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Lawrence Berkeley Laboratory
UNIVERSITY OF CALIFORNIA

APPLIED SCIENCE DIVISION

THE EFFECTS OF SKYLIGHT PARAMETERS ON DAYLIGHTING ENERGY SAVINGS

D. Arasteh, R. Johnson, and S. Selkowitz

May 1985

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APPLIED SCIENCE DIVISION

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ABSTRACT

Skylight parameters that affect lighting, cooling, heating, fan, and total energy use in office buildings are examined using the state-of-the-art building energy analysis computer code, DOE-2.1B. The lighting effects of skylight spatial distribution, skylight area, skylight visible transmission, well factor, illumination setpoint, interior partitions, ceiling height, and glazing characteristics are discussed. This study serves as the foundation for the creation of a DOE-2.1B data base and design tools for estimating daylighting energy savings from skylights.

INTRODUCTION

Lighting accounts for approximately 40% of all electricity used in commercial buildings in the United States [1]. This energy use is particularly wasteful when one considers that only a portion of the lighting energy consumed produces visible light. Much of the energy becomes unwanted heat, helping to account for another 30% of the electricity used in commercial buildings-- that used for cooling [1]. Glazing in commercial buildings is often perceived as energy extravagant compared to opaque walls. Large solar gains through glazing systems can impose significant cooling loads. With solar control and daylighting to offset electrical lighting, correctly sized glazing systems can become an energy asset instead of a liability.

Lighting energy savings through the use of skylights could be significant in many low-rise buildings such as small office buildings, industrial buildings, and warehouses. Such buildings often have large floor areas remote from exterior walls, making daylighting through windows difficult or impossible. Skylights have other advantages: partitions can readily be designed for daylighting with skylights, and daylight distribution can be more uniform than with vertical fenestration.

This sensitivity study, undertaken to determine which skylight parameters most significantly affect energy use, was preparatory to an extensive parametric study of skylight performance in many climates. This work helped define details for the parametric study, including parametric limits and building design. In the later study [2], variables having little influence on fenestration performance are held constant at values considered to represent real or average conditions. Variables having strong influences on fenestration performance are then varied parametrically. The resulting data base will help formulate simple design tools to evaluate any energy cost impacts of skylights and daylighting. Such design tools, the topic of much current research, are discussed in Refs. [2], [3], and [4]. Climates analyzed in this sensitivity study include Lake Charles, LA; Madison, WI; and Los Angeles, CA. These climates define a broad range of thermal conditions, yet their annual daylighting performance is generally similar. To date more than 15 climates have been analyzed in the second study.

DOE-2.1B, an hourly building energy simulation model, is the analytical tool used for this project. DOE-2's daylighting algorithms calculate hourly, monthly, and annual impacts of daylighting strategies on electricity consumption, cooling requirements, fan power, heating needs, and total energy use. Monthly and yearly electricity, heating, and cooling peaks are also identified. References [5] and [6] contain a description of and documentation on the DOE-2 daylighting calculation procedure. Results from DOE-2.1B have been compared against measurements from scale models tested in LBL's sky simulator. Results from the sky simulator and analytical models agreed quite well [5].

BUILDING DESCRIPTION

In stipulating a building for this simulation study, we chose a modular configuration in which we could isolate the thermal and daylighting effects of skylights. This module is a single story 100' by 100', which can be treated as either a single-story building or the top floor of a multistory building. There are no windows in the exterior envelope walls, and both the floor and exterior walls are modeled as adiabatic surfaces (no net heat transfer). In multistory buildings the effects of floor heat transfer are usually minimal. Envelope energy effects are thus confined to the roof, and results can be expressed on a square-foot basis. For a given climate, the flat roof's overall heat transfer coefficient (U-value) is fixed at three typical values: the value prescribed by ASHRAE Standard 90 [7], a value 1.5 times that value, and a value 0.75 times the Standard-90 value. Internal gains from people and equipment, ventilation, and infiltration are also studied because they influence building energy requirements. Daylighting and solar gain effects of the skylights are the predominant envelope energy factors. Our sensitivity analysis focuses on skylight parameters. Table 1 lists other building module details.

VARIABLE PARAMETERS

In this section we discuss the relative significance of fenestration and related building parameters and their influence on daylighting energy savings and total energy performance. The glazing and lighting issues we examined include:

- glazing area,
- glazing type (diffuse or transparent),
- glazing visible transmittance,
- skylight location and well geometry,
- lighting control strategy in response to changing daylight levels,
- illumination level,
- location of reference points that control the lighting control system,
- partitioning within the space,

- space equipment loads, and
- roof reflectance.

Other non-fenestration issues, including mass effects, plenum effects, and internal load variations, were studied for a similar module with vertical fenestration and found to have minimal effects [3].

Issue: Effective Aperture

Description: Three parameters govern the amount of light entering a skylighted space: the glazing area (which we express as the skylight-to-roof ratio - SRR); the glazing visible transmittance (VT); and the skylight well factor, WF ($0<WF<1$). The well factor is the ratio of the amount of light entering the space through the skylight well to the total transmitted by the skylight. Well factors for simple skylights can be determined according to IES procedures [8] and are a function of the skylight aperture dimensions (length and width), well depth, and reflectivity of the well's surfaces. DOE-2 does not directly calculate optical losses in the light well, so we utilize the IES concept of well factor as a multiplier to the visible transmittance. The net visible transmittance of the skylight system is then VT * WF. Note that standard IES procedures for estimating visible transmittance can represent average maintained transmittance and thus can account for dirt loss factors.

Results: These factors can be combined into one lumped parameter, SRR x VT x WF, which we call the effective aperture (A_e). An analysis of different configurations, each with different SRR and VT x WF but the same effective aperture, demonstrates that this simplification facilitates interpolation of results without loss of accuracy. We examined A_e's between 0 and 0.04. At the upper limit, an A_e of 0.04 can correspond to any skylight configurations from an SRR of 5% with no light well losses and a VT of 0.80 to an SRR of 10% with light well losses on the order of 30% (i.e., WF = 0.70) and a VT of 0.57. However, skylighted roofs rarely exceed an SRR of 10%; therefore an A_e of 0.04 is high enough to cover most applications. Figures 1 and 2 show annual average illuminance levels over hours for which the sun is shining and show annual percent lighting savings for A_e's between 0 and 0.04 based on two skylight areas, SRR's of 0.05 and 0.10. The results, which are virtually identical, are based on the use of diffusing skylights. The use of clear or semitransparent skylights without a diffusing light slightly alters results. Thus, for realistic SRR's, energy quantities can be evaluated as a function of effective aperture with no loss of accuracy. Other parameters, however, such as glare, may not be identical for the same A_e. Figure 3 illustrates this point; for the same A_e, a higher SRR will result in a lower net visible transmittance (VT x WF) and thus less glare. DOE-2's glare calculation procedure is detailed in Refs. [6] and [9].

Issue: Lighting Control Reference Point

Description: Daylighting levels are calculated at the lighting control reference point, which represents a lighting sensor that controls the lighting system. We calculate the effects of using a reference point in two different locations (see Fig. 4). The first point (reference point

#1) is at the intersection of the two diagonals connecting four adjacent skylights in a square grid. The second point (reference point #2) is midway between two adjacent skylights. Both reference points are placed at desk height (2.5′) and as far away as possible from side walls.

Results: Figure 5 shows the annual average illuminance for different ceiling heights at the two reference points for Lake Charles, LA. The differences in percentage energy savings (not shown) are less than for illuminance. Reference point #1, farthest from the skylight, is a more conservative choice for design purposes. We therefore use this reference point to estimate daylighting potential in the final parametric study.

Issue: Varying Ceiling Height

Description: We examined the effects of three ceiling heights (8.5′, 10′, and 11.5′) on daylighting savings. The 8.5′ height is the minimum standard for most office design. Higher ceilings improve daylight distribution but may have cost and design tradeoffs. This issue is studied in conjunction with the two lighting control reference points.

Results: With increasing ceiling height, light from the diffusing skylight covers an increasing floor area with a more uniform distribution. The light transmitted by the skylight is distributed over a larger floor area as ceiling height is increased. As one moves the reference point farther from the skylight, the intensity decreases with increasing ceiling height. Because of this, reference points far from the source (reference point #1 in Fig. 4) show increasing daylight levels with increasing ceiling height (see Fig. 5). However, for reference points directly underneath the skylight, the reverse is true: with increasing ceiling height, the daylight intensity near the skylight is diminished. For reference point #2 these trends produce average illuminance levels very close to one another for the three ceiling heights. These trends are also seen in Madison (see Fig. 6). Average annual illuminances for the high and low ceilings are shown along two cross sections through the central area bounded by four skylights. In all climates, however, for cross section A, the differences in lighting levels at the two reference points are not great. Differences in percentage lighting savings are even less significant, allowing us to consider only one ceiling height, 11.5′.

Issue: Diffusing Skylights

Description: A diffusing skylight will distribute daylight more uniformly than a transparent skylight; given equal visible transmittance, the diffusing skylight will provide greater lighting energy savings. In addition, using diffusing glazing or diffusing shades with clear glazing will, whenever direct sun is present, eliminate undesirable glare and contrast from sun penetration. With transparent glazing, a diffusing shade, acting solely as a diffuser (i.e., VT = 1.0) and activated by glare/solar gain, can be added to make interior conditions more comfortable; this shade, when deployed, will also increase energy savings. Diffusing glazing was compared to clear glazing alone and to clear glazing with a shade activated by glare or solar gain.

Results: Figures 7 and 8 show annual average illuminance levels and annual percent lighting savings for both clear and diffusing glass at both reference points for typical conditions in Madison, WI. These two graphs show that the differences in illumination levels and lighting savings is much greater between the two glazing types than between reference points. Diffusing glazing provides significantly higher illumination levels; however, because illumination levels above 50 footcandles (fc) do not add lighting energy savings, the differences in annual lighting savings between clear and diffusing glazings are not as great, especially at large apertures. Using a diffusing shade activated by high glare or incident (or transmitted) solar gain produces savings close to those available from diffusing glazing. For example, at reference point #1, under typical conditions in Madison, and at an A_e of 0.012, clear glazing provides annual lighting energy savings of approximately 32%, diffusing glazing 46%, and a movable shade 42%. Since movable interior shades and associated hardware are not easily available and because of time and computer cost limitations, the final building module is modeled with diffusing glazing, the way most skylights are currently manufactured. The results indicate a large difference between transparent and diffusing skylights; results from the second study will apply only to diffusing skylights.

Issue: Skylight Position

Description: To achieve a balanced distribution of light and also to model a space representative of an actual building, we position square skylights, equally spaced, throughout the roof area. Skylight number and spacing are varied while effective aperture is held constant. In each case, the outer skylights are positioned half the separation distance in from the side walls. To minimize the effects of side walls, we consider the full 100′ by 100′ module without partitions. Industry guidelines [10] [11] suggest that optimum lighting savings from skylights are achieved when the ratio of skylight spacing to room height is between 1.0 and 1.5 for translucent glazing. To test this hypothesis, we modeled three configurations (two outside this range and one inside): 16 skylights on a four-by-four grid (25′ between centers); 36 skylights on a six-by-six grid (16.7′ between centers); and 64 skylights on an eight-by-eight grid (12.5′ between centers). Each space has diffusing skylights and an SRR of 0.05. The visible transmittance of the skylights is 0.36 and the well factor is 0.73, bringing the SRR*VT*WF to 0.013. The ceiling height is kept at 8.5′.

Results: Changing the grid spacing by increasing from 16 to 36 to 64 skylights, but maintaining a constant overall effective aperture, increases annual lighting savings from 32.8% to 42.6% to 47.7% for Madison. This occurs because, even though the total transmitted flux is the same, smaller skylight spacing will produce a more even daylight distribution and thus more lighting energy savings. Because the amount of glazed area is kept constant for this study, building thermal loads are not significantly affected. Our final building model in the parametric study includes skylights at 12.5′ on center, a spacing representative of building practice. For ceiling heights within the scope of this study (8.5′ to 11.5′), this spacing gives a ratio of skylight spacing to ceiling height of between 1.5 and 1.1.

Issue: Lighting Control Strategy

Description: This sensitivity study covers three types of control strategies to reduce electric lighting output in response to changing daylight levels in interior spaces. With lighting power density at 1.7 W/ft^2 and 50 fc of lighting required, electric lights are controlled by continuous dimming, two-level switching, or one-level (on/off) switching. These three are compared to a building having no daylighting controls. When daylighting provides the entire 50 fc, the continuous dimming system consumes 10% (minimum power fraction) of its full power rating. From this point to the maximum, the relationship between power consumed and light produced is linear.

Results: For stepped switching, energy savings increase with the number of steps. Where there is little available daylight, the continuous dimming system responds well, outperforming the stepped system. However, when glazing area increases and daylight levels reach saturation of useful light, the continuous dimming system (because of its minimum power fraction) drops to slightly below the performance levels of a stepped system. Compared to analogous cases with no lighting control systems, the energy performances of the control strategies tend to group closely as effective aperture increases. These trends are shown in Fig. 9. While the final parametric study focuses on the energy performance of buildings that have continuous dimming systems, the comparative effects of stepped systems on energy quantities and demands are also addressed.

Issue: Illumination Levels

Description: Energy savings are calculated for illumination setpoints of 30, 50, and 70 fc. A setpoint of 50 fc is an appropriate average for general office tasks [12]. A 70-fc setpoint might be specified where more demanding visual tasks are performed; 30 fc might be specified where visual tasks are less critical or where ambient lighting is used in conjunction with task lighting.

Results: Energy requirements for these three levels with a continuous dimming lighting control system are compared in Fig. 9. With higher required illumination levels, lighting's fraction of savings drop (yet the total energy savings increases). The differences are largest for small effective apertures; as aperture size increases, lighting level becomes a less critical parameter. The final parametric study simulates a system that holds the illumination level at the control point at 50 fc. Illumination level is a significant factor, but in order to limit the size of the parametric study we restricted our analysis to the 50-fc case.

Issue: Space Partitioning

Description: To determine the effects of ceiling-height partitions on daylighting, we compared three configurations, all in a 100′ by 100′ space:

(1) an eight-by-eight grid of skylights with no partitions,

(2) partitions dividing the space into four 50′ by 50′ spaces, and

(3) partitions dividing the space into 16 spaces 25′ by 25′ each. Note that in all three cases the same eight-by-eight grid of skylights is used at 12.5′ between centers.

Results: For the first case, 47.7% of the building′s annual lighting requirements are met by daylighting; for the second case this value increases to 48.6%, while for the third case savings drop to 45.8%. These differences are minimal, but reveal a subtle tradeoff between wall reflectivity and low daylight factors from distant skylights. Going from the base case to the 50′ by 50′ case produces additional lighting savings because light from the 16 skylights, which would have left the space, is now reflected back to the reference point. This illuminance outweighs that which is lost to the reference point because it cannot "see" distant skylights. Going to smaller subdivisions of the space, however, produces an opposite effect because here the light absorbed by the wall and the light not received from the blocked skylights outweighs that reflected back to the reference point. The differences are minimal; partitions every 50′ are used in the final parametric study.

Issue: Roof Reflectances

Description: Varying roof solar reflectance affects cooling and heating loads.

Results: In the context of this study, the effects of varying roof reflectances for a flat roof with flat skylights is insignificant over the range of likely values (0.4 to 0.9). The roof reflectivity for the final building module is 0.65.

CONCLUSIONS: FINAL BUILDING MODULE AND SENSITIVITY STUDY

These sensitivity studies lead to several interesting conclusions regarding the effects of skylight parameters on building energy performance, and in particular, on daylighting energy savings. Specific conclusions have already been stated; some general conclusions are now worth mentioning.

Glazing type, area, and other parameters that directly influence the amount of light entering a space (wellfactor, glazing transmissivity) are the most important parameters affecting daylighting energy savings. These parameters can be lumped together into effective aperture in order to simplify skylight daylighting energy analysis without losing accuracy. This simplification is important in the design of simple but accurate design tools.

Average annual illumination levels from daylighting increase linearly with effective aperture. Lighting energy savings at first increase sharply with increasing effective aperture and then level off as daylight saturates the space.

Differences in interior geometry (i.e., partition spacing, ceiling heights, and to a lesser extent, skylight spacing) do not produce significant changes in daylighting energy savings, as long as the spacing is not extreme in either direction. Thus, conclusions on energy performance trends from skylights are valid for a range of geometries that fall within good design practice.

These sensitivity studies helped determine which parameters were important enough to be varied and the appropriate ranges in which to vary them. Parameters found to significantly affect energy savings from daylighting are those related to the amount of solar gain and visible light entering the space (i.e., glass area, shading coefficient, visible transmittance, and well factor); electric lighting power density; and overall heat transfer coefficient. These variables are included in the final parametric analysis [2]. Building details presented in Table 1 were used in the final building module and, unless otherwise specified, were used in this study.

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TABLE 1
Building Module Description

Site Conditions

Site: Flat, unobstructed with no adjacent shading elements.

Floors: Adiabatic surfaces consisting of carpeting over 4" thick, 80 lb/ft^3, concrete slab.

Roof: Flat, no mass; total area - 10,000 ft^2
Exterior reflectance = 0.65

Skylights: Square skylights, glazed aperture area = 500 ft^2
Shading coefficient varied from 0 to 0.8.
Visible transmittance times well factor varied from 0 to 0.8.
U_o = 0.70 $Btu/hr\text{-}ft^2\text{-}F$

Interior Wall Reflectances: Ceiling - 0.7; floor - 0.2
Walls and partitions - 0.5

Electric Lighting: Fluorescent, evenly distributed; setpoint = 50 fc

Building Operation

Occupancy Density:	100 ft^2/person
Occupancy Schedule:	SET Standard Profile No. 1 (modified) [13]
Lighting Schedule:	SET Standard Profile No. 43 [13]
Infiltration Rate:	0.6 air changes/hour at a 10 mph wind speed (corrected for other wind speeds) when fan system is off

HVAC Systems

Type: Single-zone, constant volume, variable temperature with economizer.

Thermostat Schedules:
Heating: Weekday hours 7 to 18: 72°F; 19 to 6: 63°F
Weekends and holidays: all hours 63°F

Cooling: Weekday hours 7 to 18: 78°F; 19 to 6: 90°F
Weekends and holidays: all hours 90°F

Fan Schedule: Weekday hours 7 to 18: on; 19 to 6: off
Weekends and holidays: all hours off

Night-cycle control: Fans cycle on during normally off periods when heating or cooling is required.

Humidity control: None

Economizer limit temperature: 62°F

Outside air requirement: 5 cfm/person

Plant Equipment

Gas-fired Boiler

Electric Centrifugal Chiller

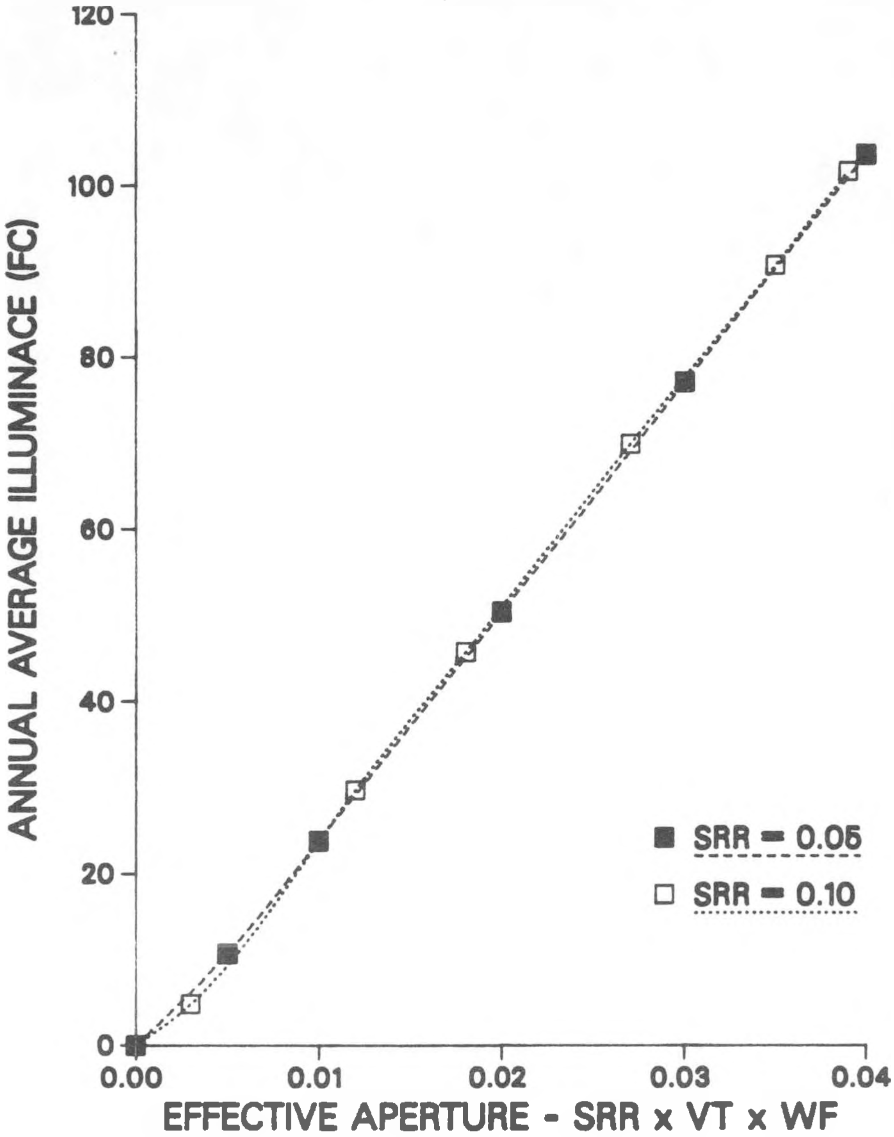

Figure 1: Annual average illuminance (fc) during daylighted hours as a function of effective aperture at reference point #1 (see Fig. 4). Madison, two skylight-to-roof ratios.

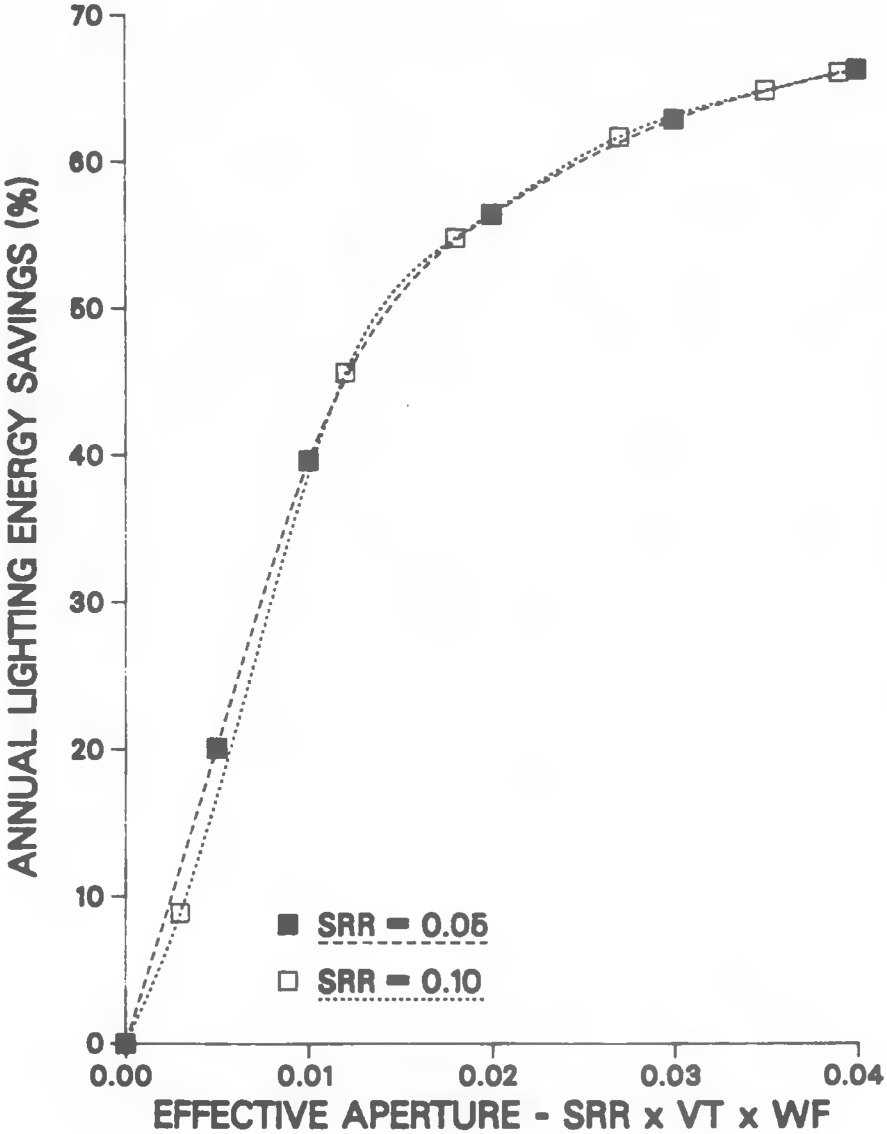

Figure 2: Annual lighting energy savings as a function of effective aperture. Madison, two skylight-to-roof area ratios.

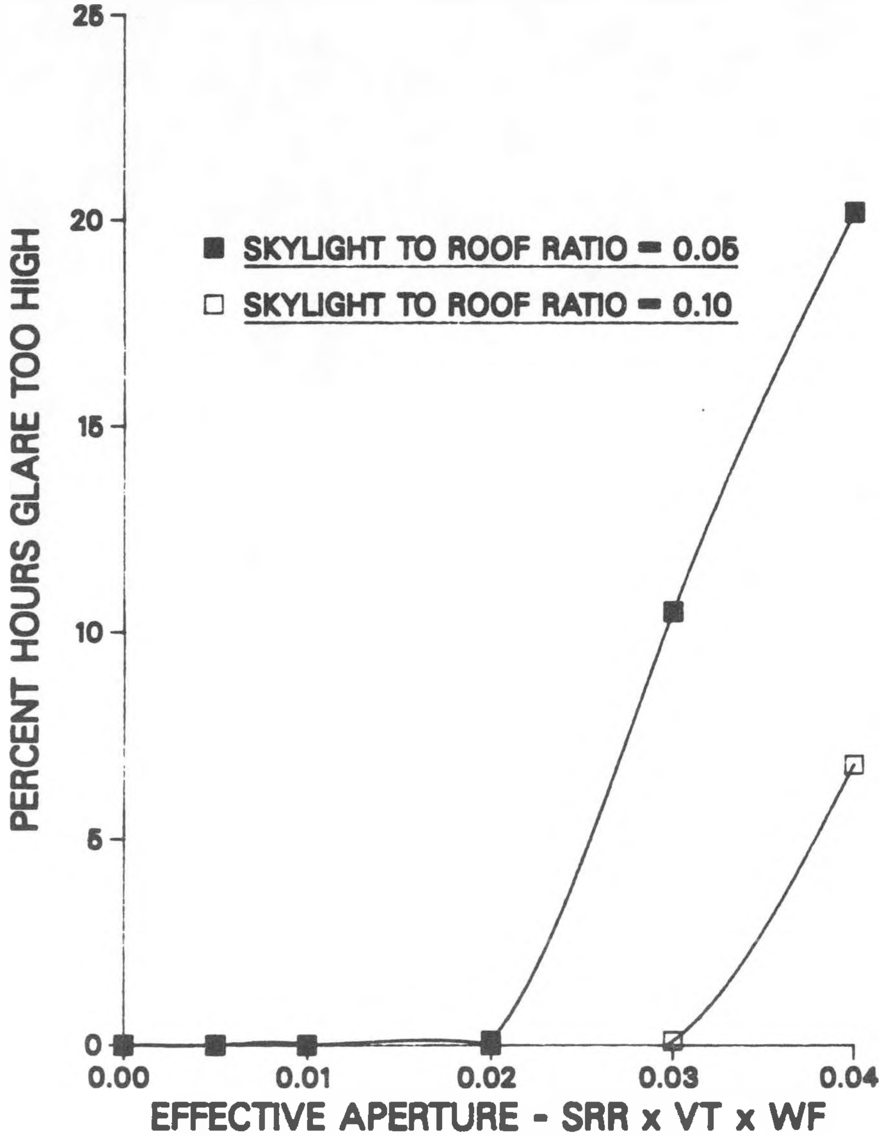

Figure 3: Percent of hours of excessive glare as a function of effective aperture. Madison, two skylight-to-roof area ratios.

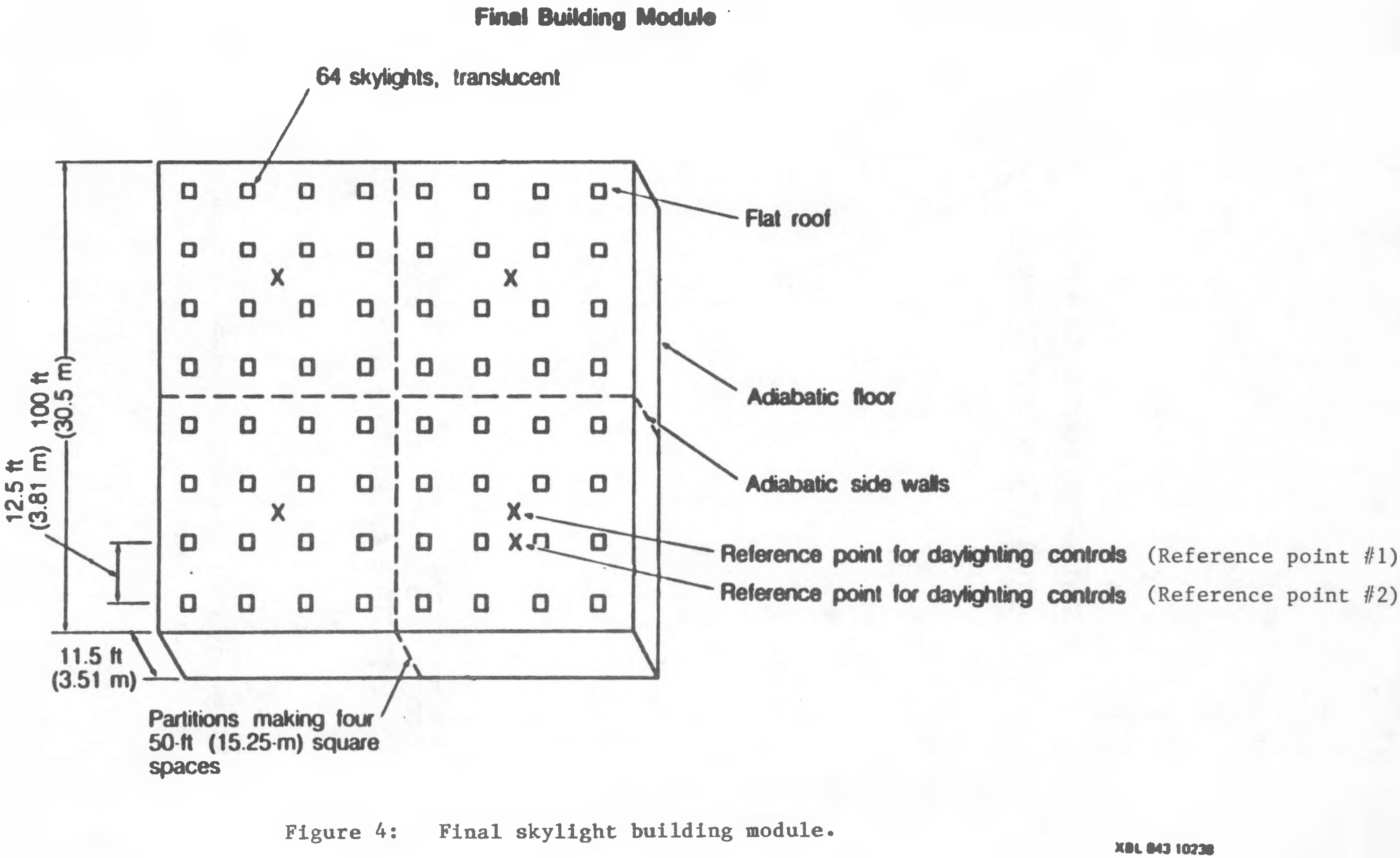

Figure 4: Final skylight building module.

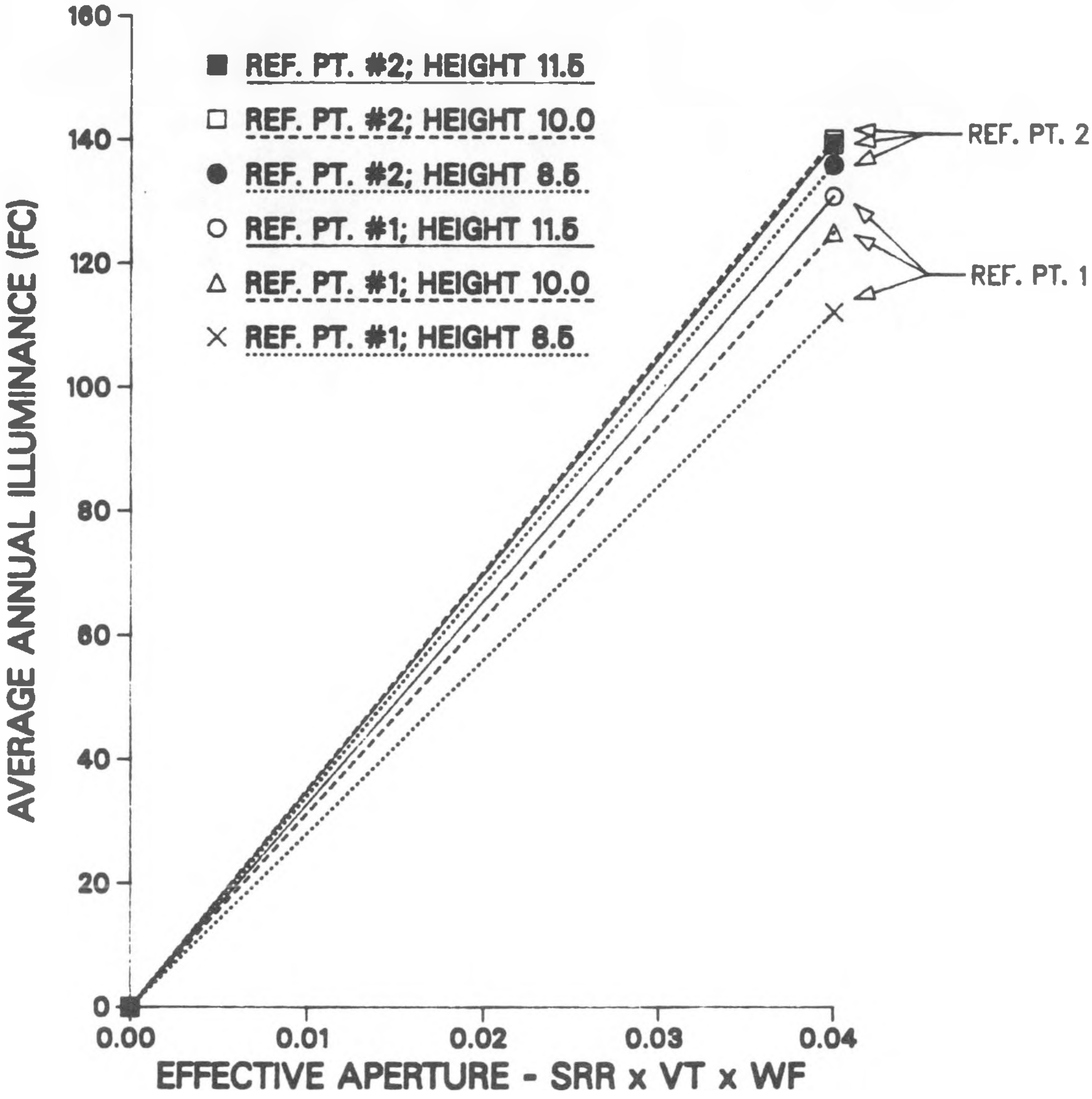

Figure 5: Annual average illuminance during daylighted hours (fc) as a function of effective aperture at reference points #1 and #2. Lake Charles, three ceiling heights.

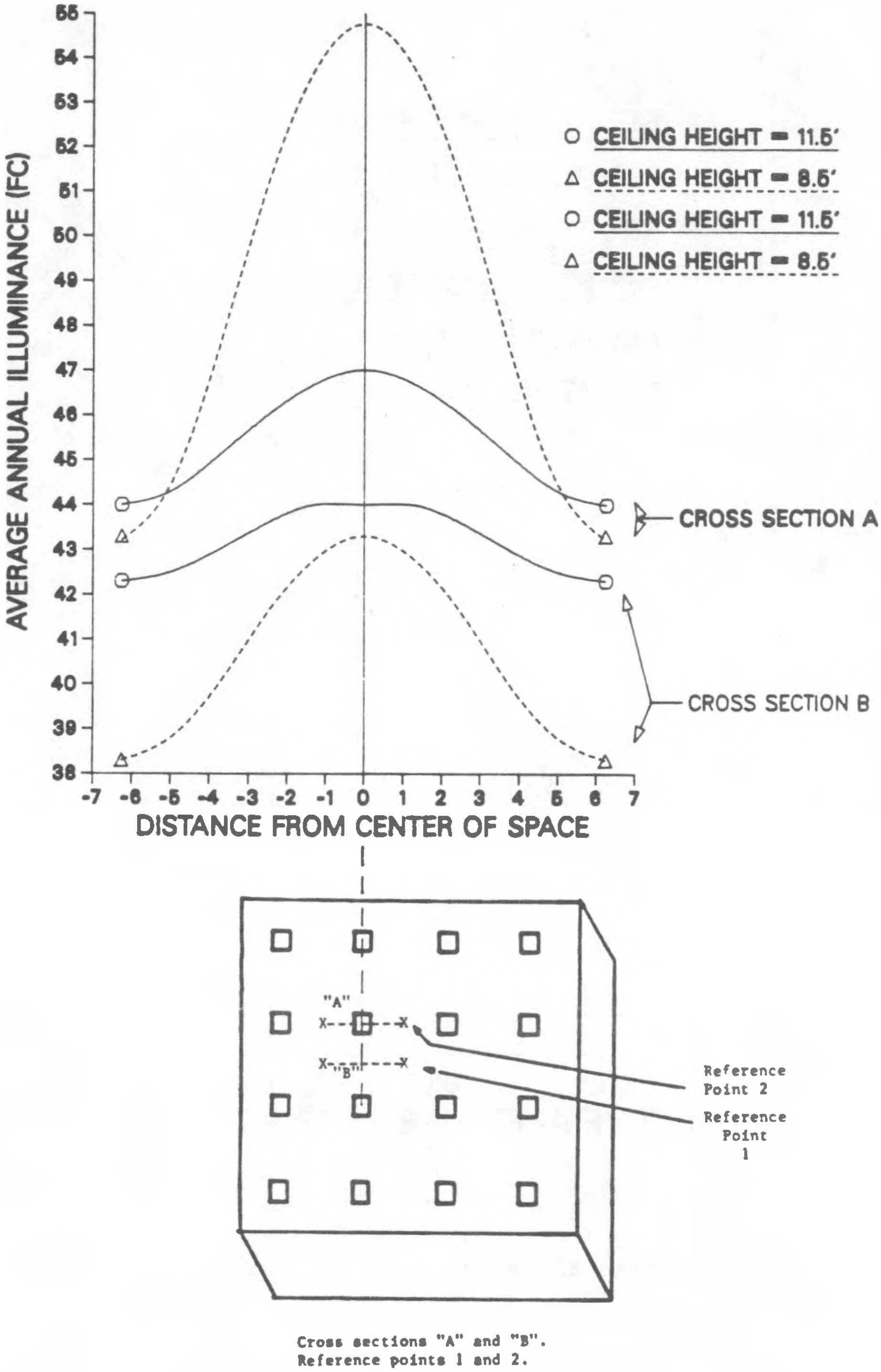

Figure 6: Annual average illuminance during daylighted hours (fc) as a function of control point location for an effective aperture = 0.01. Madison, two ceiling heights.

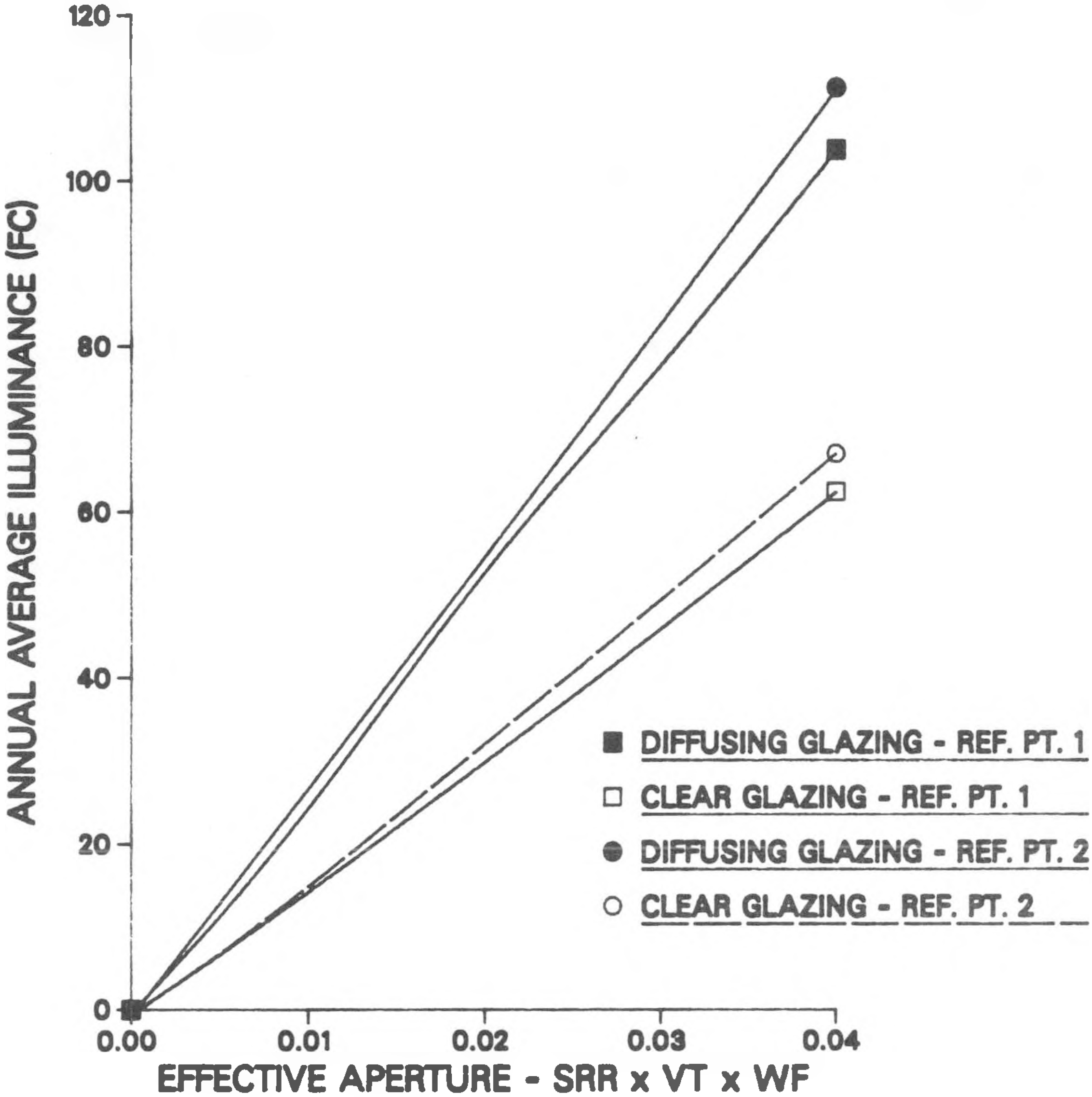

Figure 7: Average annual illuminance during daylighted hours (fc) as a function of effective aperture for clear and diffusing glazings at reference points #1 and #2, Madison.

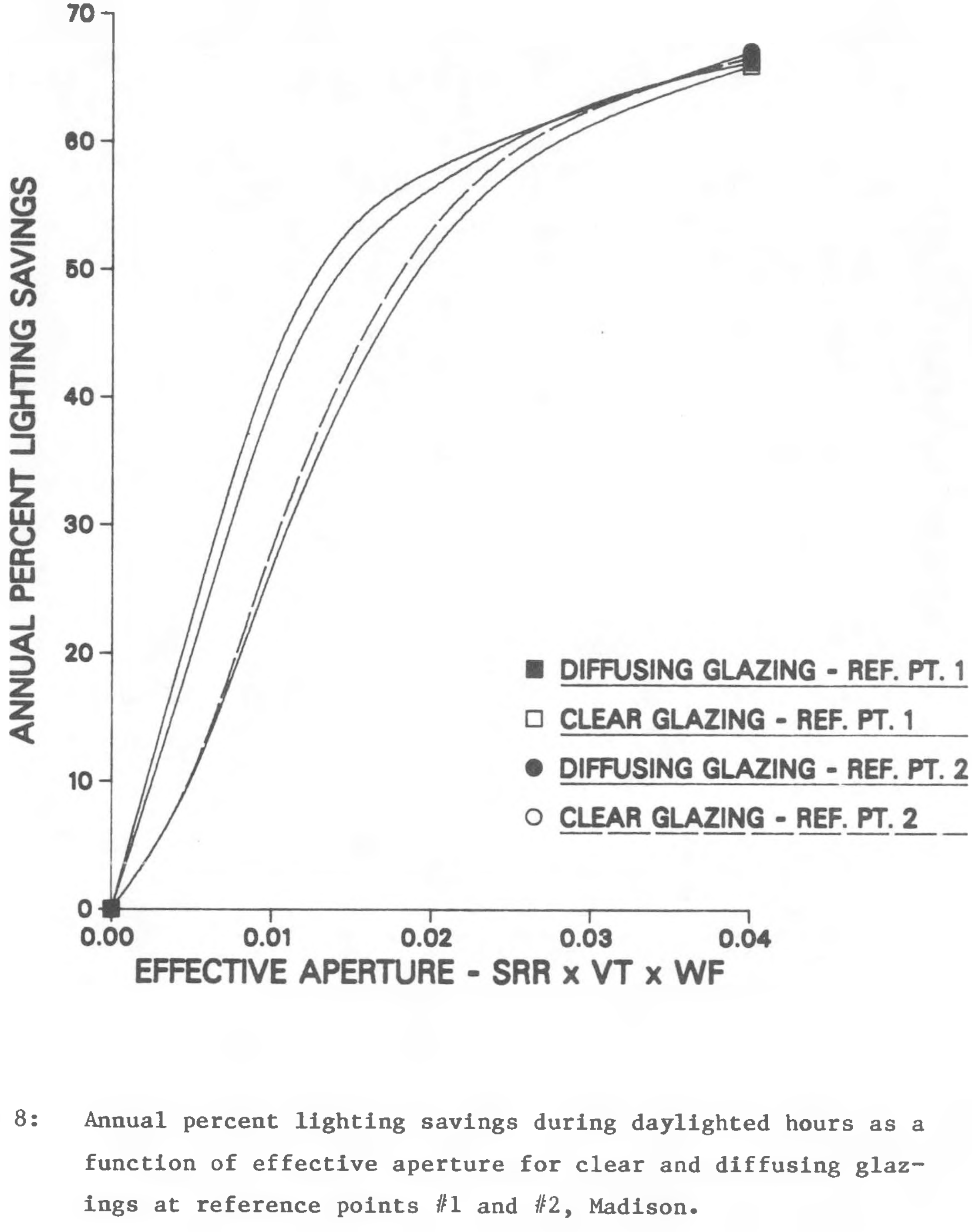

Figure 8: Annual percent lighting savings during daylighted hours as a function of effective aperture for clear and diffusing glazings at reference points #1 and #2, Madison.

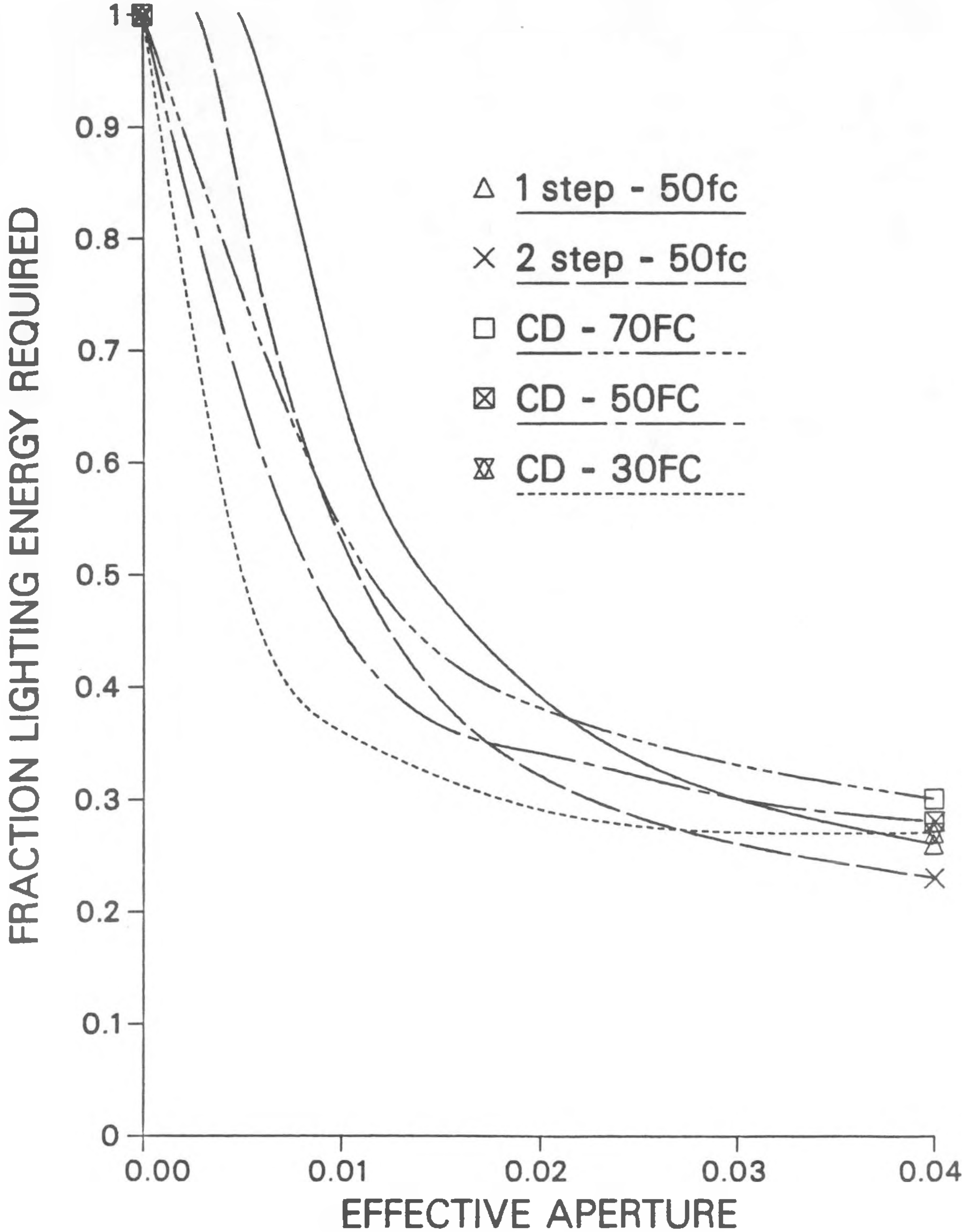

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Figure 9: Fractional lighting energy required as a function of effective aperture for a one-step and a two-step dimming system at an illumination setpoint at 50 fc and for continuous dimming (CD) systems at three illumination setpoints.