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EFFICIENT DAYLIGHTING IN THERMALLY CONTROLLED
ENVIRONMENTS

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ABSTRACT

This paper reviews many of the design considerations required to enable a design team to utilize daylight to the maximum possible extent in order to reduce electric lighting loads and associated building energy-consumption. Among steps that must be taken is a thorough analysis of all heating and cooling loads inside the building and the heat exchange through the building envelope. Data on local climate and sunshine availability must also be considered.

Although the energy aspects have recently dominated our design considerations, daylight's influence on human well-being is gaining importance. In this respect, the variability of daylight, the quality of its spectral composition, the view out, and health effects are among the aspects that should be considered when determining an appropriate role for daylighting in energy-efficient buildings.

1. INTRODUCTION

Daylight, the visible part of solar radiation, is regarded as the preferred light source for interior lighting. However, daylight cannot be considered separately from the entire spectrum of radiation received from the sun. On the thermal side, one must consider the total thermal balance to arrive at the optimal energy-conserving solution. On the visual side, one must avoid glare from direct sunlight, the sky, and external bright surfaces. Furthermore, one cannot ignore the physiological and health aspects

of ultraviolet radiation.

Historically, daylight has been the primary source for indoor illumination. However, the development of efficient electric sources, particularly the fluorescent lamp, enabled designers to rely increasingly on man-made, controlled environments. As part of this approach, electric lighting and mechanical cooling have been used as substitutes for daylight and natural ventilation.

This freedom from dependence on natural energy sources has greatly benefited designers. However, excessive reliance on mechanical technologies has caused designers to lose their feeling for the mutual relationship between the building and its surrounding. As a result, on the one hand windowless buildings were built and on the other, fully glazed buildings were constructed. Designers were seldom bothered by any adverse environmental consequences of their designs. They easily prescribed energy-consuming remedies in the form of additional lighting and air conditioning.

This approach can no longer be applied. Since energy has become expensive and scarce, we have to relearn how to live in a world where energy must be conserved.

It should be emphasized that solar heat, which is associated with daylight, is generally desirable indoors during the heating season, while it is undesirable during the cooling season. However, the glare associated with daylight should be prevented all year round. The best way to avoid undesirable thermal and visual consequences is to

carefully design the size of openings, giving due consideration to their orientation, and to provide for controllable shading devices.

2. DAYLIGHT AS A SOURCE FOR INTERIOR LIGHTING

As concern for efficient energy use in buildings has increased, designers have improved their understanding of thermal processes in buildings and the thermal environmental factors that drive those processes. The average designer's level of knowledge concerning illumination and the luminous environment is less well developed; thus we include a short review of daylight sources and the luminous properties associated with each. Daylight can usually reach a building's interior in three ways--direct sunlight, skylight, and light reflected from external surfaces.

2.1 Sunlight

Direct sunlight is associated with several undesirable effects, such as glare, fading, and excessive heat gain during hot periods. Thus, it is rarely regarded as a source for direct interior illumination, although if properly diffused and reflected, it can be effectively utilized. A variety of sun-control options is available to prevent the penetration of unwanted sunlight.

2.2 Skylight

The primary source of daylight inside the built environment is usually the sky. The sky's illuminance, E , on a small surface can be calculated by the following equation:

$$E = \int L \cdot d\Omega \quad (1)$$

where L is the luminance of the source (sky) and Ω the solid angle subtended by this source on the examined surface.

For an unobstructed horizontal surface outdoors, the solid angle of the whole sky vault is 2π , and for a uniformly bright sky ($L = \text{constant}$), the illuminance can easily be calculated. However, the luminance distribution of the real sky is never uniform, and calcu-

lating daylight for non-uniform sky conditions becomes complicated. The International Commission on Illumination (C.I.E.) adopted two standard sky luminance distributions: "The Standard Overcast Sky" (see C.I.E., 1970¹) and the "Standard Clear Sky" (see C.I.E., 1973²). Data on the integrated irradiance and spectral distribution of solar radiation can be found in C.I.E. (1972).³ For the partly cloudy sky, Kireev (1979)⁴ indicated that when the sun disc is fully covered with cloud, skylight levels approximately follow the overcast sky pattern. When the sun disc is fully clear, the clear-sky distribution can be applied.

Several methods for calculating daylight can be found in the following books and papers: Hopkinson, Petherbridge and Longmore (1966);⁵ Lynes (1968);⁶ and Krochmann and Aydinli (1979);⁷ Bryan et al (1981);⁸ Modest (1981);⁹ and Ne'eman and Shrifteilig (1979).¹⁰

2.3 Overcast Sky

For the C.I.E. Standard Overcast Sky, the luminance distribution is described by an equation proposed by Moon and Spencer (1942):¹¹

$$L_E = L_o \cdot \frac{1 + 2\cos\epsilon}{3} \quad (2)$$

L_E is the luminance of a small area, p , of the sky (see Fig. 1) at an angle ϵ from the zenith. L_o is the sky luminance at the zenith. Thus the luminance of any point on the sky depends only on the angle of that point from the zenith (or horizon).

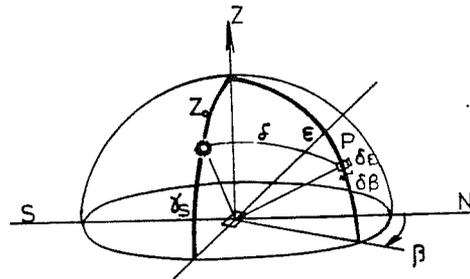


Fig. 1. Coordinates for the calculation of daylight from the clear and overcast sky.

The illuminance, E_a , on the horizontal surface, s , from a small area, p , of the sky will be:

$$E_a = \int L(\epsilon) \cdot \cos \epsilon_p \cdot d\Omega \quad (3)$$

and if we substitute $d\Omega$ by: $d\Omega = \sin \epsilon \cdot d\epsilon \cdot d\beta \cdot \Omega_0$, we can write:

$$E_a = \int \int L_0 \cdot \frac{1 + 2\cos \epsilon}{3} \cdot \cos \epsilon \cdot \sin \epsilon \cdot d\epsilon \cdot d\beta \cdot \Omega_0 \quad (4)$$

Ω_0 = unit solid angle = 1 Steradian, and β is the azimuth angle.

Integration of (4) for a horizontal surface with the unobstructed sky vault ($\beta = 2\pi$ and $\epsilon = \frac{\pi}{2}$) gives:

$$E_a = \frac{7}{9}\pi \cdot L_0 \cdot \Omega_0 \quad (5)$$

Although the distribution of luminances for the overcast sky is independent of the position of the sun, the values of luminance are determined by the height of the sun above the horizon, γ_s . Krochmann (1963)¹² suggested that the horizontal illuminance from the whole overcast sky should be calculated by the following equation (see Fig. 1):

$$E_a (\gamma_s) \text{ (lux)} = 300 + 21,000 \cdot \sin \gamma_s \quad (6)$$

The amount of daylight at any point inside the building is obviously dependent on the solid angular subtent of the sky and external reflecting surfaces seen from that point.

The solid angle becomes smaller with the square of the distance from the window, thus the levels of daylight fall rapidly as we move deeper inside away from the windows.

The effect of the glazing should also be considered. The transmittance of a clean, clear 1/8" float glass for visible radiation is normally 90%. However, soiled or tinted glass will transmit much less light, and thus reduce the amount of usable daylight. Some dark tinted and reflective glasses which are used as heat-resistant filters transmit only 10-15% of incident light.

2.4 Clear sky

Daylight under clear-sky conditions is the sum of direct sunlight and skylight, with the addition of externally reflected light. The latter component is particularly significant whenever sunlight is reflected from bright surfaces. Daylight levels with clear sky depend on the height of the sun above the horizon, which is determined by the day in the year, the hour, and also the clarity of the atmosphere expressed as turbidity factor (see C.I.E. 1973²). The intensity of direct solar radiation, E_{es} , can be expressed (Krochmann, Aydinli, 1979⁷) by:

$$E_{es} (\gamma_s, T) \text{ (w/m}^2\text{)} = E_{eo} \cdot \exp(-\bar{a}_R \cdot m \cdot T) \sin \gamma_s \quad (7)$$

(on a horizontal surface)

where E_{eo} is the solar constant. According to recent measurements, it is specified as $E_{eo} = 1370 \text{ w/m}^2$ or 128.41 klx. Also, \bar{a}_R , the mean extinction coefficient, is a function of the optical air mass, m . T is the turbidity factor according to Linke.

The calculation of daylight with clear sky is far more complicated than with overcast sky. The pattern of luminance distribution moves with the sun; thus the light admitted through a window changes constantly. However, the light reaching an unobstructed horizontal surface from the whole sky can be obtained in a similar way as direct sunlight. Several expressions relate the horizontal illuminance to solar altitude, the simplest of which was proposed by Chroscicki (1971):¹³

$$E_{ah} \text{ (lux)} = 3000 + 170 \cdot \gamma_s \quad (8)$$

E_{ah} is the illuminance on a horizontal unobstructed plane from the clear whole sky; γ_s is angle of the sun (degrees) above the horizon.

This linear relationship is fairly accurate for sun heights up to 65° above the horizon and for turbidity factor of $T = 2.75$.

Other equations were proposed by Krochmann (1970),¹⁴ Kittler (1972),¹⁵ and Dogniaux (1976).¹⁶

The luminance distribution of clear sky was defined by Kittler (1965)¹⁷ and adopted as a standard distribution by the C.I.E. in 1973:

$$L_p = \frac{(1 - e^{-0.32 \sec \epsilon})(0.91 + 10e^{-3\delta} + 0.45 \cos^2 \delta)}{0.27385(0.91 + 10e^{-3Z_0} + 0.45 \cos^2 Z_0)} \cdot L_0 \quad (9)$$

L_p = luminance of the sky element p.

L_0 = luminance of the zenith.

ϵ = angle of the sky element from the zenith

δ = angle of the sky element from the sun.

Z_0 = angle of the sun from the zenith.

2.5 Luminous Efficiency

By evaluating the "Luminous Efficiency," LE, of radiation (lm/w) we can calculate the intensity of sunlight from solar radiation measurements. The luminous efficiency of direct sunlight is the quotient of luminous flux from the sun by the corresponding solar radiant flux, and is expressed by

$$LE = K_m \frac{\int_{380\text{nm}}^{780\text{nm}} E_{es,\lambda} \cdot V(\lambda) \cdot d\lambda}{\int_0^{\infty} E_{es,\lambda} \cdot d\lambda} \quad (10)$$

$K_m = 673 \text{ lm/w}$ = maximum luminous efficiency (555 nm). $E_{es,\lambda}$ is the intensity of solar radiation in wavelength λ . $V(\lambda)$ is the spectral relative sensitivity of the average human eye, according to C.I.E. Values for the luminous efficiency of solar radiation are given in Table 1.

The total illuminance from the whole clear sky can be calculated by using diffuse radiation measurements and multiplying them by the appropriate luminous efficiency values. In this case we replace $E_{es,\lambda}$ in equation (10) by $E_{es \text{ sky}}(\lambda)$ —which is the intensity of diffuse radiation.

In real conditions we are usually exposed to the global illuminance, and again we can calculate it from global radiation measurements with the aid of luminous efficiency for the global radiation.

When we examine the luminous efficiency of electric light sources, we define it as the quotient of the total luminous flux emitted by the total power consumed.

In order to examine the energy-conserving potential of daylight, luminous efficiencies of daylight as well as of electric light sources are given in Table 1:

TABLE 1 The Luminous Efficiency (lm/w) of Light Sources

Source	Luminous efficiency (lm/w)	
	Hopkinson (1966) ⁵	Leibelt (1978) ¹⁸
Daylight		
Sunlight (solar altitude 7.5°)	90	
Sunlight (solar altitude > 25°)	117	
(mean)	100	109.2 ± 10.4
Skylight (average)	125	114 ± 9.3
(clear)	150	
Global (average)	115	110 ± 5.8
Electric light sources* (lm/w)		
Incandescent		10 - 15
Fluorescent		60 - 70
"True-life" or "de-luxe" fluorescent		40 - 50
New "Tricolour" fluorescent		65 - 75
High-efficiency fluorescent		75 - 90
with electronic ballast		
High-pressure mercury		50 - 60
Metal halide		70 - 90
High-pressure sodium		100 - 120

*mean through life; ballast losses, where applicable, are included.

For further comparison between daylight and electric light sources a few examples of spectral distribution curves are given in Fig. 2.

2.6 Daylight Factor

Because of daylight's variable nature, it is useless to specify it in absolute values. Daylight is commonly specified by the "Daylighting Factor," which is defined as the quotient of indoor illuminance at the examined point to the illuminance outdoors, measured on a horizontal surface with unobstructed sky. Sunlight excluded from both measurements.

$$DF = \frac{E_{in}}{E_{out}} \times 100 (\%) \quad (11)$$

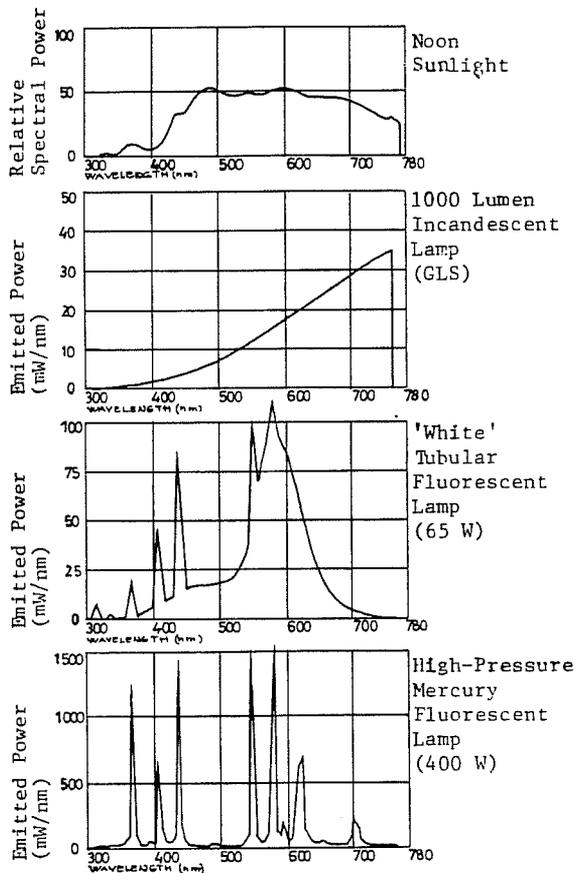


Fig. 2. Spectral power distribution.

3. AVAILABILITY AND INTENSITY OF SUNLIGHT AND DAYLIGHT

3.1 Availability

It is easy to calculate the number of daylight hours and the maximum potential duration of sunshine from sunrise to sunset for any given location on a specific date. However, the clarity (turbidity) of the atmosphere will greatly affect the intensity of skylight, and the actual sunshine duration depends on cloudiness, haze, fog, air pollution, and obstructions to sunlight propagation.

It was proposed to base design with sunlight on the duration of "available sunshine" in a location rather than on the maximum possible daily duration. The duration of "available sunshine" can be obtained by analyzing the

statistical average duration of real sunshine as a percentage of the possible duration with a clear and unobstructed sky.

Naturally, exact data on availability of sunshine are available for only a few areas. However, detailed analysis of sunshine availability in Great Britain, carried out by Ne'eman and Light (1975),¹⁹ has shown that availability data, based on London and Edinburgh, can be applied to the entire country.

Data on the availability of sunlight and daylight have been published for various parts of the world. References include: Kimbell and Hand (1921),²⁰ U.S.A.; Richards and Kennhaackkap (1959),²¹ South Africa; Paix (1963),²² Australia; Dogniaux (1978),²³ Belgium; and Hunt (1979),²⁴ Great Britain. Data are now being collected at several locations in the United States.

3.2 Light Intensity

Availability of sunlight and daylight and their intensities depends on climate, latitude, time, and local effects. Regretfully, meteorological stations generally do not record light intensities. Thus in many parts of the world the designer has to rely on inadequate data and, at best, calculate light levels by multiplying radiation data by the appropriate luminous efficiency value or by calculating nominal clear and overcast day data which is then combined to generate data for "average" conditions.

Generally, average light intensities with unobstructed overcast sky, on a horizontal plane, reaches values of between 5,000 and 15,000 lux.

With clear sky, the maximum global illuminance (direct sun and sky) can reach 100,000 to 150,000 lux on a surface normal to the sun. According to the various investigators mentioned above, illuminance from the clear sky on a horizontal plane, with unobstructed sky but excluding direct sunlight, can reach about 17,000 lux with a clear atmosphere (turbidity factor $T = 2.75$), and about 23,000 lux for a more turbid sky ($T = 5.00$).

Another difference between the overcast and clear sky should be mentioned. The overcast sky is in many cases brighter than the clear blue sky, which implies that the intensity of daylight indoors is also higher under overcast conditions. However, we must add the effect of the externally reflected component, which is much higher with the clear sky than with the overcast sky.

4. DAYLIGHT FOR WELL-BEING

Daylight has been and still is the reference light source to which the human eye is adapted. No man-made, "artificial" source can fully match its spectral composition. We wish to stress the importance of daylight and the associated contact with the outside world to occupants' well-being.

4.1 Physiological Effects

We can happily note that since the widespread utilization of electric lighting began at the end of the last century, no negative effects on human health have been found. Furthermore, the introduction of efficient and low-luminance fluorescent lamps after the Second World War enabled us to improve the indoor visual environment by increasing lighting levels and uniformity of distribution and by reducing glare. Still, we cannot be fully assured that negative effects do not exist. The fluorescent and other discharge sources used for indoor illumination are not continuous in their spectrum and are deficient in ultraviolet radiation. Also, indoors we are exposed to only 1/100 to 1/200 of the light intensities prevailing in sunny conditions outdoors. Warnings have been made that the distorted sensory information caused by non-continuous light frequency patterns can be harmful to people performing prolonged visual activities. Logan (1972)²⁵ writes, "We cannot yet be sure what the artificial indoor electromagnetic environment is doing to man, but all should be aware of the possibilities."

Deprivation of UV irradiation may be potential health hazard (Thorington, 1971).²⁶ Dutt (1978),²⁷ while examining the damage from

excessive exposure to UV radiation, notes the beneficial effects of moderate exposure. In the Soviet Union, it is customary to expose miners and children in far Polar regions to controlled doses of UV radiation (Dantzig, 1967).²⁸

People who spend all their time indoors, and do not have even an occasional exposure to sunlight, may become "photo-deprived" and may not sufficiently develop their immunologic defenses (Logan, 1972).²⁵ Among the benefits of admitting sunlight indoors we mention the germicidal and bacteriocidal effects. We also note the anti-fungus effect and the drying, anti-rot effect.

4.2 Psychological Effects

Sunlight and daylight are not just sources of light. They are associated psychologically with the inflow of visual information about the outside world, and thus help combat a sense of enclosure. Marcus (1967),²⁹ Ne'eman and Hopkinson (1970),³⁰ Hardy (1974),³¹ and Ne'eman (1974)³² dealt with the various aspects of daylight and windows and their role in creating psychological well-being.

The importance occupants attach to daylight and view seems to depend on individual subjective considerations such as interest in the work, type of activity, primary direction of view in relation to the window, availability of sunshine outdoors, etc.

Up to now, there has been no general agreement on the strength of occupants' desire for daylight and view. However, the authors believe that both daylight and view are essential for occupants' well-being. Consequently, whenever a conflict between daylighting and energy conservation arises, measures to conserve energy should be taken without sacrificing the minimum acceptable level of daylight and view.

4.3 Adverse Effects of Daylight

Skylight is rarely a cause of undesirable effects indoors. One of the few circumstances occurs in museums and art gal-

series where conservation of the art objects dictates tight control of light intensities, particularly UV radiation. High levels of daylight may also accelerate the fading of sensitive fabrics and other organic materials. In addition to increasing cooling loads and creating thermal discomfort, direct sunlight can cause glare which may be of much annoyance where occupant position and direction of view are fixed. School classrooms, offices, and industrial buildings are a few examples.

However, these negative effects can be eliminated by using appropriate sun-control strategies.

5. ENERGY BALANCE

Well-being is one side of daylighting, while the energy balance and the consequent cost is the other. Daylight is not free of cost. We do not pay for its generation, but fenestration and the associated window management devices are often more expensive than the equivalent opaque wall. Thus, initial investment for a daylit structure may be higher than for a windowless building. Furthermore, it is well known that windows can increase the demand for energy. Because of the many factors involved, including local climate and building systems, it is impossible to analyze here the full energy balance of buildings. However, we shall discuss the main aspects of daylight which influence the energy balance.

6. DAYLIGHT/ARTIFICIAL LIGHT BALANCE

The penetration of daylight depends mainly on the area of the windows and their transmittance. However, even with fully glazed external wall, daylight is not effective in deep interiors, those farther away than 3 to 5 times the ceiling height. A characteristic daylight penetration is given in Fig. 3.

In deep interiors daylight cannot substitute for all electric lighting, even on bright days. On cloudy-dull days, daylight levels are lower, so the electric lighting may need to be used throughout the day. Before we can

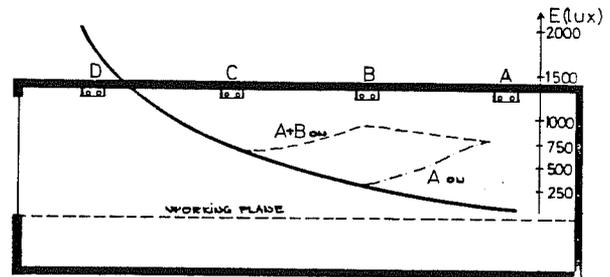


Fig. 3. Daylight penetration and artificial light supplement.

examine the savings potential of daylight, we need to estimate the energy consumption of the artificial lighting. With overall efficiency of approximately 50%, the power consumption of a domestic incandescent general lighting installation providing levels of 150 to 250 lux will be about 20 w/m^2 to 33 w/m^2 . For visual activities requiring illuminance levels of 500 to 1000 lux, and utilizing fluorescent lamps, the load can be 18 w/m^2 to 35 w/m^2 . An average load of 25 w/m^2 can generally be assumed. For all daytime hours in the year, the consumption will be 112 kWh/m^2 , and about half that amount for an office, on the basis of 10 hours per day operation for 200 days a year.

Many investigations have been carried out in recent years to establish the potential saving in electric energy by using daylight. Matsuura (1979)³³ has calculated the distance from the windows for which daylight is adequate, so that artificial lighting can be switched off. Hunt (1979),³⁴ in his paper on lighting controls, compared "on-off" switching with "top-up" dimmers that provide only enough light to top-up the level to its specified value. He has shown that for an illuminance level of 500 lux, and an interior having a glazed area that provides 2% Daylight Factor, the yearly gross saving may reach about 60%. Crisp (1978)³⁵ investigated efficient facilities for light-switching in buildings. Initial results from field tests of dimmable electronic ballasts for fluorescent lamps indicate that savings of 50-75% are achievable in typical perimeter offices. Although sophisticated lighting control sys-

tems may appear economically prohibitive at present prices, there is little doubt that they will rapidly become feasible due to the rising prices of energy.

6.1 Deep Interiors

The optimal solution for deep interiors is to utilize daylight as far as possible and supplement with electric lighting in the deeper part. The concept was originally developed by Hopkinson (Hopkinson and Longmore, 1959),³⁶ and is known as P.S.A.L.I.-- Permanent Supplementary Artificial Lighting of Interiors. P.S.A.L.I. is not just an extension of night-time electric lighting to daytime. The design approach is based on the dominance of daylight, while electric light is used only as a supplement. For other concepts of integrating daylight and electric light, see Hardy and O'Sullivan (1967)³⁷ and Ne'eman and Longmore (1973).³⁸

6.2 Lighting Savings Potential

Summing up, the maximum feasible saving on artificial lighting can be up to 50% of the gross yearly use in larger rooms. In offices the saving can be 25-35 kwh/m² of floor area per year. In school classrooms, conventional offices, and similar buildings where the distance of the far wall from windows does not exceed 2 to 3 times the ceiling height, savings can be even greater.

7. DAYLIGHT/THERMAL BALANCE

The thermal optimization of a building requires examining internal sources and heat transfer through both the opaque and the transparent parts of the outer envelope. Although they affect the overall energy balance, lighting considerations have only a minor influence on the thermal behavior of the opaque portions of the envelope. Consequently, we can concentrate on windows alone.

The intensity of solar radiation on a horizontal surface is given in Equation (7) above. Further details on solar radiation can be obtained from Robinson's book (1966).³⁹ Givoni and colleagues (1968)⁴⁰ stu-

died the effect of orientation on thermal and lighting conditions in classrooms. Givoni (1976)⁴¹ also dealt with the subject.

Data on solar radiation and solar gain can be obtained from various guides and also from Petherbridge (1974),⁴² ASHRAE Handbook of Fundamentals (1977),⁴³ and Pilkington Environmental Advisory Service (1979).⁴⁴ These data allow one to evaluate heat-transfer values for any building type and any window/shading combination.

The "Shading Coefficient" (SC) is used to compare the solar radiant heat gain of different glazing systems. It is defined as the ratio of heat gain from the glazing system to the heat gain from a single sheet of 1/8" DS clear glass. For simple glazing systems, SC can be calculated. For more complex fenestration systems it is usually measured in a solar calorimeter.

7.1 Glazing

Good-quality clear float glass, 3-4 mm (1/8" - 3/16") thick, has 0.90 visible transmittance. However, "heat-resistant," "anti-sun," or "anti-glare" tinted glasses have a light transmittance of 0.25 to 0.55, and some reflective glasses have a transmittance as low as 0.08. By installing such glasses we permanently reduce the amount of light admitted. Inevitably this reduces opportunities to substitute daylight for electric light. Some of these glasses reduce light transmittance even more than the total radiant heat transmittance. For example, Pilkington 6 mm (3/8") 41/60 grey float glass has 0.41 light transmittance, 0.60 total radiant heat transmittance, and a shading coefficient of 0.60. On the other hand, blue-green glass selectively absorbs more infrared energy so that it has 0.50 light transmittance and 0.35 total radiant heat transmittance.

In many cases where permanent reduction of light transmittance is not desirable, daylighting design would recommend clear glass. The proper shading coefficient can be obtained by suitable shading devices. How-

ever, specific solutions will vary with climate, orientation, and other design constraints.

In cold regions, heat losses during the cold season can be reduced by double glazing and suitable shading. The thermal transmittance (U-value) for single glazing is about $5.5 \text{ w/m}^2 \text{ }^\circ\text{C}$. For double glazing the U-value is about $3.2 \text{ w/m}^2 \text{ }^\circ\text{C}$, while for double-glazed windows and external sun controls it is only $2.9 \text{ w/m}^2 \text{ }^\circ\text{C}$. Even lower U-values can be obtained from low-emittance coatings, triple glazing, or movable insulation.

8. ENERGY MANAGEMENT DURING COOLING SEASON

We often assume that commercial buildings are dominated by cooling concerns. This is true for very large buildings having large internal heat sources, but is not necessarily true of small commercial buildings, which make up the bulk of the building stock. Nor is it true of buildings having efficient designs that minimize internal loads.

We can examine design concerns based upon the following climatic zones:

- a. The cold zone, where heating is the primary thermal-design consideration, while cooling is almost unnecessary if the design is based on natural ventilation. Northern parts of the United States, Canada, northern Europe, and Asia, and equivalent regions in the southern hemisphere belong to this group.
- b. The warm zone, where the predominant requirement is cooling. In this zone, interior thermal comfort during the hot season cannot be provided by natural ventilation, either because of high ambient temperatures, high relative humidity, or both. Southern parts of the United States, equatorial countries of South America, Africa, and southern Europe, the Middle East, and southern Asia belong to this group.

- c. The intermediate zone, where both winter heating and summer cooling are required for thermal comfort. Regions having a temperate climate belong to this group.

In cold regions, during the heating season, the heat generated by the electric lighting and solar radiation is helpful because it reduces the load on the heating plant. Therefore, large glazing areas, with little attention to effective shading, can be acceptable if heat and light can be introduced into the building without sacrificing thermal or visual comfort. Thermal insulation is obtained by double or triple glazing to which movable insulating devices may be added.

The situation differs in warm regions during the cooling season. Any addition of heat into the cooled space, either from electric lighting or from solar radiation, increases the load on the cooling plant. In addition, electric lighting increases the building's peak electrical load and the total demand on summer-peaking utilities. Although cooling strategies can utilize storage that shifts cooling load from the on-peak hours, lighting and daylight utilization are instantaneous phenomena which must be properly managed throughout the day. In the intermediate zone a combination of fixed and operable thermal and daylighting control strategies may provide the optimal solution.

The appropriate design strategy for buildings characterized primarily by their cooling requirements should include:

- a. Minimal utilization of electric light during the daytime peak cooling period.
- b. Maximum utilization of natural light during the daytime. The primary sources for natural light should be skylight and externally reflected light (from sun and sky).
- c. The penetration of direct solar radiation should generally be prevented by effective shading, preferably with external controllable devices. Such devices should allow maximum utilization

of available daylight when the openings are not exposed to direct sunlight.

- d. Automatic switching or, even more efficient, automatic continuous dimming of groups of lamps based upon available daylight, can increase the energy savings compared to manually operated controls.
- e. Ultimately, a fully automatic system, which would regulate both the electric lighting and the shading controls, could provide the optimal energy and load reductions while preserving the well-being of occupants. While systems of this type are becoming commercially available, little documentation yet exists on operating experience. The combined systems approach is important because inadequate control of solar gain may increase cooling loads and reduce the energy saved by lowering electric lighting levels.

9. DESIGN METHODS

Daylighting was for generations an art based on intuition and experience. Methods for predicting daylight illumination in buildings have been developed only during the last few decades. However, the theory and calculation tools that were adequate to determine compliance with building codes based upon minimum (e.g., overcast) sky conditions could not cope with the increasing complexity of the subject, particularly for clear sky.

Only in the last 20 years has an improved understanding of sky and sun characteristics enabled researchers to formulate internationally agreed upon equations for the sky luminance distribution of the overcast sky¹ and the clear sky.² However, accurate calculation of daylight could not be easily performed without computers. Several large computer programs that calculate daylight illumination are currently available (DiLaura and Hauser, 1978).⁴⁵ SUPERLITE, a program under development, will allow calculation of the effects of complex shading systems exposed to direct sunlight.⁹

Programmable calculators and small computers

have accelerated the development of sophisticated design tools.⁸ These computational tools can allow accurate predictions of daylight levels at any point in the building and can be used by designers who do not have expertise with or accessibility to large computers.

Powerful computational tools may be used to generate other design methods for use throughout the design process. Methods based upon tabular data, nomographs, protractors, and graphic overlays have been developed for designing daylight interiors.

In many situations involving interaction of direct sunlight with geometrically complex shading systems it is difficult or impossible to calculate interior daylight levels. In these circumstances, scale models may prove helpful. Since the interreflectance of a light flux in a geometrical volume is scale-independent, measurements made in scaled models of proposed buildings can be used to predict quantitative daylight levels in the full-scale building. Scale models can also be used to assess lighting quality, view, glare, and the aesthetics of the daylight spaces.

If scale-model measurements are made outdoors, the changing sky luminance conditions must be carefully documented, or comparisons between different model measurements difficult or impossible. One is also dependent on the vagaries of local weather and may experience long waits until conditions recur. One solution to these problems is to build an indoor sky simulator that provides a stable sky of constant and known luminance distribution. Such sky simulators range from the very simple (an illuminated sheet adjacent to a scale model) to the large and complex (dome skies that allow designers or researchers to work within them). A newly completed, 24-foot-diameter hemispherical sky at Lawrence Berkeley Laboratory will permit modeling studies under overcast, uniform, and clear sky conditions and will duplicate sunlit ground conditions (Selkowitz et al, 1981).⁴⁶ A sun simulator is currently being added to the facility, which will be used for research, teaching, and design.

The design methods discussed above provide data on interior daylight illumination and may be used to predict hour-by-hour values throughout the year. However, in order to predict the consequences for energy use, including thermal tradeoffs, daylighting tools must be merged with an annual building energy analysis program. Simplified daylighting models have been incorporated into several building energy analysis programs, but these are generally limited to modeling simple fenestration systems. A flexible and powerful set of algorithms that will model light shelves and complex shading is now being added to DOE-2.

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