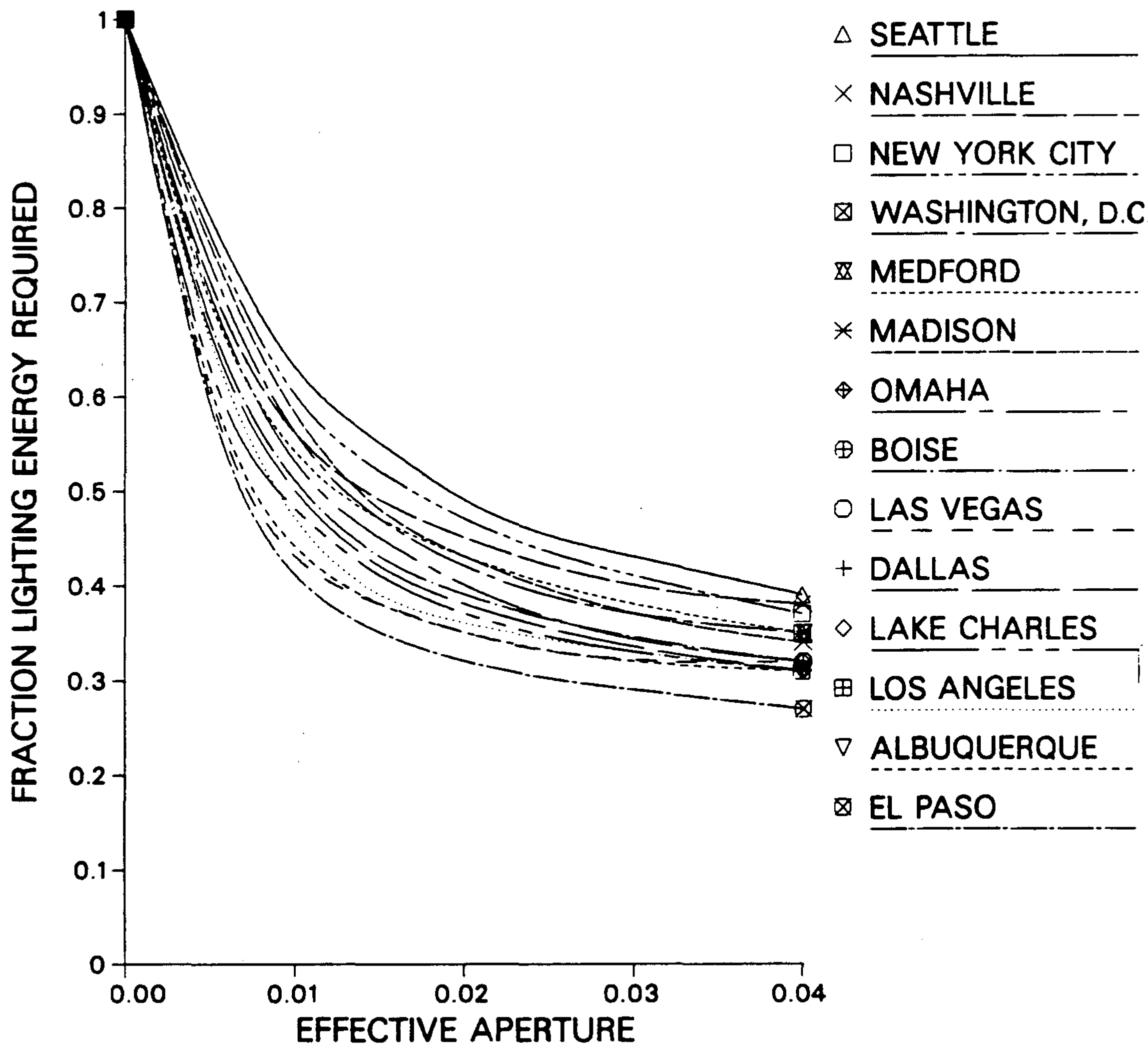

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Figure 3: Annual skylight lighting requirements with continuous dimming controls as a fraction of annual lighting requirements without daylighting for effective apertures from 0 to 0.04 at an illumination level of 50 fc.

PERCENT LIGHTING ENERGY REDUCTION BY DAYLIGHT: EFFECTIVE APERTURE = 0.01

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	5	24	50	77	84	84	83	65	37	14	0	0	0	0	0	0	0	44
FEB	0	0	0	0	0	0	0	10	34	67	87	89	89	87	82	54	24	4	0	0	0	0	0	0	52
MAR	0	0	0	0	0	0	3	21	56	86	88	88	87	87	84	72	37	11	0	0	0	0	0	0	59
APR	0	0	0	0	0	0	14	46	85	88	90	89	90	90	89	86	52	18	1	0	0	0	0	0	67
MAY	0	0	0	0	0	3	25	66	89	89	90	90	90	90	89	89	67	26	4	0	0	0	0	0	71
JUN	0	0	0	0	0	4	24	62	87	87	87	88	89	90	89	89	73	29	7	0	0	0	0	0	70
JUL	0	0	0	0	0	2	24	65	87	88	87	90	89	89	86	84	82	37	7	0	0	0	0	0	71
AUG	0	0	0	0	0	0	16	49	86	89	89	88	88	87	83	80	55	21	2	0	0	0	0	0	66
SEP	0	0	0	0	0	0	9	35	76	87	88	89	90	90	88	77	40	11	0	0	0	0	0	0	64
OCT	0	0	0	0	0	0	4	26	58	85	88	89	89	88	84	48	18	1	0	0	0	0	0	0	56
NOV	0	0	0	0	0	0	0	15	40	69	87	90	90	83	58	30	9	0	0	0	0	0	0	0	47
DEC	0	0	0	0	0	0	0	6	28	54	77	80	82	77	53	29	7	0	0	0	0	0	0	0	41
ANNUAL	0	0	0	0	0	1	13	42	63	78	86	88	88	87	79	62	35	11	2	0	0	0	0	0	59

PERCENT LIGHTING REDUCTION BY DAYLIGHT: EFFECTIVE APERTURE = 0.02

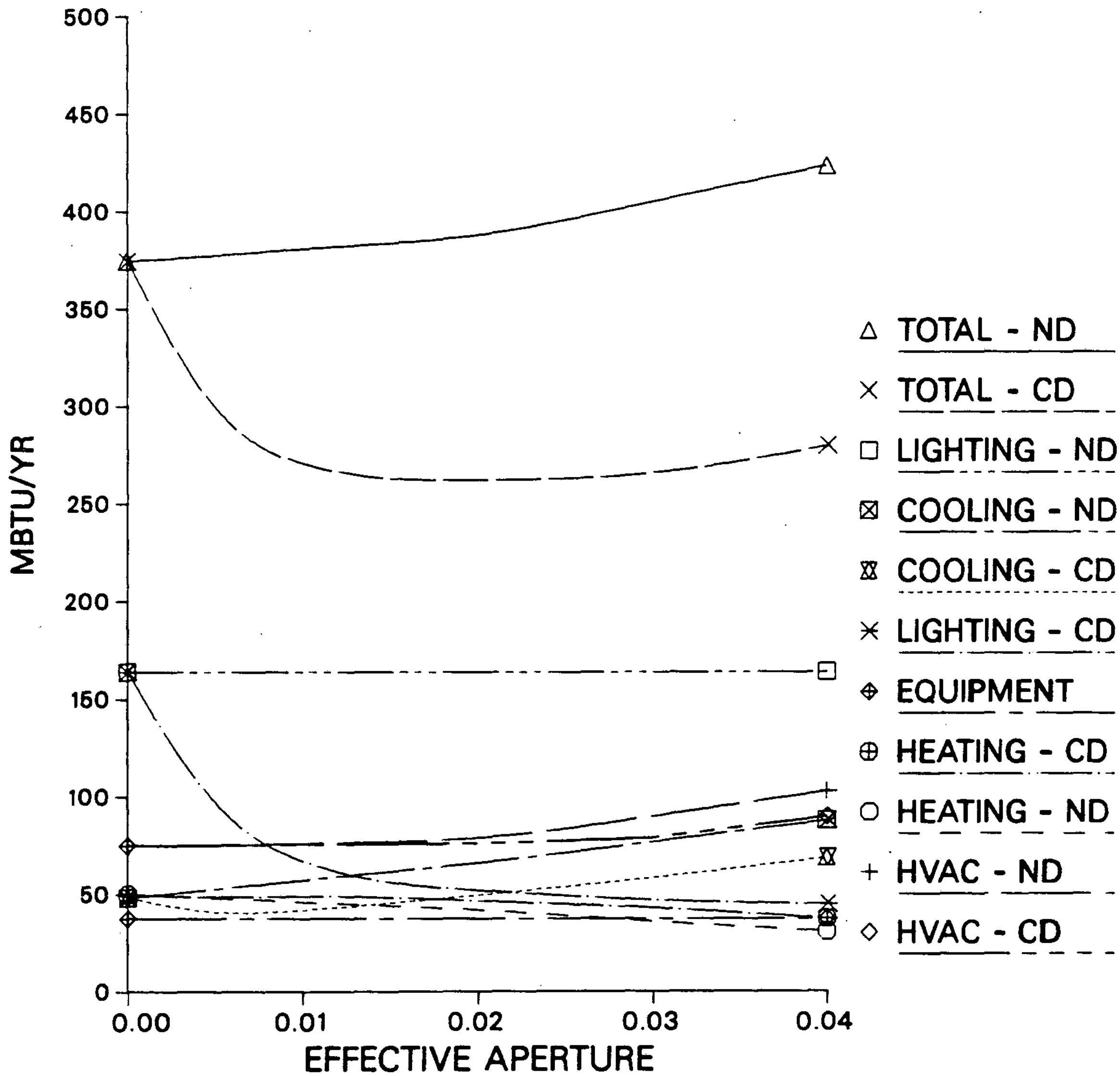
MONTH	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	17	18	19	20	21	22	23	24	ALL HOURS
JAN	0	0	0	0	0	0	0	10	44	84	88	88	88	89	88	74	28	1	0	0	0	0	0	0	57
FEB	0	0	0	0	0	0	0	21	67	90	90	90	90	90	90	88	47	0	0	0	0	0	0	0	64
MAR	0	0	0	0	0	0	6	41	85	90	90	90	89	87	88	89	73	21	0	0	0	0	0	0	68
APR	0	0	0	0	0	1	27	63	88	90	90	90	90	90	90	90	87	36	2	0	0	0	0	0	73
MAY	0	0	0	0	0	6	49	89	90	90	90	90	90	90	90	90	86	52	7	0	0	0	0	0	75
JUN	0	0	0	0	0	9	48	90	90	90	90	90	90	90	90	90	90	58	14	0	0	0	0	0	77
JUL	0	0	0	0	0	5	48	87	90	90	89	90	90	90	90	89	89	73	14	0	0	0	0	0	76
AUG	0	0	0	0	0	1	32	84	90	90	90	90	90	88	88	89	88	43	5	0	0	0	0	0	74
SEP	0	0	0	0	0	0	19	69	87	90	90	90	90	90	90	87	75	22	0	0	0	0	0	0	71
OCT	0	0	0	0	0	0	8	51	86	88	90	90	90	90	90	86	36	2	0	0	0	0	0	0	66
NOV	0	0	0	0	0	0	1	29	80	90	90	90	90	90	90	61	17	0	0	0	0	0	0	0	60
DEC	0	0	0	0	0	0	0	12	56	83	84	84	85	86	85	57	14	0	0	0	0	0	0	0	54
ANNUAL	0	0	0	0	0	2	26	68	80	89	89	89	89	89	89	83	56	23	4	0	0	0	0	0	68

PERCENT LIGHTING ENERGY REDUCTION BY DAYLIGHT: EFFECTIVE APERTURE = 0.04

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	21	83	89	90	90	90	90	90	88	55	2	0	0	0	0	0	0	65
FEB	0	0	0	0	0	0	0	42	90	90	90	90	90	90	90	90	86	15	0	0	0	0	0	0	70
MAR	0	0	0	0	0	0	12	75	89	90	90	90	90	89	89	90	89	42	0	0	0	0	0	0	73
APR	0	0	0	0	0	1	55	89	90	90	90	90	90	90	90	90	90	72	3	0	0	0	0	0	76
MAY	0	0	0	0	0	12	89	90	90	90	90	90	90	90	90	90	87	87	15	0	0	0	0	0	78
JUN	0	0	0	0	0	17	85	90	90	90	90	90	90	90	90	90	90	87	29	0	0	0	0	0	79
JUL	0	0	0	0	0	10	84	88	90	90	90	90	90	90	90	90	90	89	29	0	0	0	0	0	79
AUG	0	0	0	0	0	2	63	90	90	90	90	90	90	90	90	90	89	74	10	0	0	0	0	0	77
SEP	0	0	0	0	0	0	37	55	90	90	90	90	90	90	90	89	89	43	0	0	0	0	0	0	75
OCT	0	0	0	0	0	0	16	85	88	90	90	90	90	90	90	90	70	3	0	0	0	0	0	0	71
NOV	0	0	0	0	0	0	1	59	90	90	90	90	90	90	90	89	34	0	0	0	0	0	0	0	65
DEC	0	0	0	0	0	0	0	25	83	86	86	87	86	87	88	88	28	0	0	0	0	0	0	0	62
ANNUAL	0	0	0	0	0	5	49	79	89	89	90	90	90	90	90	89	72	30	7	0	0	0	0	0	73

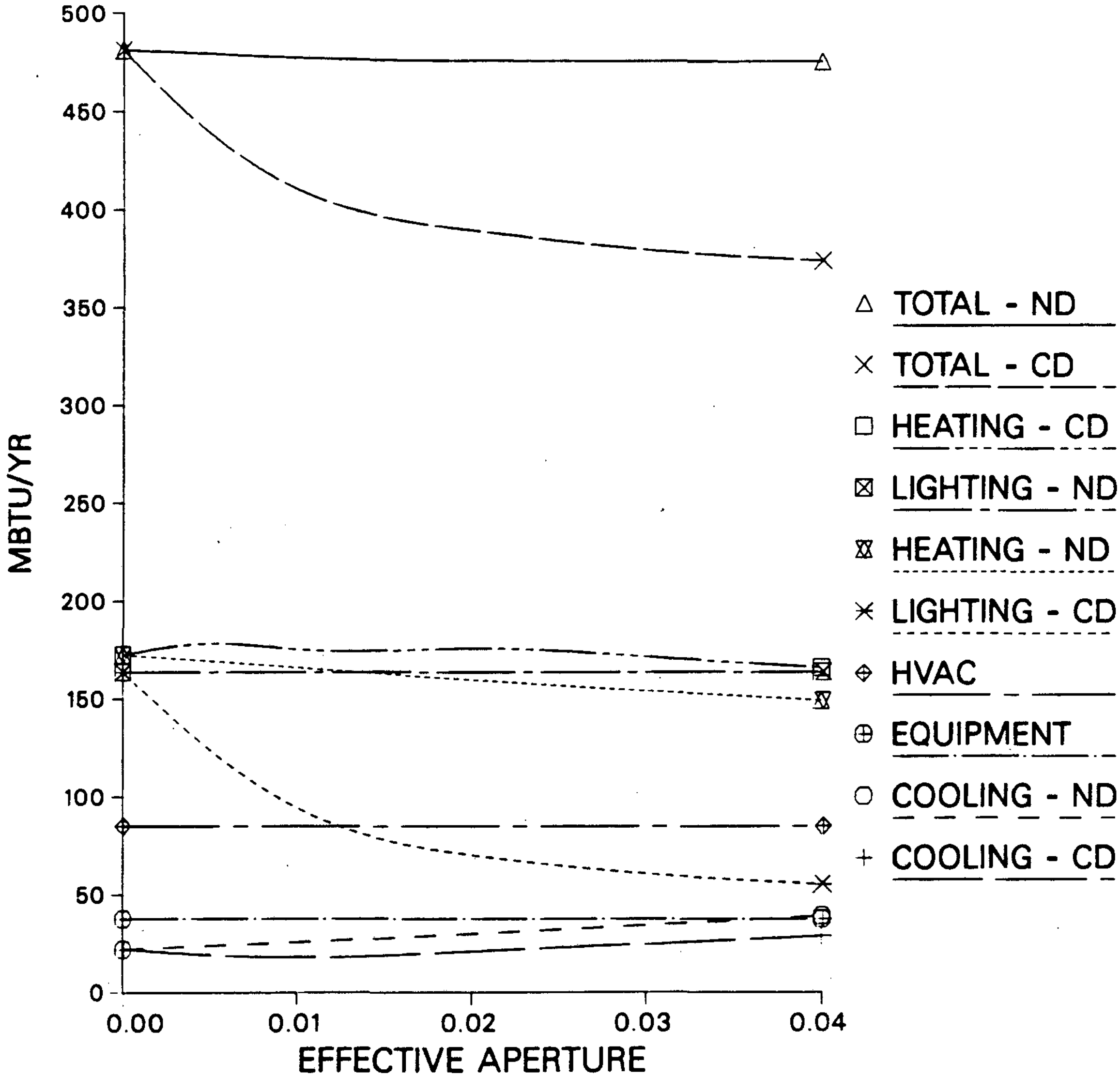
XBL 846-2438

Figure 4: Monthly average percent lighting savings for each hour of the day for effective apertures of 0.01, 0.02, and 0.04 in El Paso, TX.



XBL 8411-4630

Figure 5: Total annual skylight module plant energy and component breakdown as a function of effective aperture in El Paso TX; no daylighting (ND) and continuous dimming (CD) controls for an illumination level of 50 fc, K_e = 1.0, a lighting power density of 1.7 W/ft^2, and a roof U-value of 0.098 $Btu/hr\text{-}ft^2\text{-}F$.



XBL 8411-4631

Figure 6: Total annual skylight module plant energy and component breakdown as a function of effective aperture in Madison WI; no daylighting (ND) and continuous dimming (CD) controls for an illumination level of 50 fc, $K_e = 1.0$, a lighting power density of 1.7 W/ft^2, and a roof U-value of 0.055 Btu/hr-ft^2-F.

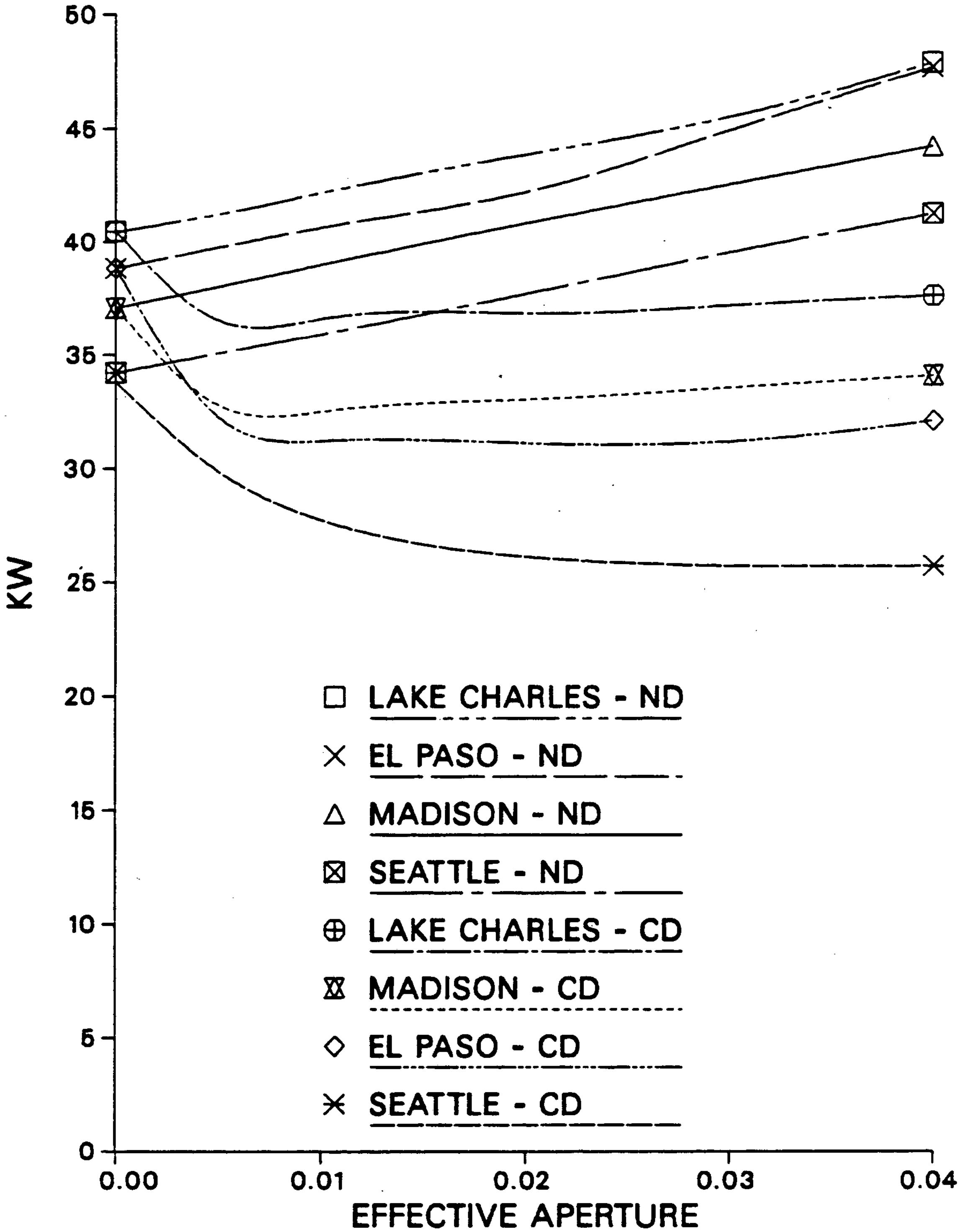


Figure 7: Total annual electrical peak for the skylight module as a function of effective aperture; no daylighting (ND) and continuous dimming (CD) controls for an illumination level of 50 fc, K_e = 1.0, a lighting power density of 1.7 W/ft^2, and ASHRAE Standard 90A-1980 roof U-values.

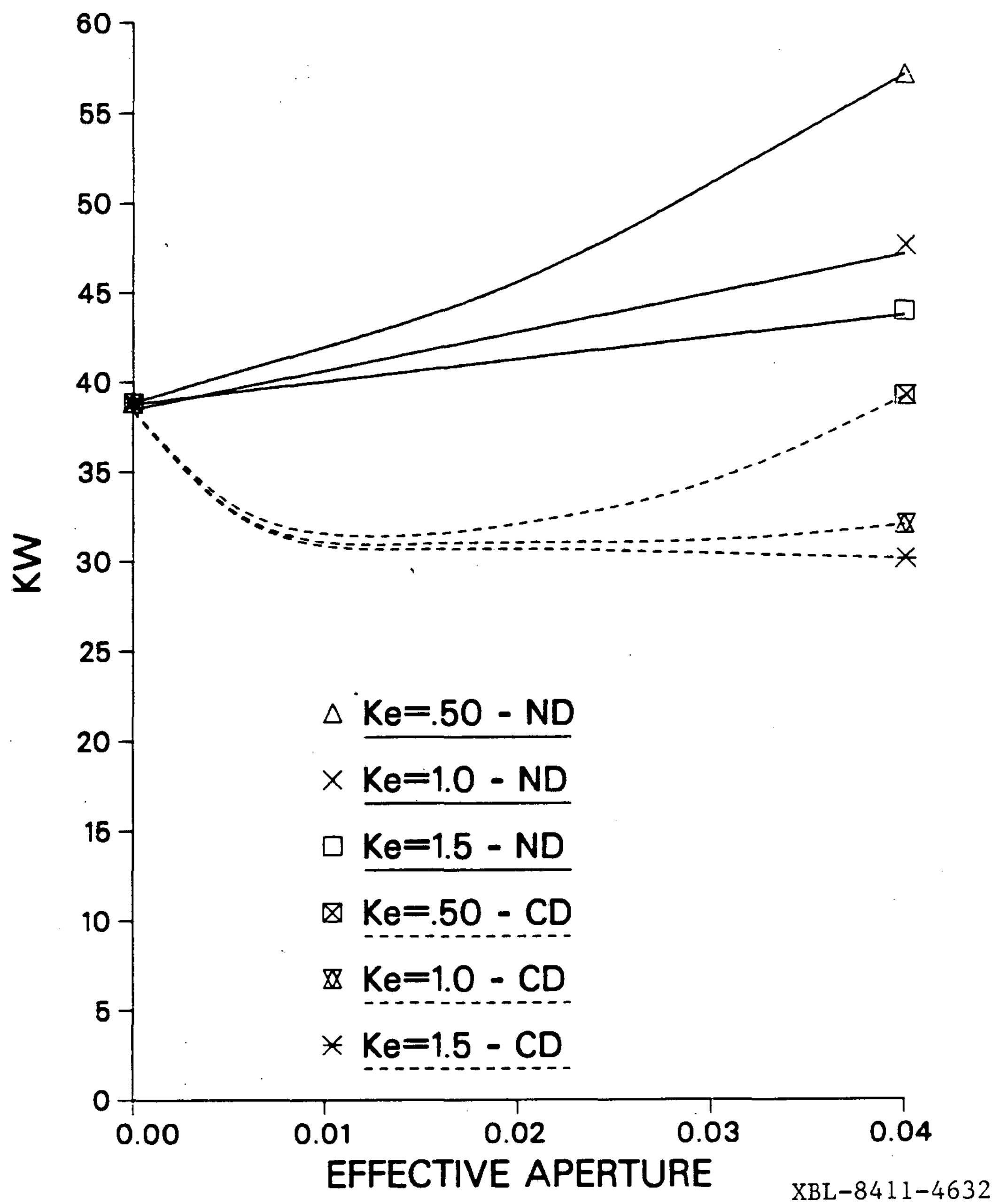


Figure 8: Total annual electrical peak for the skylight module as a function of effective aperture in El Paso TX; no daylighting (ND) and continuous dimming (CD) controls. K_e varies; illumination level of 50 fc, lighting power density of 1.7 W/ft^2, and roof U-value of 0.098 Btu/hr-ft^2-F remain constant.

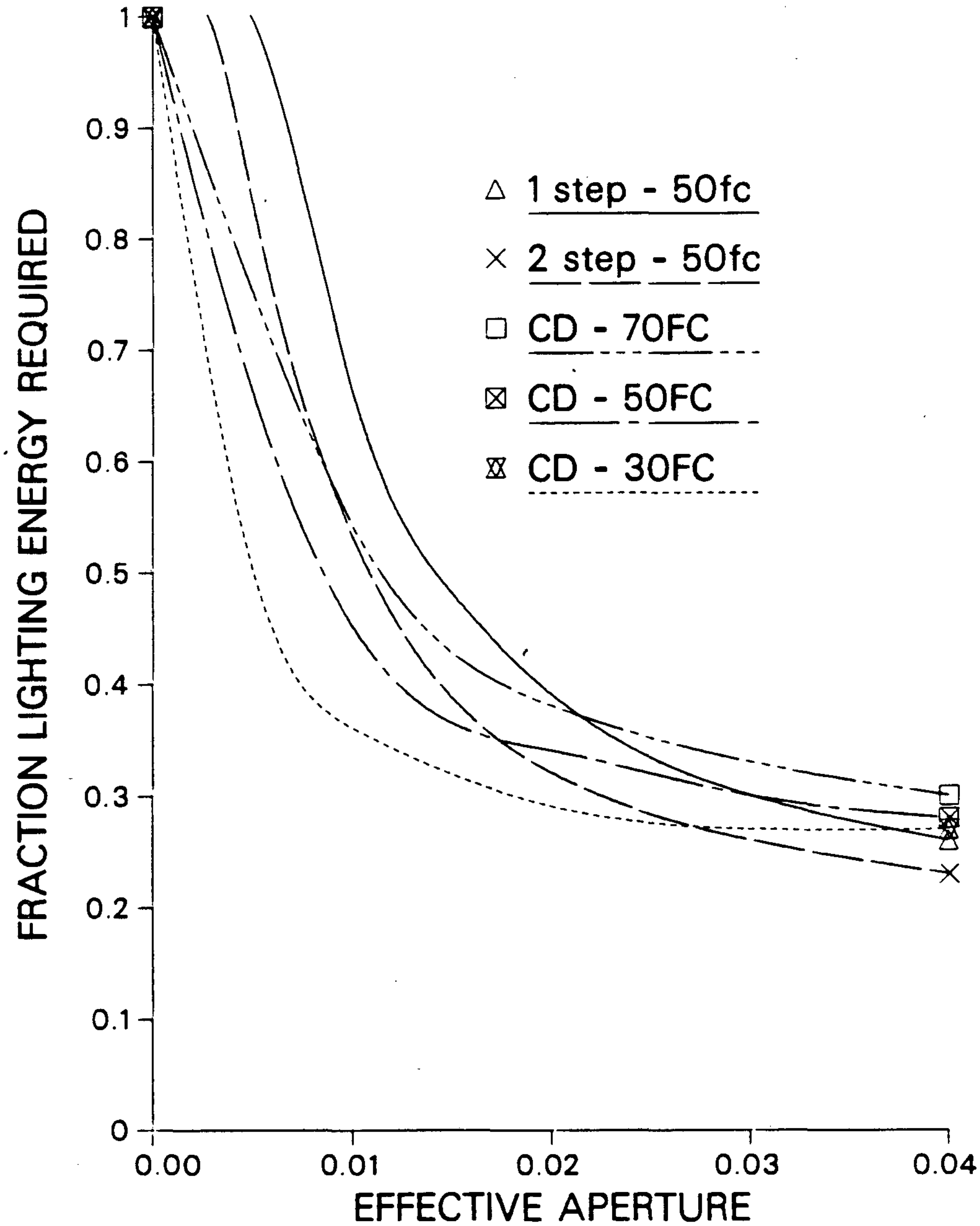


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Figure 9: Annual skylight lighting requirements with continuous dimming controls as a fraction of annual lighting requirements without daylighting for effective apertures between 0 and 0.04 in Los Angeles CA. This shows stepped (step) and contінous dimming (CD) dimming control systems at illumination levels of 30, 50, and 70 fc.

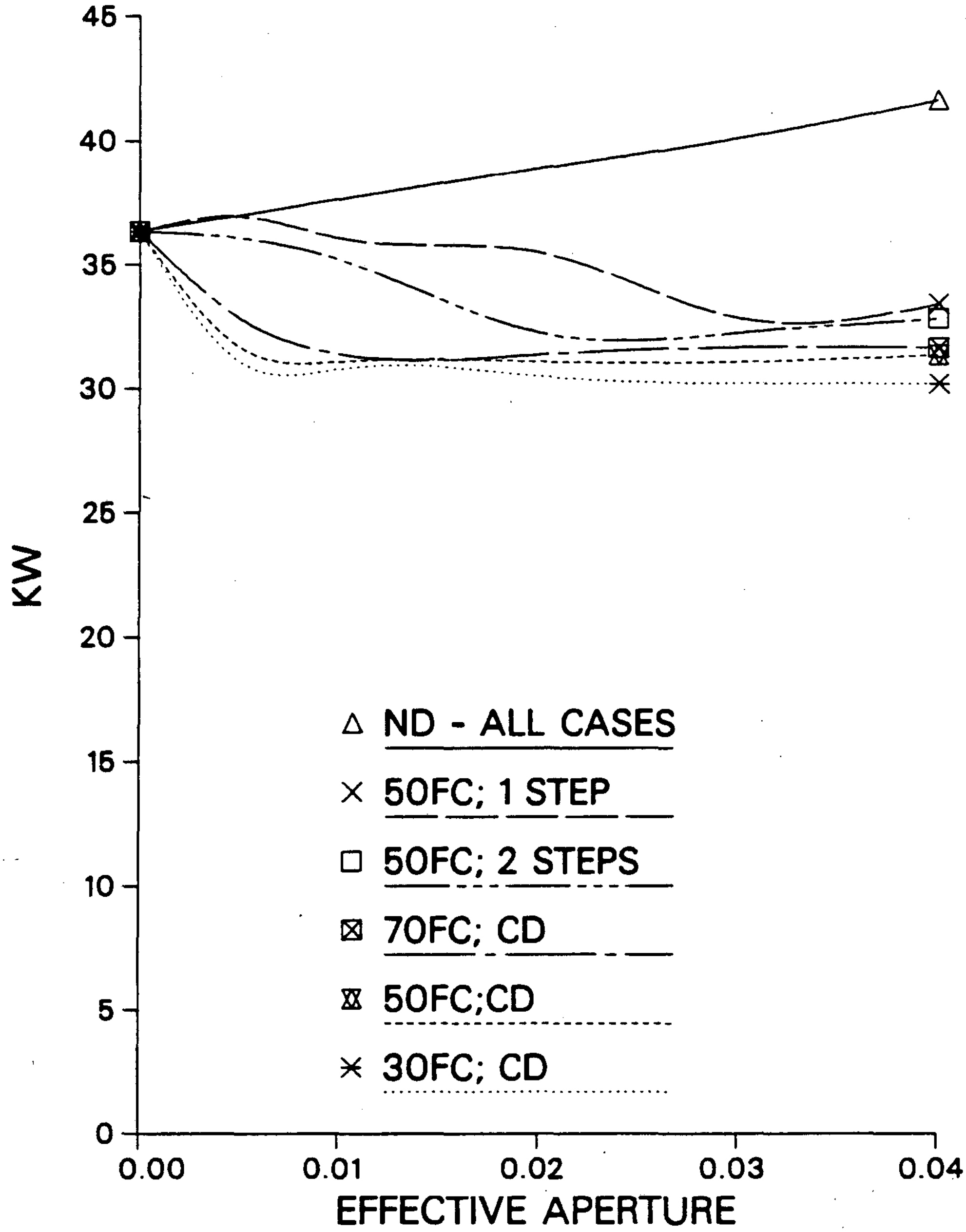

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Figure 10: Total annual electrical peak for skylight module as a function of effective apertures in Los Angeles CA. Stepped (step) and continous dimming (CD) dimming control systems at illumination levels of 30, 50, and 70 fc are compared to the case of no daylighting. K_e = 1.0, lighting power density is 1.7 W/ft^2, and roof U-value is 0.090 Btu/hr-ft^2-F.

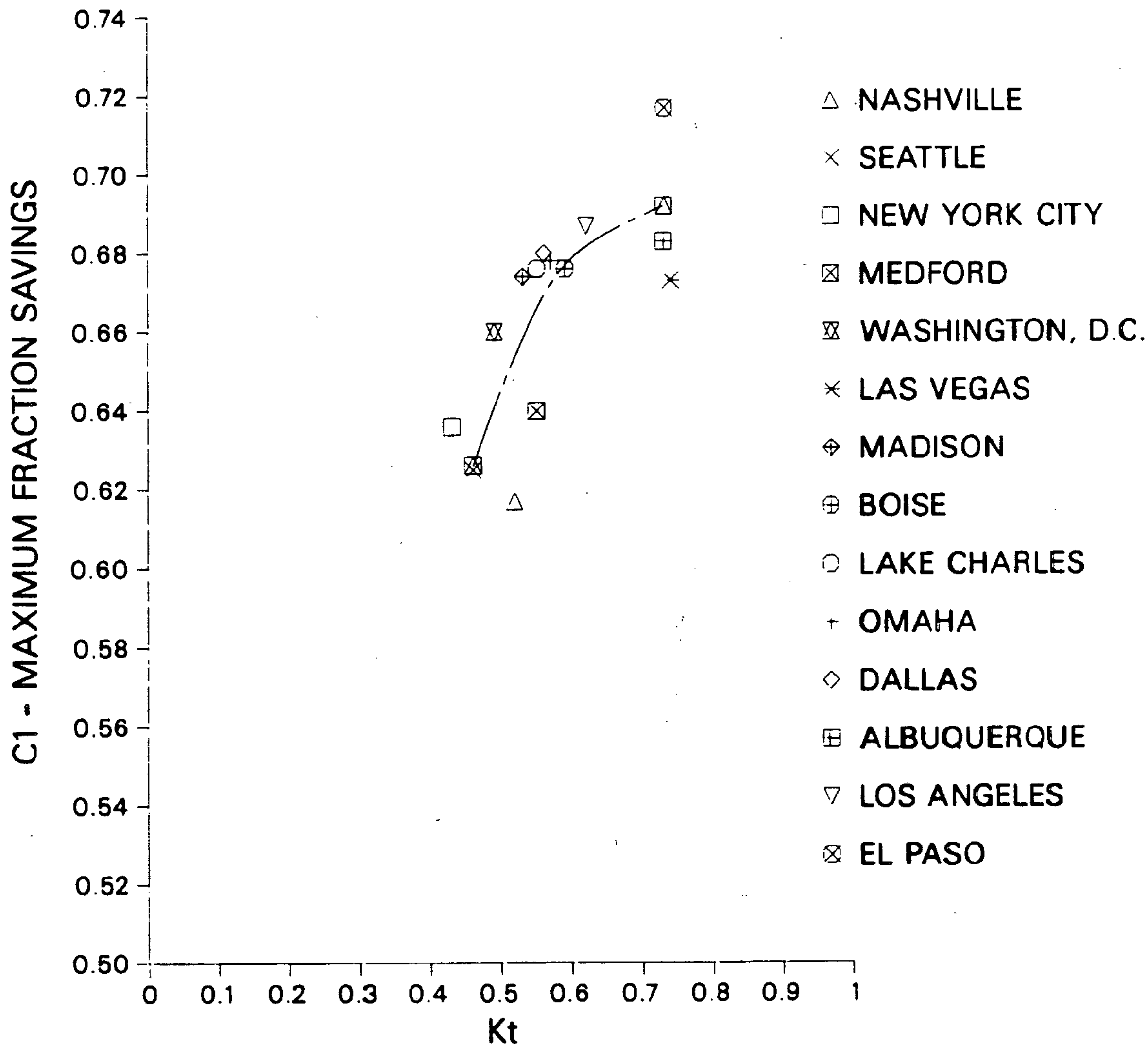

Figure 11: C_1, the maximum fractional lighting savings with daylighting (from the expression for K_d) as a function of K_t, the ratio of monthly average daily total radiation to extraterrestrial daily insolation. The best fit through these 14 points is given by $C_1 = 0.145 + 1.55 (K_t) - 1.10 (K_t)^2$ ($r^2 = 0.61$).

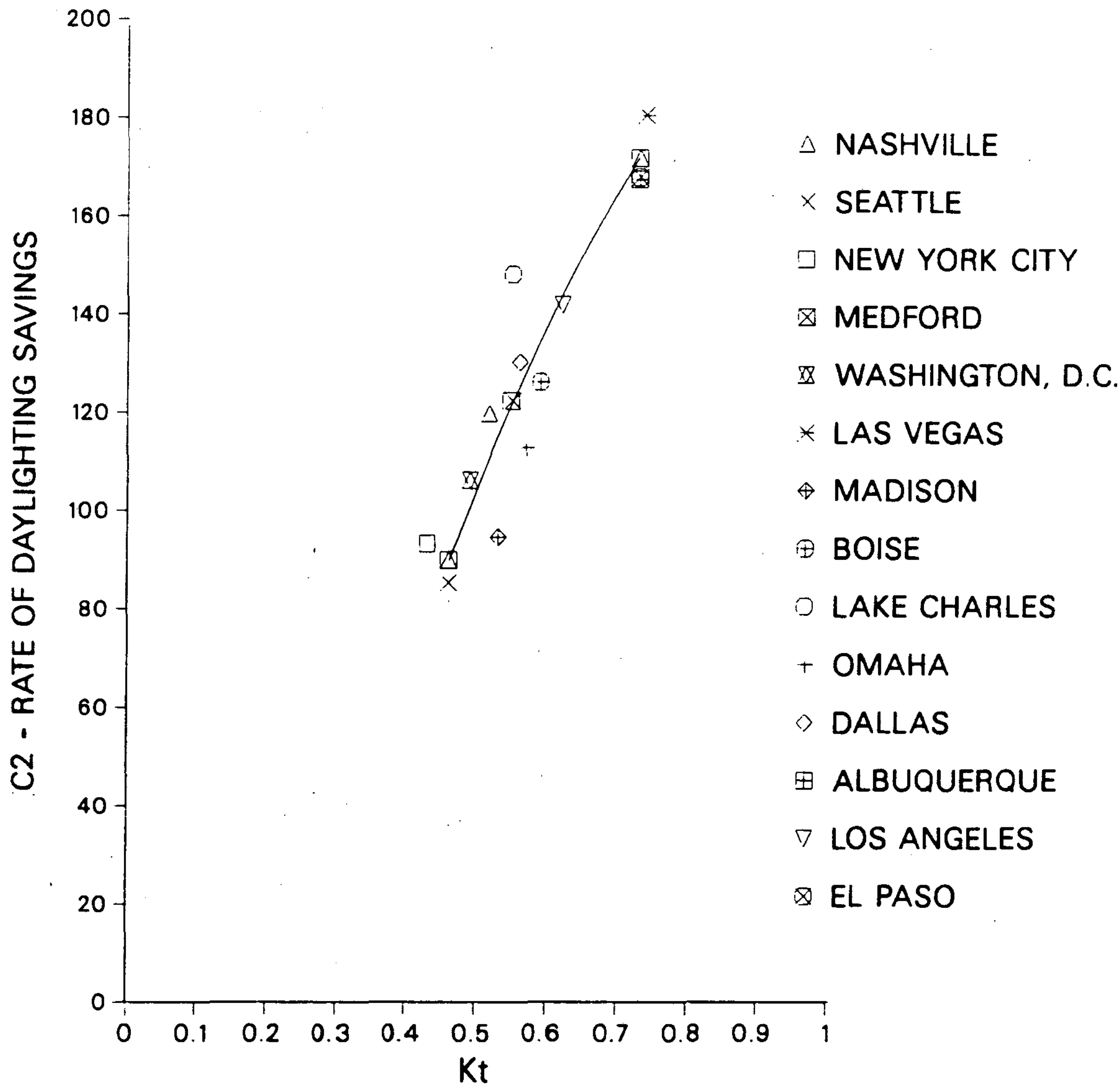

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Figure 12: C_2, the rate of daylighting savings (from the expression for K_d) as a function of K_t, the ratio of monthly average daily total radiation to extraterrestrial daily insolation. The best fit through these 14 points is given by $C_2 = -139.1 + 619.9(K_t) - 265.3\ (K_t)^2\ (r^2 = 0.84)$.

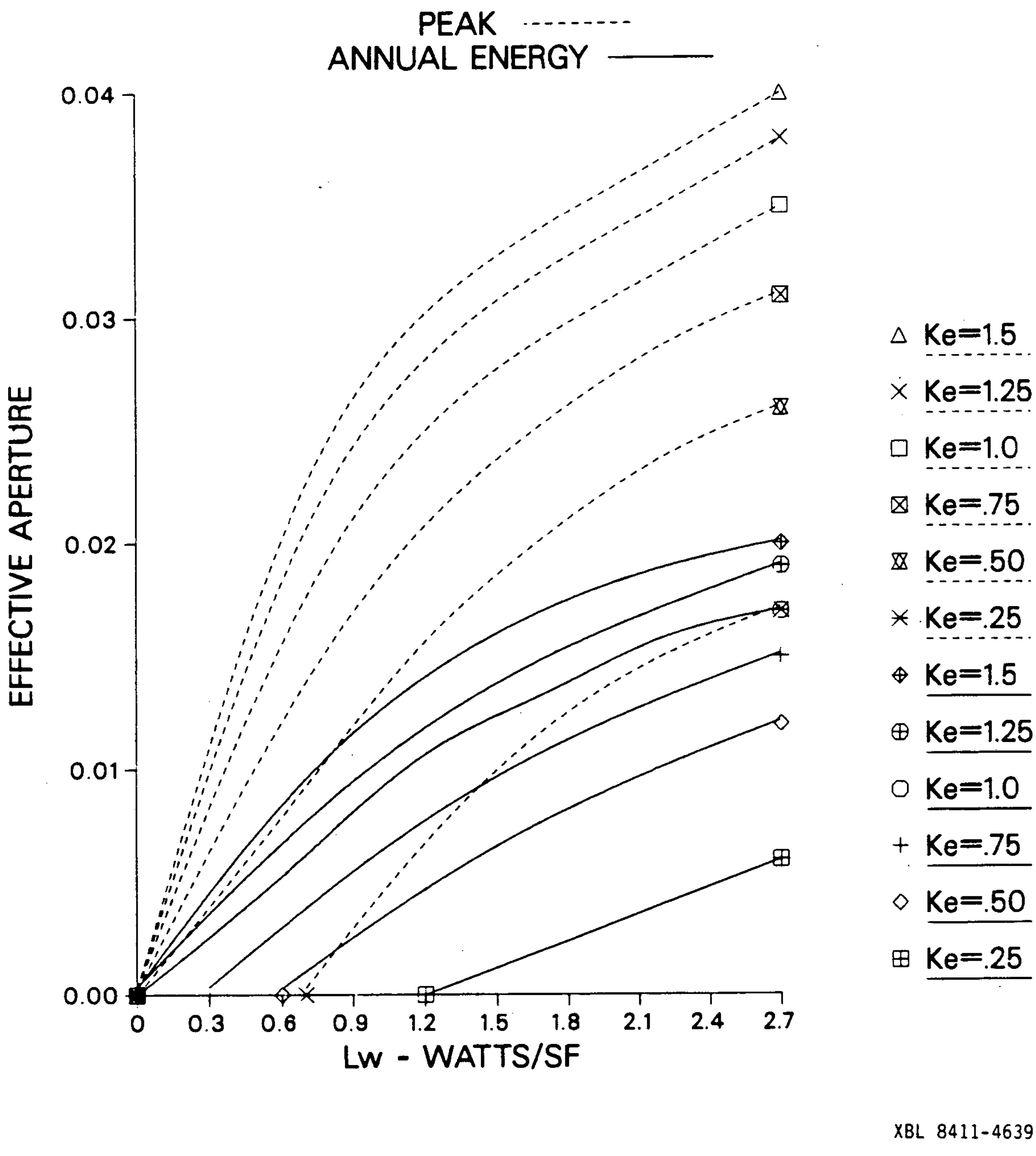

Figure 13: Effective apertures resulting in minimum annual peak and annual total energy consumption as a function of installed lighting power density (L_w) and K_e, in El Paso, TX.

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