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Definition and Use of a Daylight "Coolness" Index

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ABSTRACT

This paper examines the relationship between lighting energy savings from daylighting and daylight-imposed cooling loads. From DOE2.1C simulation results for specific commercial buildings and glazing options, we show that for any daylighted or electrically lighted space, the cooling load component from natural or artificial lighting can be broken into three component factors. Each of these factors can be expressed mathematically as constants that are a function of glazing characteristics and illumination levels within the space. These three constants can then be combined into a single daylight coolness index. Thus, from (model or simulation) illuminance measurements for a proposed daylighted space, a designer can quickly compare the relative cooling load impacts of different daylighting designs.

INTRODUCTION

Without daylighting, fenestration's energy impact in a nonresidential building is often detrimental: glazing's comparatively low thermal resistance increases heating loads while the transmission of solar radiation increases cooling loads. Using daylight properly to offset electric lighting requirements offers the potential for fenestration to be an energy asset instead of a liability. The savings in electric lighting energy resulting from daylighting mean lower annual electricity consumption, reduced peak electrical demands, reduced cooling loads, and, for new construction, the potential for smaller HVAC equipment sizes.

Previous papers have identified optimum glazing configurations for daylighted commercial buildings. Allowing less than the optimum amount of daylight into the space reduces potential electric lighting energy savings. On the other hand, because daylight is always accompanied by solar gains, allowing too much "unneeded" daylight into a space can lead to excessive cooling loads. Optimum glazing characteristics for a typical commercial office building have been identified in our previous papers, which show the results of balancing variable amounts of daylight (free lighting) vs. increased cooling loads and cooling peaks (Arasteh et al. 1985a; Johnson et al. 1982, 1984, 1985; Choi et al. 1983; Selkowitz et al. 1984). This trade-off is complicated by glazing characteristics, the daylighting and spatial design, shading systems, and the alternative lighting source's efficacy. While several means to quantify the daylighting potential in a space already exist (illuminance calculations, model measurements), no simple means to compare the relative cooling impacts of different daylighting designs are available to the daylighting designer. In this paper we present one such means to do this, breaking the cooling load associated with fenestration into three components, describing simple equations for these three components, and then showing how they can be combined into a relative cooling index for a particular daylighting design.

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METHODOLOGY

This paper builds upon the methods and results of previous studies on the energy impacts of daylighting in commercial buildings. Different glazing systems are analyzed in the context of whole building energy consumption using the DOE-2.1B and 2.1C building energy simulation models (LBL and LASL 1982; Winkelmann 1984). Shading systems are not considered in this study. Based on a series of sensitivity studies (Arasteh et al. 1985b, Johnson et al. 1983), we defined two standard building models for parametric computer simulations. One model contains vertical fenestration only, the other only skylights. Detailed simulation studies were then carried out varying those parameters found to have the greatest potential energy impact. These include the glazing window-to-wall area ratio (WWR) or the skylight-to-floor area ratio (SFR), the glazing's shading coefficient (SC) and visible transmittance (T_v), lighting control strategy, window management option, lighting power density, and, for skylights, the light well transmission factor (WF). All other variables were held constant. Details are given in Johnson et al. (1983) for the window module and in Arasteh et al. (1985) for the skylight module. We note that in the design of these studies we were primarily interested in the relative performance between alternative envelope designs, rather than absolute energy consumption.

BACKGROUND: THE IMPACT OF DAYLIGHT ON COOLING

Results of previous studies can be summarized as follows:

1. To simplify our analysis of fenestration characteristics, a single parameter consisting of the product of the WWR (or SFR) and T_v (or T_v x WF for the case with skylights) was used. This dimensionless parameter quantifies the visible light flux entering through the fenestration. We call this lumped parameter the *effective aperture* (A_e). Effects of mullions and other opaque elements can be accounted for in the WWR term and a dirt depreciation factor can be incorporated into T_v.
2. The luminous efficacy of a light source (defined in lumens per watt) is usually used to compare the ratio of light output to power input of different light sources. During the cooling mode, all of the power input ultimately becomes part of the cooling load. Comparing luminous efficacies of different lamps, as light sources, is valid and useful. However, the efficacy of the system will be a function of luminaire design and placement. The luminous efficacy of daylight is usually the source efficacy and is measured outdoors.

With daylighting, we are interested in expressing the cooling load impact of the thermal gain associated with daylight. The annual cooling load impact of daylight will be affected by glazing and shading system characteristics and by how the daylight is distributed in the space. We therefore introduce the concept of "task efficacy," which refers to the cooling load associated with light delivered to a specific location, i.e. for a given luminous flux at a task location, there will be an associated cooling load to the whole space. The task efficacy of uniformly distributed electric light can be fairly constant, but the task efficacy of daylight for a given fenestration design can vary tremendously.

This concept is best seen in Figure 1, which shows annual HVAC systems' cooling loads increasing as a function of percentage lighting requirement met for four different fenestration systems. To increase the percentage of lighting energy met by daylighting, fenestration size is increased. A continuous dimming system modulates electric power to the lights in order to maintain a constant 50 fc at a control point two-thirds of the depth (10 ft) into the space or midway between skylights. When daylight provides 50 fc or more, the electric lights are dimmed to 0 output but still consume 10% of the maximum power intake. The lighting schedule calls for full lighting on weekdays between 8 a.m. and 5 p.m., fractional lighting requirements for the hours before and after the work day and on Saturdays, and 5% of the total lighting requirement during the night and on Sundays. This control system and lighting schedule explain why the maximum fractional lighting energy savings does not increase beyond 70%. For comparison's sake, three different lighting systems (with no fenestration) are also shown, each delivering a workplane illuminance of 50 fc at varying installed lighting power densities. These seven systems are roughly representative of:

1. Tinted and some reflective glazings; the the visible transmittance (T_v) is 0.67 times the Shading Coefficient (SC)
2. Clear, blue-green, or some low-E glazings; T_v is equal to SC
3. diffusing skylights with T_v=SC

4. Optically variable glass with T_v and SC controlled to hold daylight levels to a maximum of 50 fc at the reference point in the room. The maximum T_v is 0.8 and T_v=SC
5. Existing inefficient lighting systems found in older buildings consuming 2.7 W/ft^2 to deliver 50 fc (18.5 lm/W)
6. Existing efficient lighting used in new buildings consuming 1.7 W/ft^2 to deliver 50 fc (29.4 lm/W)
7. Future highly efficient lighting consuming 0.7 W/ft^2 to deliver 50 fc (71.4 lm/W).

The inverse of the slopes of the curves in Figure 1 represents the task efficacy of the lighting source (luminous flux at task/associated cooling load to the space). In the electric lighting cases, the slopes are constant and, as one might expect, rise faster with increasing power density. However, for the different fenestration systems, the slopes are different and changing.

The behavior of the slopes is explained by the fact that the task efficacy of daylight is a result of the following three phenomena:

(a) The relative shading coefficient and visible transmittance of the fenestration system. The ratio of net visible transmittance to shading coefficient is defined by K_e. (For skylights, the net visible transmittance includes a well factor term and is thus T_v x WF.) For daylighting purposes, a higher K_e means that less solar gain is associated with a given quantity of daylight. Table 1 presents approximate K_e values for typical and daylight = oriented glazings. The differences in annual cooling loads resulting from using fenestration systems with different K_e values is seen by comparing fenestration systems (1) and (2) in Figure 1.

(b) The lighting distribution within the space as a function of fenestration orientation and glazing and room characteristics. Figure 2 shows the illumination distribution within both skylighted and sidelighted spaces during the peak hour of the year in Lake Charles; both apertures were sized to provide 50 fc. In a sidelighted space, average annual illumination levels are often several times higher near the window than in the back of the room. In the skylighted space, however, the average annual maximum and minimum workplane illumination usually does not differ by more than 20% to 30%. This difference is due to the fact that the skylights are diffusing, they are uniformly distributed over the daylighted area, and toplighting is inherently more efficient at distributing light evenly than sidelighting. The cooling load differences resulting from using skylights instead of vertical fenestration— all other factors held constant—are seen by comparing fenestration systems (2) and (3) in Figure 1. Although not analyzed in this paper, the proper use of some shading systems can improve the daylight distribution within a space.

(c) The time-dependent absolute solar energy transmitted through the fenestration. Because of the varying intensity of the transmitted solar radiation, instantaneous interior daylight levels vary significantly depending on time of day, season, and sky conditions. Moderate and large apertures provide daylighting savings on cloudy days and/or on early mornings or late afternoons. At other times (e.g., clear sky with sun) these apertures provide daylight levels in excess of the design level (thus excess solar gains). Fixed or operable window shading devices are one means of modulating light and solar gain. Optically switching glazing materials, a promising future option, are the subject of current research. Fenestration system (4), an optically switching glazing system which linearly reduces both T_{vis} and SC, is one possibility. Comparing systems (4) and (2) shows the effect on cooling loads of continually modulating daylight transmittance so that design illumination levels are not exceeded. The effects are modest for small apertures (little daylight transmittance and thus low electric lighting savings) but become very large when lighting savings greater than 50% are desired. Automatically controlled shading devices can also modulate daylight transmittance; analysis of their operation is a complex problem currently under study.

RESULTS: THE COOLNESS INDICES

We now define a simple numerical index corresponding to each of the above three factors:

1. $K_e = T_{vis} / SC \; * \; (Tv_m/SC_m)$, where Tv_m and SC_m are factors by which an operable shading system might alter T_{vis} and SC when deployed. The theoretical maximum K_e (when the glazing system transmits only visible light) is about 2.4; (glazing at the

theoretical limit would have a T_{vis} =1.0, T_{solar}=0.36 and absorptance =0. resulting in SC=0.42). We therefore normalize K_e by dividing it by 2.4 and call this K_e'. The maximum K_e' is therefore 1.0.

2. K_s = (illuminance at control point) / (ideal illuminance at the control point), where the ideal illuminance at the control point is that which would occur if the luminous flux transmitted through the glazing system were evenly spread throughout the entire space. A K_s =1.0 would mean that daylight is equally distributed throughout the space without any surface absorptance losses. For a given space, K_s will generally be a function of room geometry and surface properties, of glazing characteristics, fenestration location and geometry, and of the shading system's characteristics and will vary with orientation.
3. K_f = useful illuminance/total illuminance, where both quantities are measured at the control point. The "useful illuminance" is defined as only that illuminance which goes toward reducing the lighting power, i.e., illuminance that does not exceed the design level or lighting set point. K_f will primarily be a function of aperture size, shading system, and control point location. The numerator in this term takes into account the effects of the desired light setpoint and control systems. There is no credit for illuminance levels above the lighting setpoint. Again, the maximum value for K_f is 1.0.

These three indices are independent of one another but together they determine the relative impact of daylight on cooling for a given space. Note that each of these indices is defined for a particular instant in time. While some may be constant over time, (i.e., K_e'), others will vary. We can therefore define a daylight coolness index (DCI) at an instant i in time as:

$$DCI_i = K_e' \;*\; K_s \; K_f.$$

The maximum DCI of 1.0 would represent an idealized daylighting design that minimized cooling load impact; lower numbers would indicate overall decreasing performance. We can also use this method to compare the "coolness" of electric lighting systems with one another or with daylighting designs. In the case of electric lighting systems, K_s and K_f are constants and both should be near 1.0 for good designs while K_e' is redefined slightly. As noted earlier, the maximum K_e' of 1.0 corresponds to T_v =1.0, T_s =0.36, and no solar absorptance in the glazing. If we assume that the luminous efficacy of solar radiation outdoors is approximately 110 lumens/Watt, then the maximum luminous efficacy of solar radiation transmitted through glazing with a K_e of 1.0 is (110 lumens/Watt) / (0.36) or 306 lumens/Watt. We therefore define K_e' for electric lighting as the lighting source's efficacy divided by 306 lumens/Watt.

Before proceeding, let us analyze the DCI_i for a specific hour of the year. Figure 3 presents HVAC system cooling load increases at the hour of peak electrical demand as a function of lighting energy savings for the same seven daylighting and electric lighting options presented in Figure 1. While the curves in Figure 3 have trends similar to those in Figure 1, they are not as smooth because they represent only one hour and not average data for thousands of hours. As in Figure 1, glazings with higher K_e values or glazings more efficient at distributing daylight (i.e., skylights) do better at small apertures. However, once the space becomes saturated with daylight, fenestration systems with a solar control mechanism keep solar gains from rising quickly without any added daylighting.

For the same amount of lighting energy provided, cooling loads (Q_c) from different daylighting or electrical lighting systems will scale inversely to the DCI. Expressed mathematically:

$$\frac{Q_{c-1}}{Q_{c-2}} = \frac{(1/DCI_{i-1})}{(1/DCI_{i-2})}. \tag{1}$$

Thus

$$Q_{c-1} * DCI_{i-1} = Q_{c-2} * DCI_{i-2}. \tag{2}$$

For each fraction of lighting energy provided, the cooling load increase multiplied by the DCI is constant. In Figure 4 the data plotted in Figure 3 has had cooling loads multiplied by their appropriate DCI_i values. These "normalized cooling loads" are the systems cooling loads which would be expected if the DCI_i were always 1.0. From Equation 2, one might expect that the seven lines in Figure 4 would all be coincident.

Instead, they group into three close but distinct families: vertical fenestration, skylights, and electric lighting. This deviation from Equation 2 is due to the differences in thermal lag calculations in DOE2 between solar radiation and electric lighting and from the differences in building geometry between the skylight and vertical fenestration modules.

Also of interest is a daylight coolness index for longer time periods (daily or yearly). We therefore define

$$DCI_t = K_{e,t}' * K_{s,t} * K_{f,t}$$

where

$K_{e,t}'$, $K_{s,t}$, and $K_{f,t}$ are all functions of time.

$K_{e,t}'$, $K_{s,t}$, and $K_{f,t}$ will depend on location, orientation, HVAC system, thermal mass, and other building design parameters. Current research is aimed at determining if these factors can be easily calculated.

CONCLUSIONS

Although daylighting can greatly reduce electric energy for lighting requirements, it can lead—with poor fenestration design or improper use—to unnecessary cooling load increases that are higher than those associated with electric lighting. We showed that the three factors affecting the "coolness" of daylight—the relative glazing efficacy, the distribution of daylight within the space, and the time dependency of daylight—can all be represented by simple ratios. These indices are derived from the glazing properties, the illuminance distribution within the space, and the transmitted solar radiation for representative hours of the year and can be combined into one DCI. For different natural or artificial lighting options that provide the same fraction of illuminance requirements, cooling loads from lighting will scale inversely to the DCI. This procedure could easily be incorporated into a daylight illuminance simulation program or model measurement procedure.

Often, the peak electrical demands for different fenestration systems are of great interest to designers. The primary components of peak electrical demand are lighting- and fenestration-imposed cooling loads. Using the method outlined above, with the appropriate illuminance measurements (or calculations), the designer can compare both peak daylighting savings as well as peak cooling load impacts from different fenestration systems.

Using DCIs to compare annual cooling effects from different fenestration systems becomes more difficult because of the variation of the $K_{e,t}$, $K_{s,t}$, and $K_{f,t}$ factors with time and because of the dependence on building operating schedule. Of course, it would be possible to determine the DCI for each hour of the year and then take a weighted average. The number of calculations required would be quite large and the time requirements would be better spent on full building simulations such as with DOE-2 rather than on an extensive simplified analysis. On the other extreme, one might average the two extreme hourly conditions: the peak electrical demand hour and, say, a cloudy winter hour. For preliminary analysis, the designer may choose either extreme or tailor a procedure somewhere in between that is appropriate for the fenestration options, available resources, and climate.

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TABLE 1
Sample Glazing Properties

Glazing	T_v	SC	K_e
Reflective (bronze) insulated glass	0.10	0.20	0.5
Tinted (bronze) insulated glass	0.47	0.57	0.8
Clear insulated glass	0.80	0.82	1.0
Low-E (on bronze) insulated glass	0.41	0.42	1.0
Low-E (on clear) insulated glass	0.72	0.66	1.1
Tinted (green) insulated glass	0.67	0.52	1.2
Low-E (on green) monolithic	0.65	0.53	1.2
Triple glazing (green) with low-E film as inner layer	0.58	0.47	1.2
Low-E (on green) insulated glass	0.61	0.41	1.5

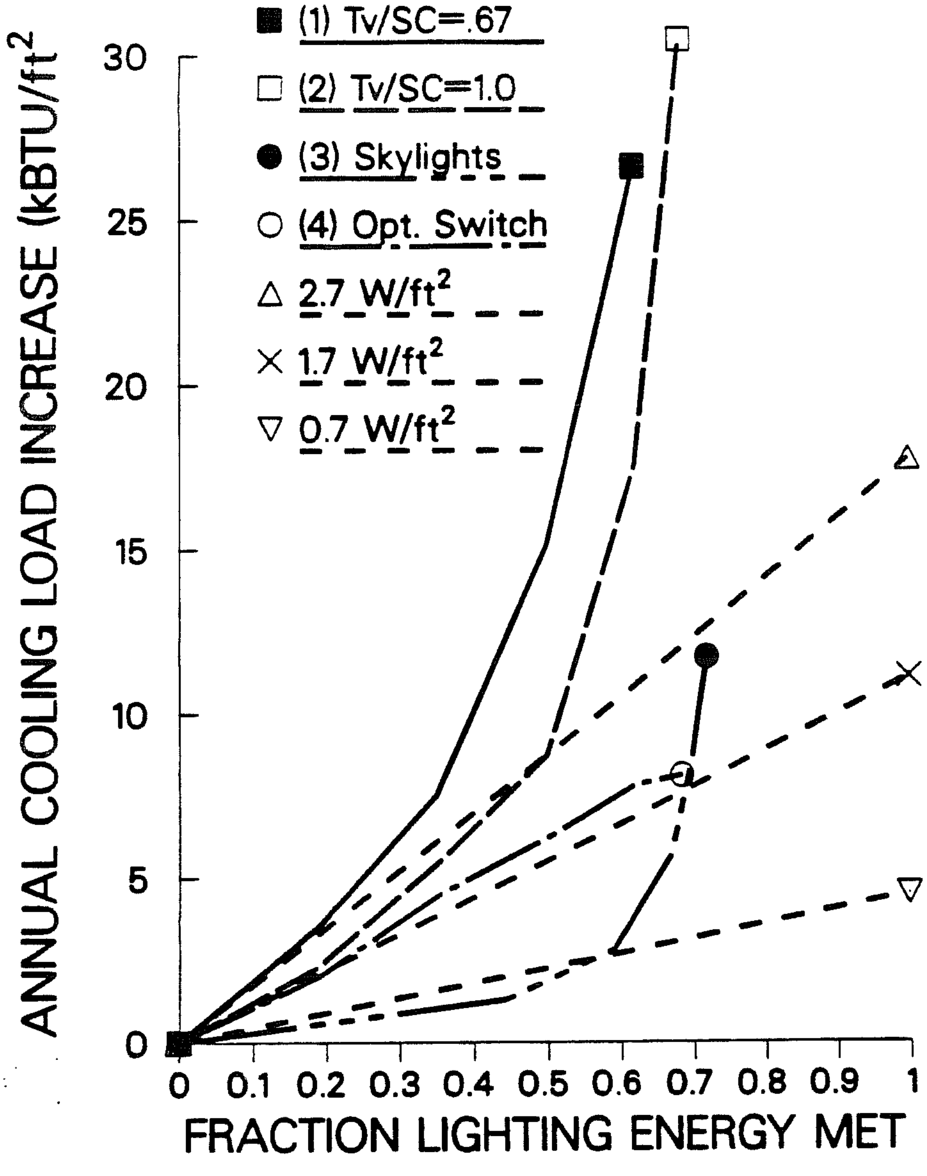

Figure 1: Annual cooling load increases as a function of the fractional lighting energy met from four fenestration systems and three electric lighting power densities in a prototypical office module in Lake Charles, LA. The required illuminance is 50 fc; vertical glazing is west facing.

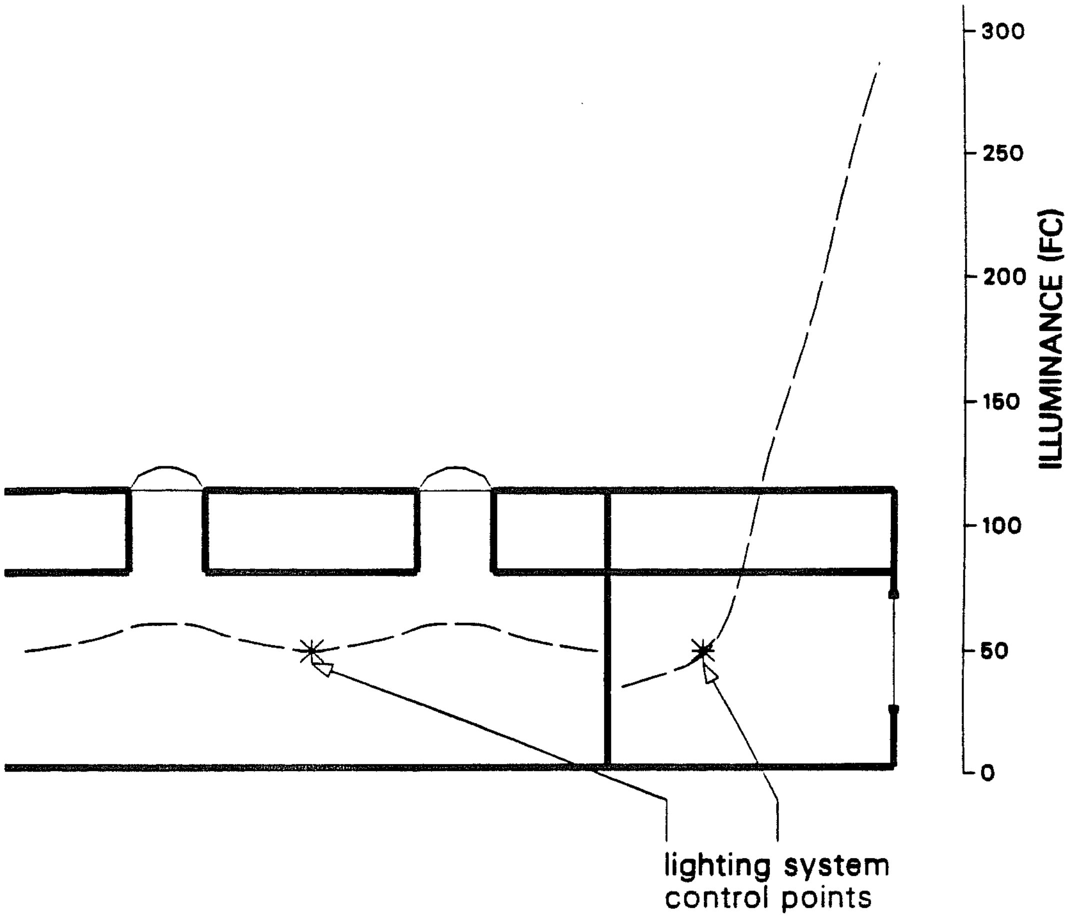

Figure 2: Daylighting illuminance distribution within both sidelighted and toplighted spaces for the peak hour in Lake Charles, LA. Apertures were sized to provide 50 fc at the lighting system control points. Vertical glazing is west facing. No shading devices are considered.

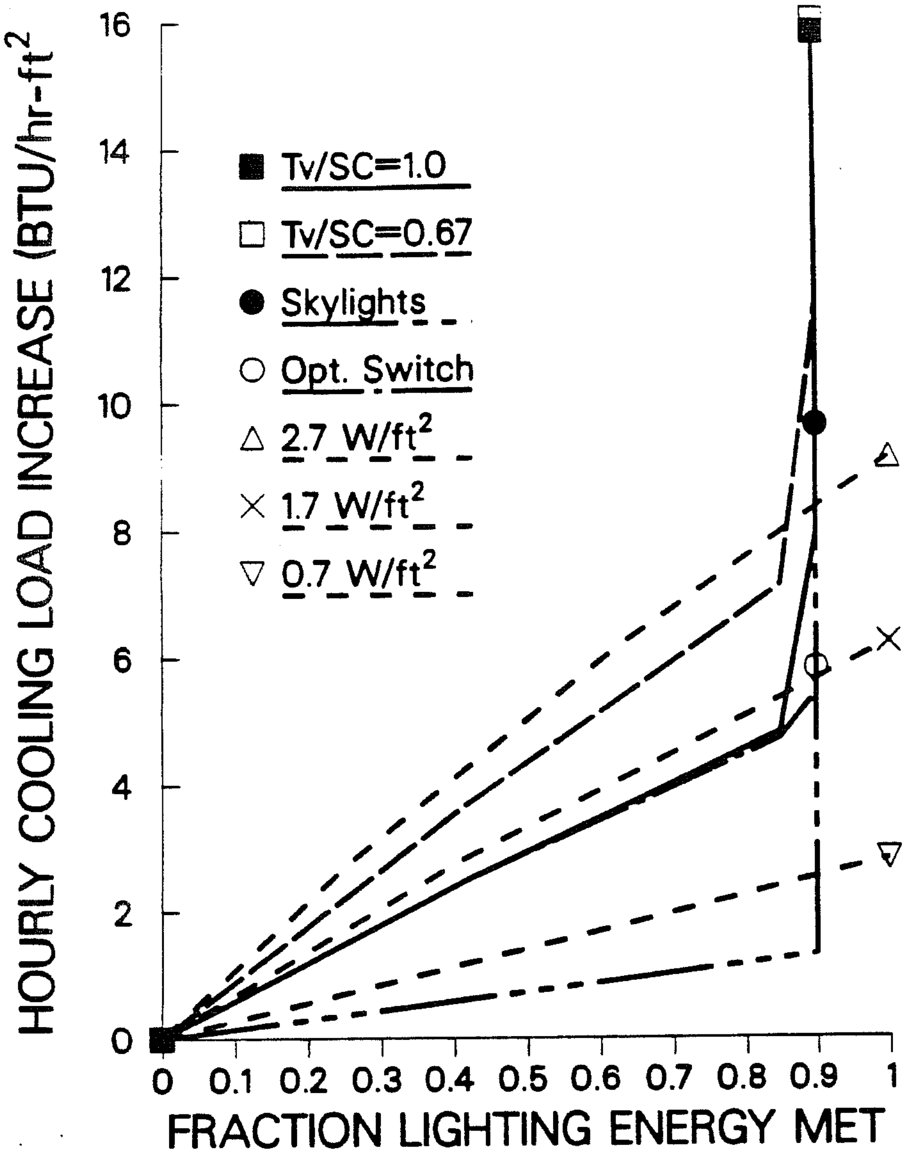

Figure 3: Peak hour cooling load increases as a function of the fractional lighting energy met from four fenestration systems and three electric lighting power densities in a prototypical office module in Lake Charles, LA. The required illuminance is 50 fc; vertical glazing is west facing.

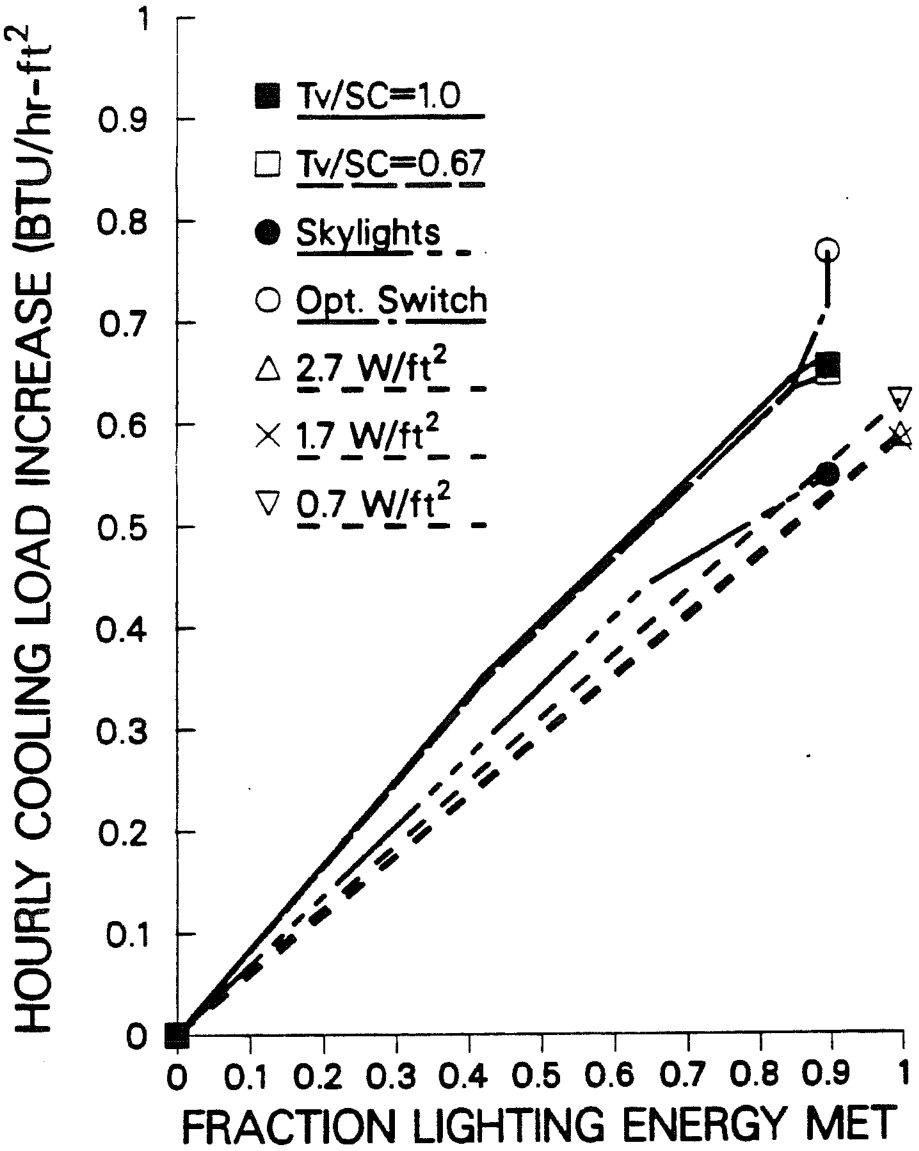

Figure 4: Peak hour cooling load increases normalized by the daylight coolness index as a function of the fractional lighting energy met from four fenestration systems and three electric lighting power densities in a prototypical office module in Lake Charles, LA. The required illuminance is 50 fc; vertical glazing is west facing.