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Daylighting Calculation in DOE-2

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May 1983

APPLIED SCIENCE
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DAYLIGHTING CALCULATION IN DOE-2

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ABSTRACT

Lighting accounts for about 20% of total electrical energy consumption in the United States. Using natural lighting is a cost-effective way to reduce this consumption and, at the same time, enhance the quality of the indoor environment. For several years, architects and engineers have used scale models, hand calculator programs, and sophisticated main-frame computer programs (such as LUMEN-II) to determine levels of interior daylight for different building configurations. However, none of these tools determines the annual energy savings from daylighting, information which could have an important effect on design decisions.

For this reason, a daylighting simulation has been added to DOE-2. Taken into account are such factors as window size, glass transmittance, inside surface reflectances of the space, sun-control devices such as blinds and overhangs, and the luminance distribution of the sky. Because this distribution depends on the position of the sun and the cloudiness of the sky, the calculation is made for standard clear- and overcast-sky conditions and for a series of 20 solar altitude and azimuth values covering the annual range of sun positions. The calculations are performed prior to the complete simulation, and the the resulting daylight factors are stored for later use. Analogous factors for glare are also calculated and stored.

For the hourly envelope simulation, the illuminance from each window is found by interpolating the stored daylight factors (using the current-hour sun-position and cloud cover), then multiplying by the current-hour exterior horizontal illuminance. If the glare-control option has been specified, the program will automatically close window blinds or drapes to decrease glare below a pre-defined comfort level. Adding the illuminance contributions from all the windows gives the total number of footcandles at each reference point.

This report describes the equations and algorithms used to perform the daylighting calculations in DOE-2.1B, and is intended as a supplement to the DOE-2 Engineers Manual, Version 2.1A, LBL-11353. Supporting user documentation may be found in the DOE-2 Reference Manual, LBL-8706, Rev.2, LA-7689-M, Ver. 2.1A, the DOE-2 BDL Summary, LBL-8688, Rev.3, the DOE-2 Users Guide, LBL-8689, Rev.2, the DOE-2 Sample Run Book, LBL-8678, Rev.1, and the DOE-2 Supplement, LBL-8706, Rev.3.Suppl.

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DAYLIGHTING CALCULATION IN DOE-2

1. Introduction

The DOE-2.1B daylighting model, in conjunction with the thermal loads analysis, determines the energy impact of daylighting strategies based upon hour-by-hour analysis of daylight availability, site conditions, window management in response to sun control and glare, and various lighting control strategies.

The daylighting calculation has three main stages. In the first stage (which is flow-charted in Table 1) a preprocessor calculates daylight factors for later use in the hourly loads calculation. The user specifies the coordinates of one or two reference points in a space. DOE-2 then integrates over the area of each window to obtain the contribution of direct light from the window to the illuminance at the reference points, and the contribution of light which reflects from the walls, floor, and ceiling before reaching the reference points. Taken into account are such factors as the luminance distribution of the sky, window size and orientation, glass transmittance, inside surface reflectances, sun control devices such as drapes and overhangs, and external obstructions. The calculation is carried out for standard CIE clear and overcast sky conditions for a series of 20 different solar altitude and azimuth values covering the annual range of sun positions. Analogous daylight factors for discomfort glare are also calculated and stored.

In stage two (see flow-chart Table 2) an hourly daylighting calculation is performed every hour that the sun is up. The illuminance from each window is found by interpolating the stored daylight factors using the current-hour sun position and cloud cover, then multiplying by the current-hour exterior horizontal illuminance. If the glare-control option has been specified, the program will automatically close window blinds or drapes in order to decrease glare below a pre-defined comfort level. A similar option uses window shading devices to automatically control solar gain.

In stage three, the program simulates the lighting control system (which may be either stepped or continuously dimming) to determine the electrical lighting energy needed to make up the difference between the daylighting level and the design illuminance. Each thermal zone can be divided into two independently controlled lighting zones. Finally, the zone lighting electrical requirements are passed to the thermal calculation which determines hourly heating and cooling loads.

The illuminance calculation has been validated by comparing DOE-2 predictions with scale-model measurements made in the LBL Sky Simulator and with SUPERLITE, a very detailed illuminance program. The results are shown and discussed in Ref. 1. Good agreement is observed among the three methods except far from the window-wall in side-lit geometries where the spilt-flux method used in DOE-2 overpredicts the inter-reflected illuminance.

The daylighting model in DOE-2.1B has been designed with future expansion in mind. At the present time, the program calculates interior illuminance for conventional window designs using a preprocessor

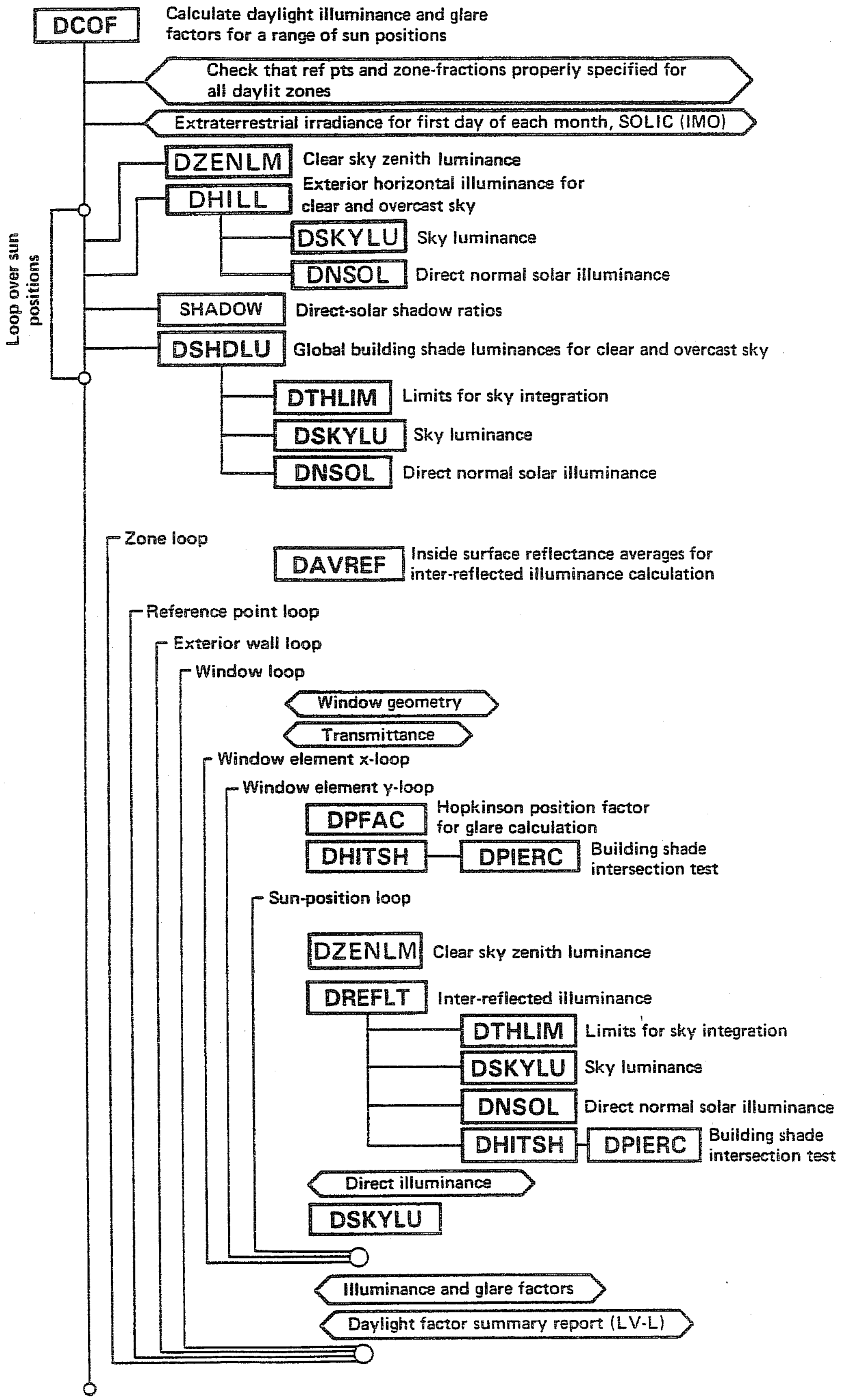

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Table 1. DOE-2.1B daylighting preprocessor flowchart. Daylighting subroutines are in boldface.

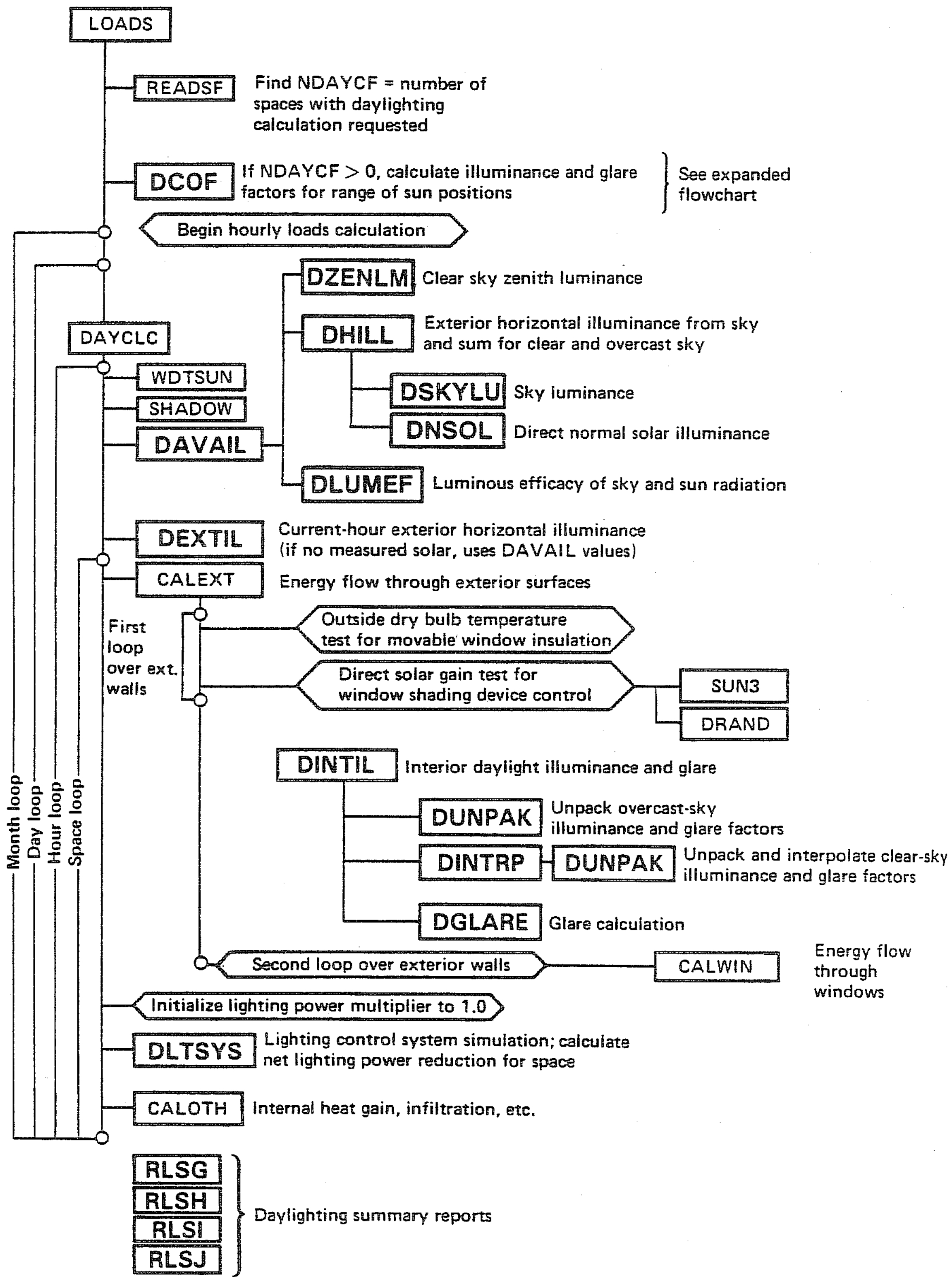

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Table 2. DOE-2.1B daylighting calculation flowchart. Daylighting subroutines are in boldface. Some LOADS non-daylighting subroutines are also shown.

calculation and sun control systems such as shades, drapes and blinds that are assumed to be ideal diffusers. The program will be expanded to allow modeling of more geometrically complex sunshading solutions such as horizontal or vertical louvers based upon results calculated in the SUPERLITE program or determined by model measurements. These results would be stored in a library and could be specified by the user. For one-of-a-kind building designs, the user will be allowed to input his/her own daylight coefficients based upon model tests made on that unique design. The final model should be responsive to the latest in architectural design strategies.

2. The Daylighting Preprocessor (Subroutine DCOF)

2.1 Overview

For each daylit space, the preprocessor calculates a set of illuminance and glare factors for later use in the hourly loads calculation. The basic steps are:

1. Calculate exterior horizontal daylight illuminance from sun and sky for standard (CIE) clear and overcast skies for a range of solar altitudes.
2. Calculate interior illuminance and glare for each window/reference-point combination, for bare and for shaded window conditions (if a shading device has been specified), for overcast sky, and for standard clear sky for a series of sun positions covering the annual range of solar altitude and azimuth for the specified building latitude.
3. Divide interior illuminance and glare quantities by exterior horizontal illuminance to obtain daylight factors, which are then packed and stored in the AA array.

2.2 Interior Illuminance Components

In the preprocessor, daylight incident on a window is separated into two components: (1) light which originates from the sky, and reaches the window directly or by reflection from exterior surfaces; and (2) light which originates from the sun, and reaches the window directly or by reflection from exterior surfaces. Light from the window then reaches the workplane directly or via reflection from the interior surfaces of the room.

Fig.1a-e shows schematically the various paths by which diffuse light originating from the sky can pass through a window (without a shading device) and reach a reference point on the workplane:

(a) light from sky passes through window directly and reaches workplane without internal reflection.

(b) as in (a) but light reflects internally before reaching workplane.

(c) light from sky reflects from ground, then enters window and reaches workplane after internal refraction. (Note that light reflected from a horizontal ground plane cannot reach the workplane directly.)

(d) light from sky illuminates an obstruction or is reflected from the ground onto the obstruction. Light reflected from the obstruction passes through the window and reaches workplane without internal reflection.

(e) as in (d), but light reflects internally before reaching workplane.

Fig. 1f-i shows similar paths for light originating from the sun.

Fig. 2a-f shows the situation in which the window is covered by a diffusing shade:*

(a) light from sky illuminates shade. Light transmitted by shade reaches workplane directly or by internal reflection.

(b) as in (a) but shade is illuminated by light from sky after reflecting from ground.

(c) light from sky illuminates an obstruction or is reflected from ground onto the obstruction. Light reflected from the obstruction illuminates the shade. Light transmitted by shade reaches workplane directly or by internal reflection.

(d)-(f) as in (a)-(c) above but light originates from sun.

For fixed sun position, sky condition (clear or overcast) and room geometry, the sky-related interior daylight will be proportional to the exterior horizontal illuminance, $E_{h,sky}$, due to light from the sky. Similarly, the sun-related interior daylight will be proportional to the exterior horizontal solar illuminance $E_{h,sun}$.

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* By "shades" or "window-shades" are meant devices such as drapes, blinds, pull-down shades, etc., which are used on a window for sun or glare control. They are distinguished from "building-shades" (also called "obstructions") such as fins, overhangs, neighboring buildings etc.

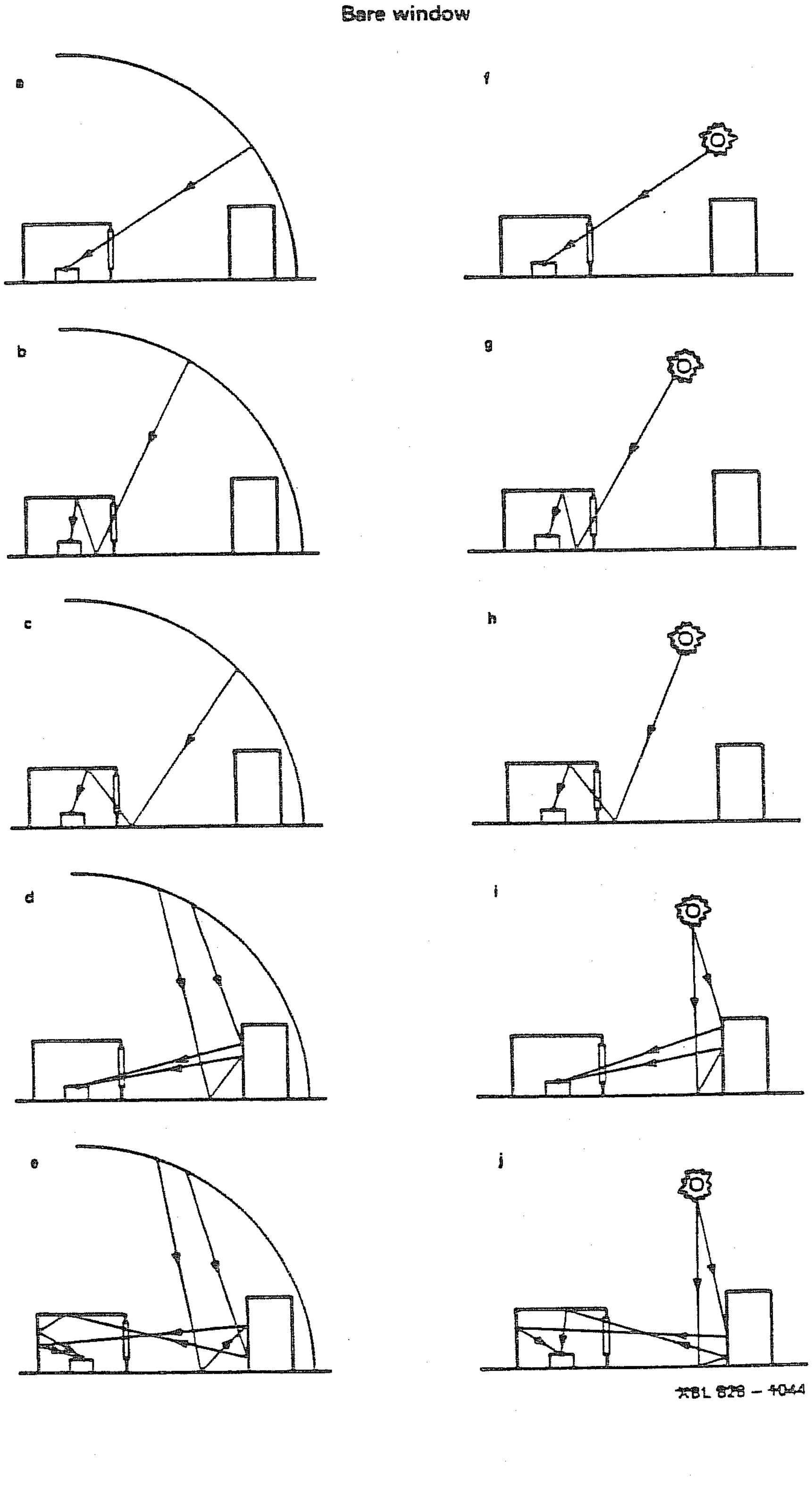


Fig. 1. Paths by which light originating from sky (a-e) and from sun (f-j) can reach workplane through a transparent window without a shading device.

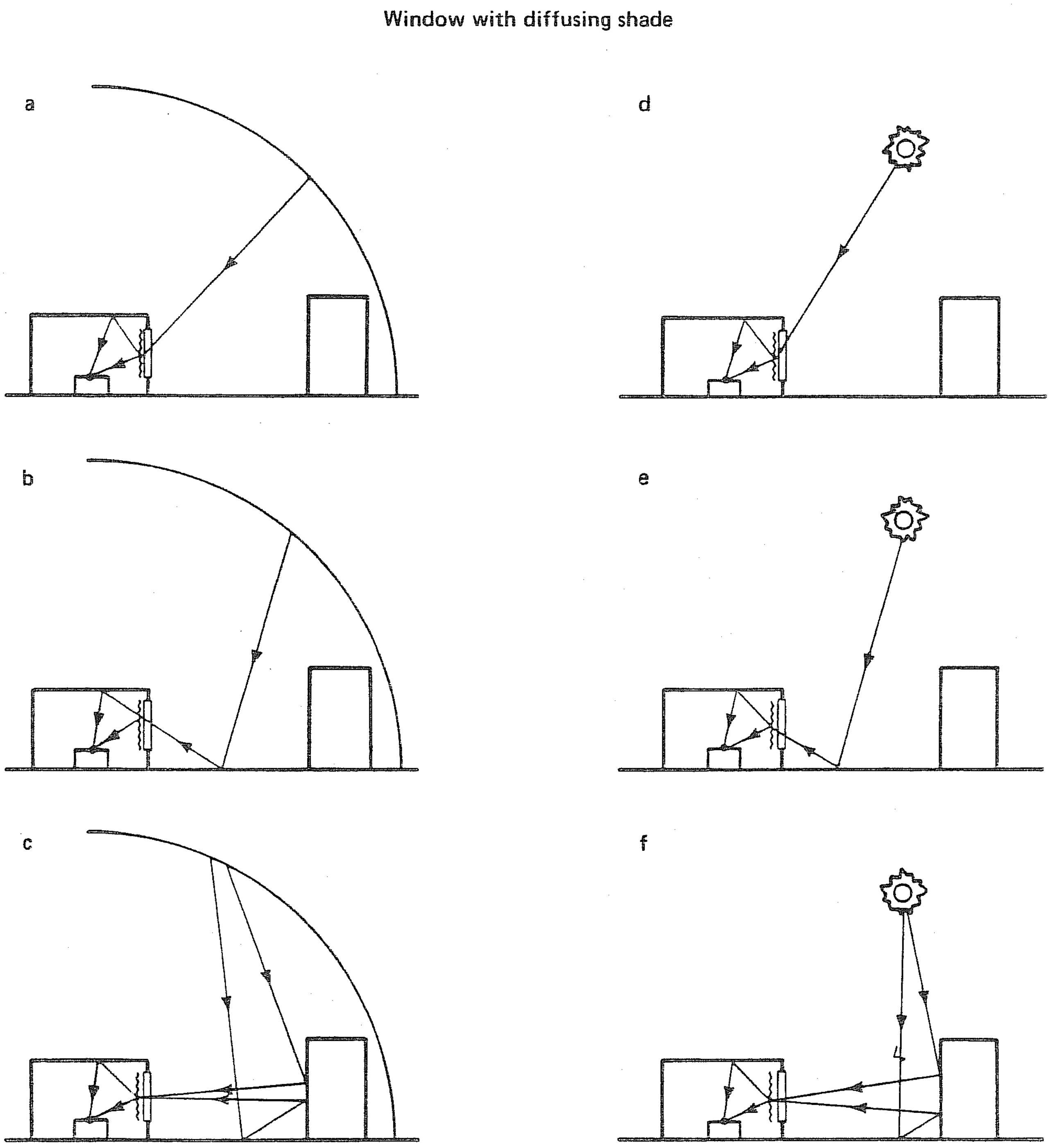


Fig. 2. Paths by which light originating from sky (a-c) and from sun (d-f) can reach workplane through a transparent window with a diffusing shading device.

2.3 Daylight Factors

The following interior/exterior illuminance ratios, called "daylight factors", are calculated and stored for later use in the hourly LOADS calculation:

$$d_{sky} = \frac{\text{illuminance at reference point due to sky-related light}}{E_{h,sky}}$$

$$d_{sun} = \frac{\text{illuminance at reference point due to sun-related light}}{E_{h,sun}}$$

$$w_{sky} = \frac{\text{average window luminance due to sky-related light}}{E_{h,sky}}$$

$$w_{sun} = \frac{\text{average window luminance due to sun-related light}}{E_{h,sun}}$$

$$b_{sky} = \frac{\text{window background luminance due to sky-related light}}{E_{h,sky}}$$

$$b_{sun} = \frac{\text{window background luminance due to sun-related light}}{E_{h,sun}}$$

These factors depend, in general, on:

1. room geometry 2. interior surface reflectances 3. position of reference point 4. window geometry 5. glass transmittance 6. position of window shade (exterior vs interior) 7. transmittance of window shade	room conditions
8. location of external obstructions (e.g. fins, overhangs, or adjacent buildings) 9. reflectance of external obstructions 10. condition of sky - clear vs overcast 11. position of sun (for clear sky)	external conditions

For a daylit space with N windows the 6 daylight factors

$$d_{sky},\ d_{sun},\ w_{sky},\ w_{sun},\ b_{sky}, \text{ and } b_{sun}$$

are calculated for each of the following combinations of window, reference point, sky condition, sun position, and shading device:

$$\begin{bmatrix}\text{Ref. pt. \#1}\\ \text{(and \#2}\\ \text{if defined)}\end{bmatrix}\begin{bmatrix}\text{Window \#1}\\ \text{Window \#2}\\ \cdot\\ \cdot\\ \cdot\\ \text{Window \#N}\end{bmatrix}\begin{bmatrix}\text{Clear sky,}\\ \text{sun pos. \#1}\\ \cdot\\ \cdot\\ \cdot\\ \text{Clear sky,}\\ \text{sun pos. \#20}\\ \text{Overcast sky,}\\ \text{sun pos. \#1}\end{bmatrix}\begin{bmatrix}\text{Bare window}\\ \text{Window plus shade}\\ \text{(if shade is}\\ \text{specified)}\end{bmatrix}$$

For example, for a room with one window, one reference point, and no window-shade, we have

$$6 \times (1 \times 1 \times 21 \times 1) = 126 \text{ daylight factors}$$

For building latitude λ degrees, the 20 sun positions for the clear sky case are

azimuth (clockwise from north): 70, 125, 180, 235, 290 degrees;

altitude (degrees): $10,\ 10 + \frac{1}{3}(\phi_m - 10),\ 10 + \frac{2}{3}(\phi_m - 10),\ \phi_m$

where ϕ_m, the maximum solar altitude, is $\min(113.5^{\circ}-\lambda, 90^{\circ})$. Fig. 3 shows the sun positions for $\lambda=40^{\circ}$.

2.4 Sky Luminance Distributions

Clear Sky

The clear sky luminance distribution, which was derived by Kittler from measurements in Europe, has the form (Refs. 2 and 3):

$$L(\theta_{sky},\phi_{sky}) = L_z \frac{(0.91+10e^{-3\gamma}+0.45\cos^2\gamma)(1-e^{-0.32\ \mathrm{cosec}\phi_{sky}})}{.27385\ (0.91+10e^{-3(\pi/2-\phi_{sun})}+0.45\sin^2\phi_{sun})} \qquad (1)$$

where

ϕ_{sky} = altitude of sky element,
θ_{sky} = azimuth of sky element,

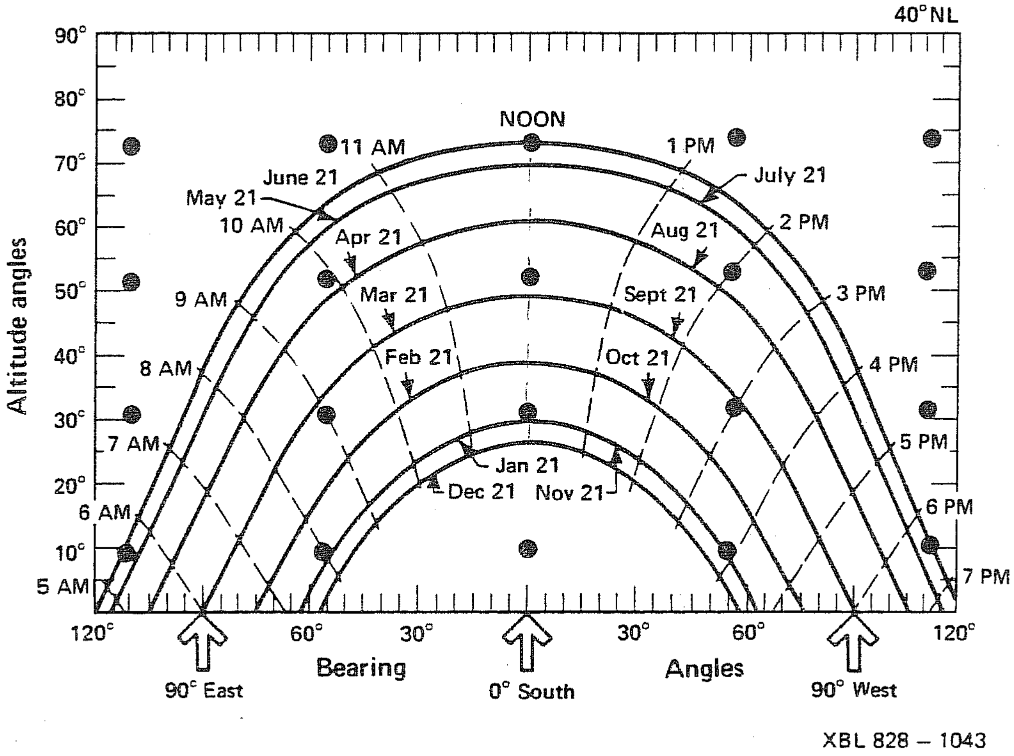


Fig. 3. Sun positions (●) for calculation of clear sky daylight factors for 40° north latitude. (Sunchart reproduced from "The Passive Solar Energy Book", Edward Mazria, Rodale Press, Emmaus, PA, 1979.)

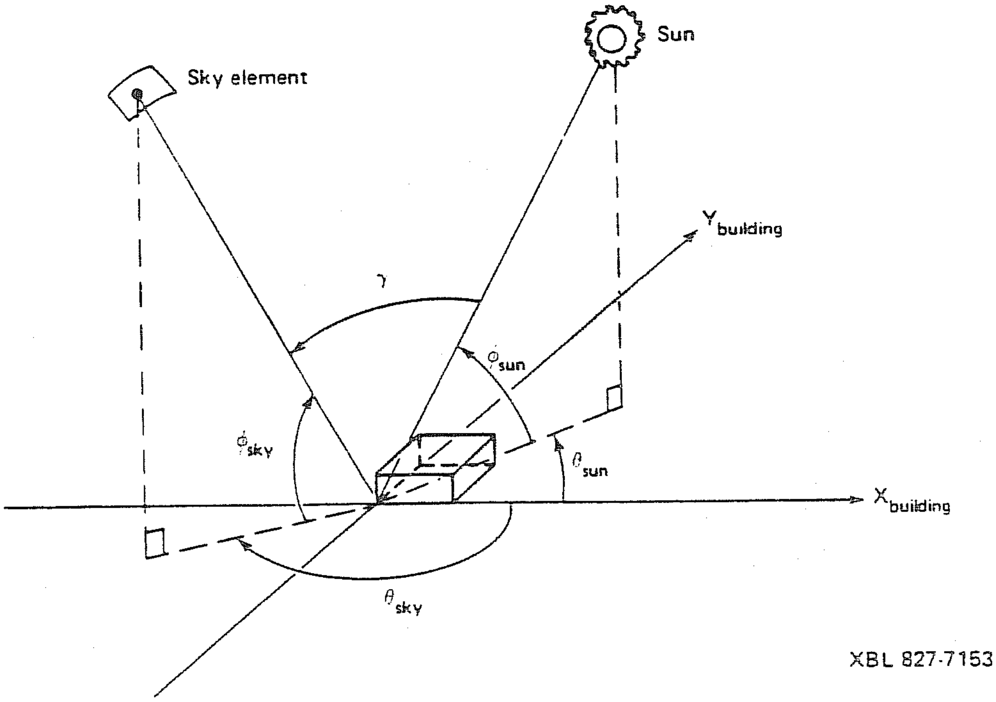


Fig. 4. Angles used in clear sky luminance distribution.

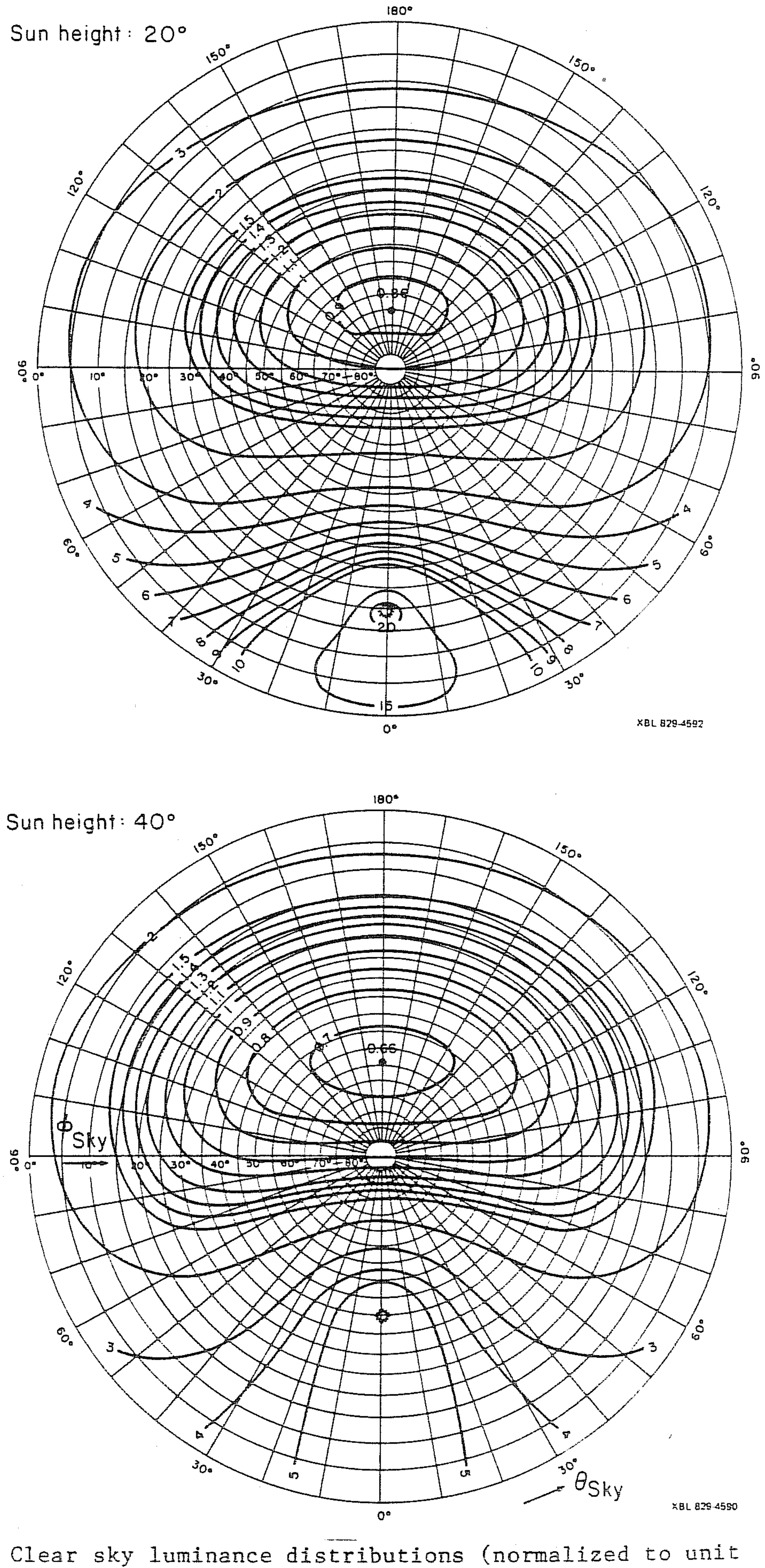
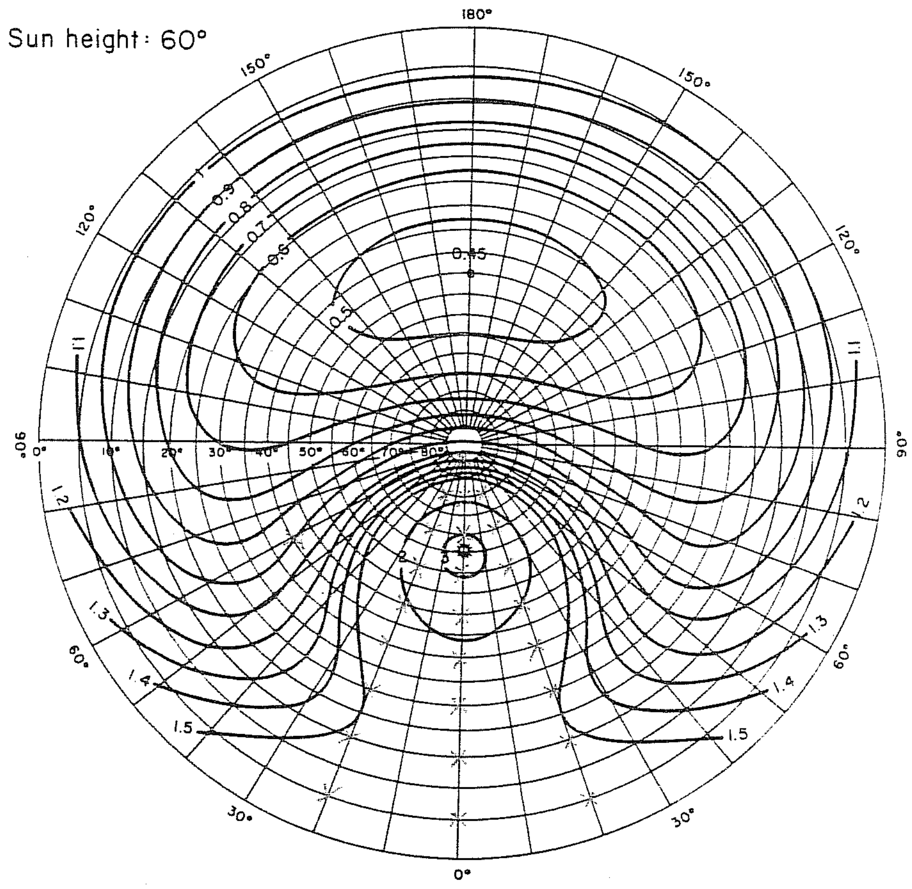


Fig. 5. Clear sky luminance distributions (normalized to unit zenith luminance) for different solar altitudes [Ref. 3].



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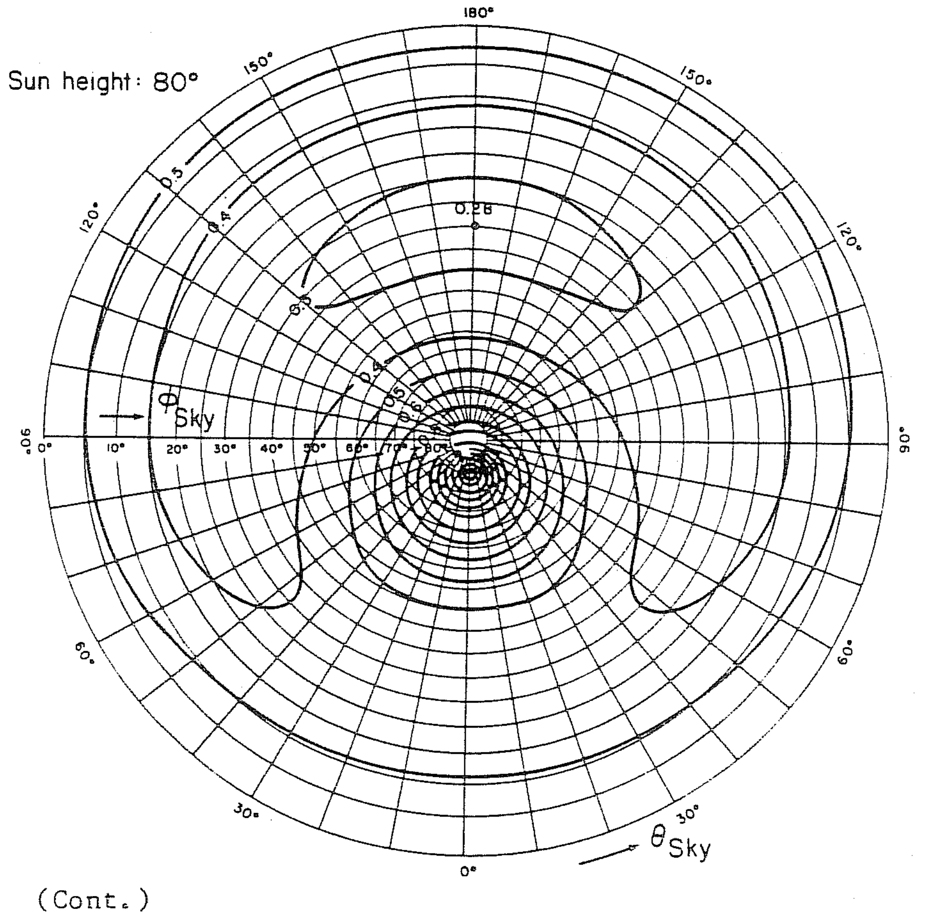

Fig. 5. (Cont.)

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ϕ_{sun} = altitude of sun,
L_z = luminance of sky at zenith,
γ = angle between sun and sky element.

The various angles, which are defined in the building coordinate system, are shown in Fig. 4. The angle γ between sun and sky element is given by

$$\gamma = \cos^{-1}[\sin\phi_{sky}\sin\phi_{sun}+\cos\phi_{sky}\cos\phi_{sun}\cos(\theta_{sky}-\theta_{sun})] \tag{2}$$

Contour plots of $L(\theta_{sky}, \phi_{sky})/L_z$ are shown in Fig. 5 for solar altitude angles of 20°, 40°, 60°, and 80° (reproduced from Ref. 3). A three-dimensional plot of $L(\theta_{sky}, \phi_{sky})/L_z$ as measured by Liebelt (Ref. 4) for $\phi_{sun}=27^o$ is shown in Fig. 6. From these figures, the general characteristics of the distribution are seen to be a large peak near the sun; a minimum at a point on the other side of the zenith from the sun, in the vertical plane containing the sun; and an increase in luminance as the horizon is approached.

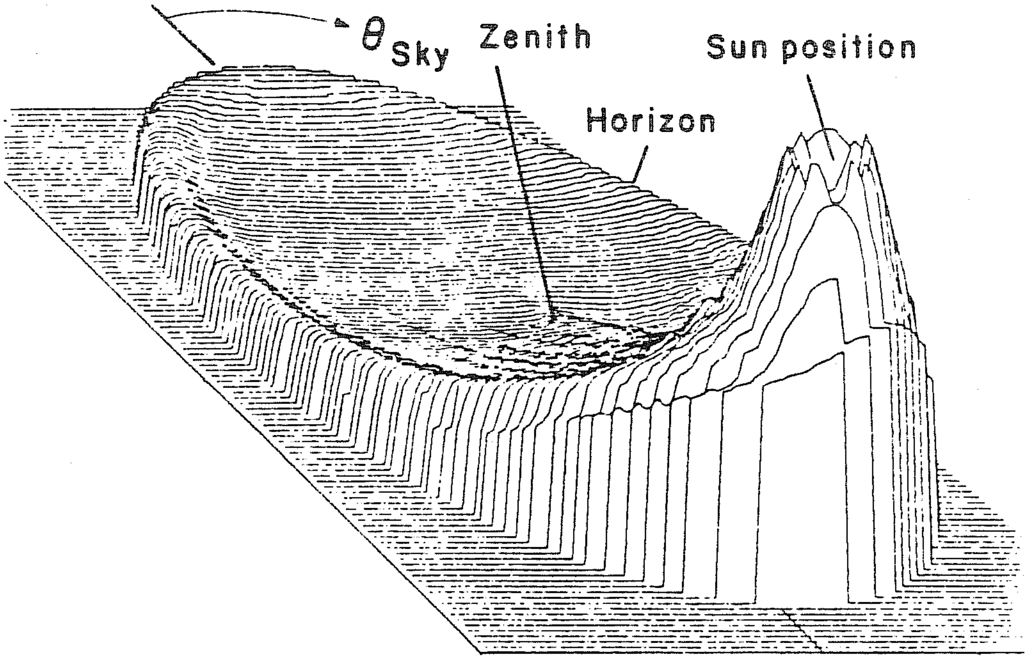

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Fig. 6. Clear sky luminance distribution as measured by Liebelt [Ref. 4] for a solar altitude of 27°.

The zenith luminance in Eq. 1 is given by

$$L_z[\text{kcd/m}^2] = (1.34T-3.46)\tan\phi_{sun}+0.10T+0.90,\ \phi_{sun} \le 60^o,\ T > 3 \tag{3}$$
$$= 0.56\tan\phi_{sun}+1.2,\ \phi_{sun} \le 60^o,\ T \le 3$$

where T is Linke's turbidity factor. This equation was was derived by Liebelt (Ref. 4) from measurements made in Germany at 49° North Latitude.

For $\phi_{sun}>60^o$, where Eq. 3 is invalid, L_z is found by constraining the horizontal illuminance, E_{hcl}, to increase as $\sin\phi_{sun}$, i.e.

$$E_{hcl}\ (\phi_{sun} \geq 60^o) = \frac{E_{hcl}\ (60^o)\ \sin\phi_{sun}}{\sin 60^o}$$

The correlation between L_z and E_{hcl} is found by integrating Eq. 1 over the skydome to obtain E_{hcl}:

$$\begin{aligned} E_{hcl}(\phi_{sun},T) &= \int L(\theta_{sky},\phi_{sky})\ \sin\phi_{sky}\ d\Omega_{sky} \\ &= L_z\ (\phi_{sun},T)\ A(\phi_{sun})\ , \end{aligned}$$

where $A(\phi_{sun})$ is the integral over the right-hand side of Eq. 1 excluding the L_z factor. We have then

$$\begin{aligned} L_z(\phi_{sun},T) &= \frac{E_{hcl}(\phi_{sun},T)}{A(\phi_{sun})} \\ &= \frac{L_z(60^o,T)\ A(60^o)\ \sin\phi_{sun}}{A(\phi_{sun})\ \sin 60^o}\ , \quad \phi_{sun} \geq 60^o \end{aligned}$$

Fig. 13 of Ref. 19 shows that A decreases almost quadratically above 60°. It can be approximated to a few percent by

$$A(\phi_{sun}) = 3.25 - .1050(\phi_{sun}-60) + .0010(\phi_{sun}-60)^2,$$

$\phi_{sun} \geq 60^o.$

Thus,

$$L_z(\phi_{sun},T) = \frac{3.25 L_z(60^o)\sin\phi_{sun}}{[3.25-.1050(\phi_{sun}-60)+.0010(\phi_{sun}-60)^2]\sin 60^o},$$

$$\phi_{sun} \geq 60^o. \qquad (4)$$

The turbidity factor, T, relates the direct normal solar illuminance at the earth's surface, E_{DN}, to the extraterrestrial direct normal illuminance, E^o_{DN}, according to

$$E_{DN} = E^o_{DN}\ e^{-\bar{a}_R m T} \qquad (5)$$

where

$\overline{a}_R$ = atmospheric extinction coefficient due to Rayleigh scattering
m = optical air mass of atmosphere.

T is a measure of the aerosol and moisture content of the atmosphere. It has been empirically determined by Dogniaux (Refs. 5 and 6) to have the form

$$T = \left[\frac{\phi_{sun,deg} + 85}{39.5\ e^{-w} + 47.4} + 0.1 \right] + (16 + 0.22w)\ \beta \qquad (6)$$

where

w = amount of precipitable moisture in the atmosphere [cm]
β = Angstrom's turbidity coefficient.

The value of T ranges from about 2 for a very clean, dry atmosphere, to 5 and above for moist, polluted conditions. w and β vary with time and with geographical location. In DOE-2, monthly average values of w and β are entered. Tables 3 and 4 list monthly average values of w and β for different locations in the United States (Refs. 7, 8, and 9). As described in Refs. 6 and 8, w is determined by integrating radiosonde measurements of moisture content at different altitudes, and β is found from sunphotometer measurements by comparing, at specific wavelengths, direct normal solar irradiance at the earth's surface with the corresponding extraterrestrial irradiance, taking into account the optical air mass.

Table 3

Monthly Average Atmospheric Moisture (inches of water) for U.S. Cities

City	Month											
	J	F	M	A	M	J	J	A	S	O	N	D
Montgomery, AL	.65	.56	.65	.85	1.00	1.31	1.58	1.60	1.39	.95	.67	.69
Ft. Smith, AR	.48	.47	.56	.78	1.08	1.39	1.66	1.56	1.16	1.03	.53	.48
Little Rock, AR	.51	.46	.55	.81	.94	1.26	1.47	1.42	1.29	.86	.63	.59
Ft. Huachuca, AZ	.27	.27	.24	.26	.36	.59	1.01	1.01	.73	.48	.31	.27
Phoeniz, AZ	.42	.38	.38	.45	.51	.67	1.29	1.31	.92	.63	.43	.40
China Lake, CA	.28	.25	.28	.34	.38	.40	.66	.68	.47	.33	.29	.32
Point Mugu, CA	.46	.45	.48	.51	.65	.79	1.04	.97	.89	.69	.54	.49
San Diego, CA	.46	.46	.47	.50	.60	.71	.98	1.04	.83	.62	.60	.48
San Nicolas Is., CA	.47	.42	.43	.42	.52	.65	.85	.80	.73	.61	.53	.46
Santa Maria, CA	.48	.48	.48	.52	.61	.68	.82	.80	.74	.63	.55	.49
Santa Monica, CA	.48	.51	.49	.56	.65	.75	.93	.95	.85	.72	.54	.50
Oakland, CA	.52	.49	.48	.45	.53	.63	.64	.67	.64	.59	.61	.50
Denver, CO	.20	.19	.21	.27	.41	.57	.75	.71	.51	.35	.25	.20
Grand Junction, CO	.25	.24	.24	.28	.39	.51	.73	.72	.52	.41	.31	.26
Key West, FL	1.04	1.03	1.06	1.13	1.34	1.65	1.64	1.71	1.78	1.53	1.20	1.05
Cocoa Beach, FL	.86	.85	.95	1.03	1.26	1.60	1.73	1.79	1.76	1.37	1.02	.90
Miami, FL	.96	.95	1.00	1.10	1.31	1.64	1.69	1.74	1.77	1.50	1.16	1.10
Atlanta, GA	.54	.52	.56	.72	.95	1.26	1.48	1.45	1.20	.83	.59	.54
Boise, ID	.35	.32	.30	.34	.44	.59	.60	.60	.52	.42	.40	.32
Peoria, IL	.30	.31	.37	.55	.76	1.02	1.17	1.13	.96	.65	.46	.36
Salem, IL	.31	.35	.41	.57	.72	1.09	1.19	1.19	1.12	.74	.46	.42
Joliet, IL	.36	.32	.40	.53	.76	1.11	1.21	1.12	.88	.66	.43	.35
Dodge City, KS	.28	.27	.30	.42	.61	.86	1.09	1.04	.81	.53	.37	.30
Lake Charles, LA	.74	.72	.77	.95	1.17	1.45	1.70	1.67	1.50	1.05	.83	.78
Boothville, LA	.82	.72	.78	1.00	1.13	1.41	1.69	1.72	1.60	1.17	.87	.94
Nantucket, MA	.38	.36	.40	.53	.73	.97	1.15	1.26	.95	.71	.56	.42
Caribou, ME	.23	.22	.26	.36	.55	.79	.95	.90	.74	.55	.40	.27
Portland, ME	.30	.29	.33	.46	.66	.93	1.08	1.05	.87	.63	.49	.34
Sault Ste. Marie, MI	.23	.22	.27	.39	.57	.83	.92	.93	.78	.58	.39	.28
Flint, MI	.27	.26	.31	.46	.64	.89	.99	.97	.86	.61	.43	.33
Int'l Falls, MN	.19	.19	.23	.35	.52	.77	.90	.87	.68	.49	.30	.22
St. Cloud, MN	.22	.23	.27	.42	.63	.86	1.00	.99	.77	.56	.34	.26
Columbia, MO	.36	.32	.42	.62	.78	1.10	1.23	1.21	.98	.70	.52	.42
Jackson, MS	.59	.60	.65	.87	1.05	1.36	1.59	1.56	1.36	.92	.71	.65
Great Falls, MT	.23	.22	.23	.27	.39	.54	.58	.58	.46	.34	.28	.23
Glasgow, MT	.23	.24	.25	.34	.49	.68	.77	.73	.57	.42	.31	.25
North Platte, NB	.26	.28	.30	.41	.62	.85	1.02	.99	.72	.49	.33	.28
Omaha, NB	.28	.29	.35	.50	.74	1.03	1.18	1.13	.87	.62	.40	.31
Greensboro, NC	.47	.45	.50	.65	.90	1.18	1.39	1.37	1.11	.77	.55	.47
Cape Hatteras, NC	.59	.52	.56	.70	.96	1.20	1.57	1.57	1.25	.97	.67	.63
Bismarck, ND	.22	.24	.26	.38	.56	.81	.93	.88	.65	.47	.31	.25
Rapid City, ND	.26	.26	.28	.37	.53	.75	.87	.81	.59	.42	.30	.26
Ely, NE	.21	.20	.20	.22	.31	.42	.54	.57	.38	.29	.26	.21
Albuquerque, NM	.21	.20	.21	.24	.33	.47	.80	.79	.58	.38	.27	.22
Albany, NY	.30	.28	.35	.48	.70	.98	1.11	1.10	.93	.65	.49	.36
Buffalo, NY	.30	.29	.34	.47	.66	.91	1.04	1.02	.87	.63	.46	.35

New York City, NY	.34	.33	.40	.54	.76	1.02	1.18	1.16	1.01	.69	.55	.42
Dayton, OH	.33	.33	.39	.56	.74	1.00	1.13	1.08	.93	.65	.47	.38
Medford, OR	.46	.42	.40	.41	.51	.65	.67	.67	.59	.52	.53	.43
Salem, OR	.52	.48	.45	.47	.56	.71	.73	.76	.70	.62	.60	.51
Pittsburgh, PA	.34	.32	.38	.52	.72	.97	1.09	1.06	.90	.63	.47	.37
Charleston, SC	.65	.63	.68	.83	1.11	1.42	1.67	1.66	1.43	1.02	.75	.66
Nashville, TN	.45	.41	.49	.70	.85	1.13	1.33	1.31	1.19	.77	.55	.53
Amarillo, TX	.28	.26	.30	.39	.55	.80	1.03	1.00	.80	.52	.37	.30
El Paso, TX	.29	.28	.30	.33	.44	.67	.98	1.00	.83	.52	.37	.32
Midland, TX	.34	.33	.37	.48	.65	.89	1.06	1.10	.97	.64	.44	.36
Ft. Worth, TX	.48	.51	.58	.80	1.06	1.32	1.48	1.46	1.28	.90	.65	.54
Del Rio, TX	.53	.55	.59	.85	1.09	1.33	1.39	1.43	1.37	1.01	.70	.55
Brownsville, TX	.90	.90	.94	1.12	1.31	1.48	1.57	1.60	1.64	1.31	1.07	.96
Salt Lake City, UT	.29	.26	.25	.30	.40	.54	.66	.66	.50	.38	.34	.27
Quillayute - Tatoosh Is., WA	.46	.47	.44	.48	.57	.71	.77	.82	.75	.67	.55	.50
Green Bay, WI	.23	.23	.28	.44	.63	.89	1.02	.99	.82	.60	.39	.28
Huntington, WV	.39	.37	.47	.62	.82	1.08	1.25	1.19	1.04	.72	.53	.45
Lander, WY	.18	.17	.18	.24	.33	.47	.54	.53	.40	.29	.23	.18

Source: George A. Lott, "Precipitable Water Over the United States, Volume 1: Monthly Means", National Oceanic and Atmospheric administration Technical Report NWS 20, November 1976.

Table 4

Monthly Average Atmospheric Turbidity for U. S. Cities

City	Source	Month											
		J	F	M	A	M	J	J	A	S	O	N	D
Eielson AB, AL	2	.03	.03	.11	.11	.20	.07	.09	.12	.07	.04	.04	.04
Little Rock, AR	2	.11	.16	.17	.22	.22	.20	.22	.20	.19	.13	.10	.09
Tucson, AZ	1	.05	.05	.06	.07	.07	.07	.07	.07	.07	.06	.06	.07
Los Angeles, CA	1	.11	.14	.15	.16	.18	.21	.20	.21	.19	.17	.11	.11
Edwards AFB, CA	2	.02	.02	.06	.09	.09	.08	.08	.08	.07	.06	.04	.04
Boulder, CO	1	.04	.05	.07	.09	.08	.07	.07	.07	.07	.05	.05	.04
Alamosa, CO	2	.09	.11	.12	.15	.13	.10	.10	.06	.07	.07	.07	.07
Washington, DC	1	.11	.12	.15	.17	.19	.21	.24	.20	.17	.13	.13	.13
Tallahassee, FL	2	.12	.18	.19	.20	.28	.34	.35	.25	.25	.19	.18	.12
Miami, FL	2	.19	.29	.30	.31	.36	.54	.51	.55	.40	.33	.31	.24
Idaho Falls, ID	1	.03	.04	.06	.07	.07	.07	.06	.06	.06	.05	.04	.03
Chicago, IL	1	.15	.18	.21	.18	.18	.19	.22	.16	.16	.14	.13	.15
Salem, IL	2	.09	.10	.16	.17	.21	.22	.23	.21	.17	.16	.10	.09
Topeka, KS	1	.05	.07	.07	.07	.09	.12	.09	.07	.07	.06	.04	.04
Blue Hill, MA	1	.07	.07	.09	.11	.13	.16	.17	.13	.08	.07	.07	.06
Baltimore, MD	1	.12	.18	.18	.19	.22	.27	.31	.32	.31	.12	.17	.18
College Park, MD	2	.07	.08	.13	.17	.23	.21	.13	.23	.17	.13	.08	.07
St. Cloude, MN	2	.08	.06	.08	.13	.11	.09	.11	.10	.08	.06	.05	.05
St. Louis, MO	1	.12	.12	.16	.17	.21	.20	.22	.19	.19	.12	.12	.11
Meridian, MS	1	.07	.07	.07	.09	.12	.15	.15	.13	.11	.07	.07	.07
Missoula, MT	1	.06	.07	.07	.08	.09	.07	.07	.06	.09	.08	.07	.07
Greensboro, NC	1	.07	.08	.09	.11	.14	.24	.22	.21	.14	.08	.07	.07
Raleigh, NC	2	.06	.10	.10	.10	.12	.14	.24	.15	.13	.06	.06	.04
Bismarck, ND	2	.04	.02	.04	.08	.08	.07	.05	.06	.07	.08	.08	.05
Brookhaven, NY	1	.07	.07	.10	.11	.12	.14	.15	.11	.12	.07	.07	.07
Albany, NY	1	.10	.09	.11	.12	.14	.14	.15	.15	.14	.11	.10	.09
New York City, NY	1	.11	.11	.12	.15	.17	.22	.21	.24	.20	.15	.11	.11
Cincinnati, OH	1	.07	.09	.12	.13	.14	.20	.20	.19	.17	.12	.10	.08
Toledo, OH	2	.09	.08	.12	.11	.15	.13	.15	.11	.09	.05	.06	.06
Youngstown, OH	2	.14	.14	.16	.19	.25	.29	.22	.28	.22	.17	.15	.13
Pendleton, OR	2	.10	.12	.16	.20	.19	.19	.16	.15	.11	.09	.09	.09
Philadelphia, PA	1	.12	.15	.18	.20	.22	.25	.27	.23	.17	.15	.14	.14
Huron, SD	1	.04	.05	.07	.07	.08	.09	.08	.07	.07	.06	.05	.04
Memphis, TN	1	.08	.08	.10	.16	.15	.18	.19	.16	.16	.09	.10	.08
Oak Ridge, TN	2	.10	.14	.13	.17	.33	.26	.37	.31	.25	.13	.09	.09
College Stn., TX	1	.10	.10	.11	.12	.13	.08	.15	.12	.11	.09	.08	.07
Victoria, TX	2	.03	.03	.05	.02	.08	.08	.06	.05	.04	.04	.03	.02
Grand Prarie, TX	2	.07	.12	.16	.16	.36	.35	.36	.53	.45	.23	.19	.21
Green Bay, WI	2	.09	.09	.15	.16	.19	.17	.16	.10	.09	.10	.05	.06
Elkins, WV	1	.07	.07	.09	.14	.15	.21	.21	.19	.14	.07	.07	.07

Source: 1. E. C. Flowers, R. A. McCormick, and K. R. Kurfis, "Atmospheric Turbidity over the United States, 1961-66", Journal of Applied Meteorology, Vol. 8, No. 6, 1969, pp. 955-962.

2. "Global Monitoring of the Environment for Selected Atmospheric Constituents, 1977", Environmental Data and Information Service, National Climatic Center, Asheville, NC, June 1980.

Note: This table contains values for the Angstrom turbidity coefficient (β).

Overcast Sky

The standard overcast sky luminance distribution, which was originally derived by Moon and Spencer (Ref. 10) from empirical data, has the form

$$L_{oc}\ (\phi_{sky}) = L_{z,oc}\ \frac{1+2\ \sin\ \phi_{sky}}{3}\ , \qquad (7)$$

where $L_{z,oc}$, the zenith luminance derived by Krochmann (Ref. 11), is

$$L_{z,oc}\ [\mathrm{kcd/m^2}] = 0.123 + 8.6\ \sin\phi_{sun} \qquad (8)$$

This is plotted in Fig. 7.

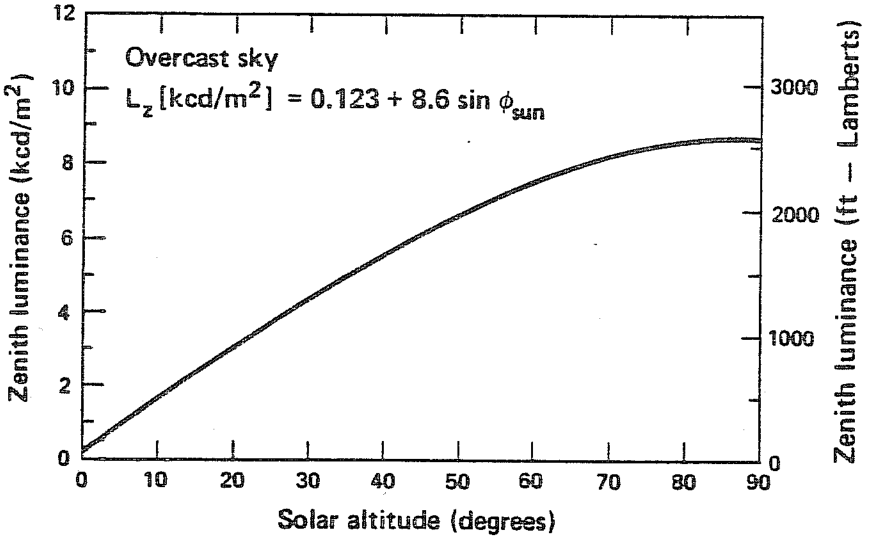

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Fig. 7. Overcast sky zenith luminance, L_z, according to Krochmann [Ref. 11].

From Eq. 7 we note that the overcast sky luminance distribution, unlike the clear sky case, does not depend on either the solar azimuth or the sky azimuth. We also note that, at fixed solar altitude, the zenith ($\phi_{sky} = \pi/2$) is three times brighter than the horizon ($\phi_{sky} = 0$).

2.5 Direct Normal Solar Illuminance, Clear Sky

The direct normal solar illuminance at the earth's surface under clear sky conditions is determined from Eq. 5. From Dogniaux (Ref. 5) we have the following parameterizations for E^o_{DN}, $\bar{a}_R$ and m:

$$\begin{aligned} E^o_{DN}\ [\mathrm{klx}] = {} & 126.82 + 4.248\ \cos\ \omega\ J + 0.08250\ \cos\ 2\omega\ J \\ & - 0.00043\ \cos 3\omega\ J + 0.1691\ \sin\ \omega\ J \\ & + 0.00914\ \sin\ 2\ \omega\ J + 0.01726\ \sin\ \omega\ J \end{aligned} \qquad (9)$$

where J is the number of the day of the year ($1 \leq J \leq 366$) and $\omega = 2\pi/366$. The dependence on J accounts for the variation of the solar constant with changing earth-sun distance.

$$\bar{a}_R = \begin{cases} 0.1512 - 0.0262T \text{ for } \beta < 0.075, \\ 0.1656 - 0.0215T \text{ for } 0.075 \leq \beta < 0.15, \\ 0.2021 - 0.0193T \text{ for } \beta \geq 0.015. \end{cases} \tag{10}$$

$$m = (1-0.1h)/[\sin\phi_{sun} + 0.15(\phi_{sun} + 3.885)^{-1.253}] , \tag{11}$$

where h is the building altitude in km.

2.6 Exterior Horizontal Illuminance

The illuminance, E_h, on an unobstructed horizontal plane due to diffuse radiation from the sky is calculated for clear sky and for overcast sky by integrating over the appropriate sky luminance distribution, L:

$$E_h = \int L(\theta_{sky},\phi_{sky}) \sin\phi_{sky} \, d\Omega_{sky} \tag{12}$$

$$= \int_0^{2\pi} \int_0^{\pi/2} L(\theta_{sky},\phi_{sky}) \sin\phi_{sky} \cos\phi_{sky} \, d\theta_{sky} \, d\phi_{sky} ,$$

where L is in cd/ft^2 (1 cd/ft^2 = π ft-Lamberts) and E_h is in lm/ft^2 (foot-candles). For the overcast-sky luminance distribution, Eq. 7, the integration in Eq. 12 can be done in closed form, yielding

$$E_{hoc} \text{ [footcandles]} = \frac{7\pi}{9} L_{z,oc} \text{ [cd/ft}^2\text{]} \tag{13}$$

Using Eq. 7 converted to cd/ft^2 (1 kcd/m^2=92.94 cd/ft^2), we have

$L_{z,oc}$ [cd/ft^2] = $11.4 + 799.3 \sin\phi_{sun}$ which gives

$$E_{hoc} \text{ [footcandles]} = 28 + 1953 \sin\phi_{sun} \tag{14}$$

This is plotted in Fig. 8.

For the clear sky luminance distribution, Eq. 1, the integral in Eq. 12 is replaced by a double summation:

$$E_{hcl} = \sum_{i=1}^{N_\theta} \sum_{j=1}^{N_\phi} L(\theta_{sky}(i),\phi_{sky}(j)) \sin\phi_{sky}(j) \cos\phi_{sky}(j) \Delta\theta_{sky} \, \Delta\phi_{sky} \tag{15}$$

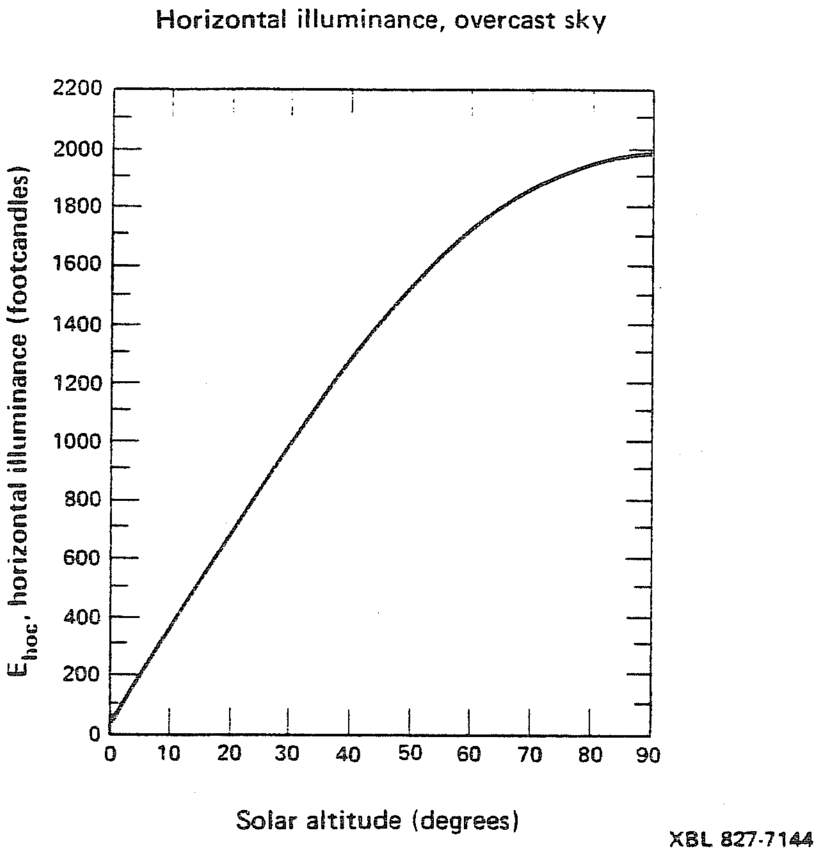

Fig. 8. Exterior horizontal illuminance from CIE overcast sky.

where

$$\theta_{sky}(i) = (i-\tfrac{1}{2})\Delta\theta_{sky},$$

$$\phi_{sky}(j) = (j-\tfrac{1}{2})\Delta\phi_{sky},$$

$$\Delta\theta_{sky} = \frac{2\pi}{N_\theta},$$

$$\Delta\phi_{sky} = \frac{\pi}{2N_\phi}.$$

$N_\theta = 9$ and $N_\phi = 4$ were found to give a ±5% accuracy in the calculation of E_{hcl}.

2.7 Direct Component of Interior Daylight Illuminance

The direct daylight illuminance at a reference point from a particular window is determined by dividing the window into an x-y grid and finding the flux reaching the reference point from each grid element. The geometry involved is shown in Fig. 9. The horizontal illuminance at the reference point, $\overline{R}_{ref}$, due to a window element is

$$dE_h \text{ [footcandles]} = L_w \text{ [cd/ft}^2\text{]} \, d\Omega \cos \gamma , \tag{16}$$

where

L_w = luminance of window element as seen from reference point,
$d\Omega$ = solid angle subtended by window element with respect to reference point,
γ = angle between vertical and ray from reference point to center of window element.

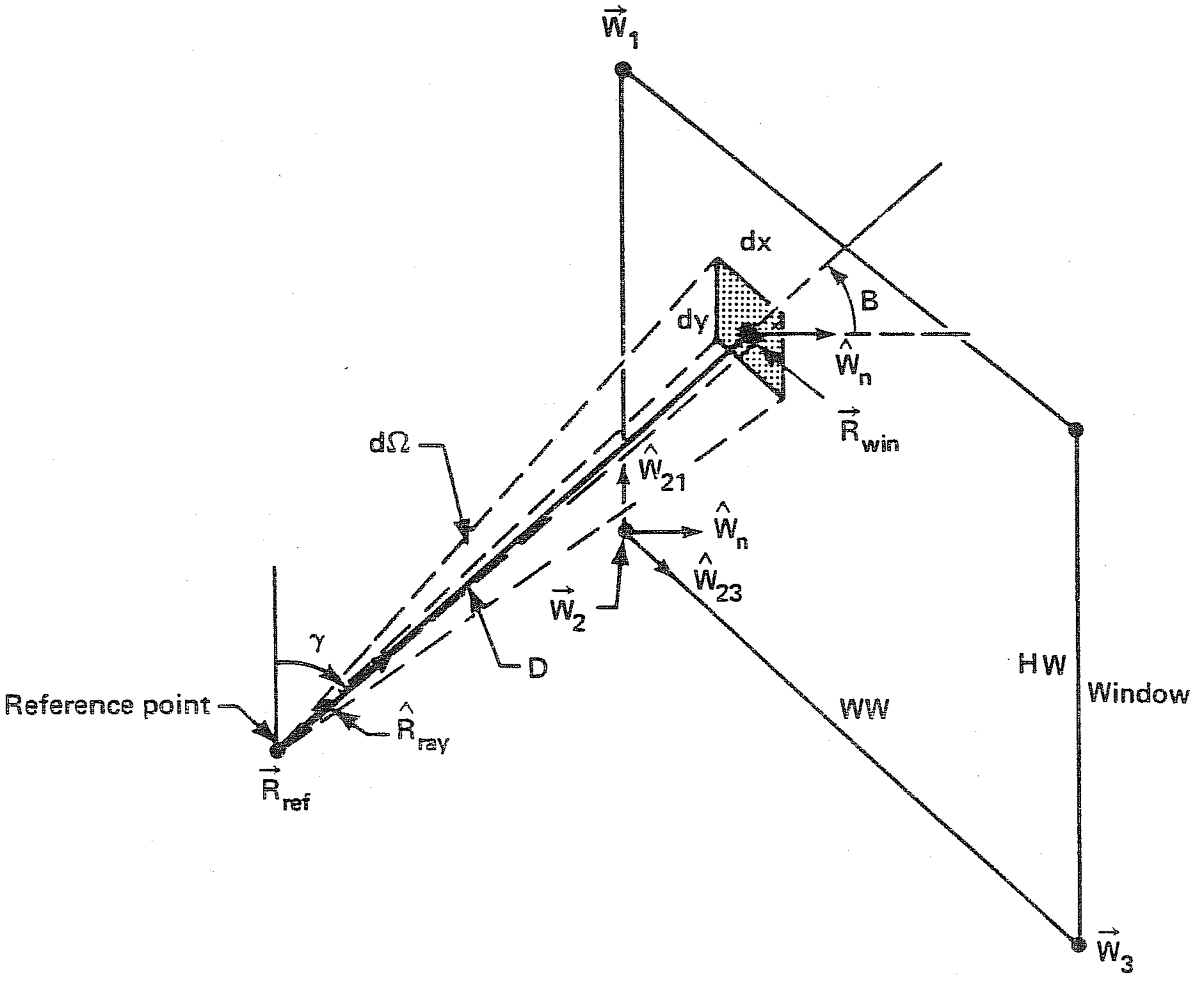

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Fig. 9. Geometry for calculation of direct component of daylight illuminance at a reference point. Vectors $\overline{R}_{ref}$, $\overline{W}_1$, $\overline{W}_2$, $\overline{W}_3$, and $\overline{R}_{win}$ are in the building coordinate system.

The subtended solid angle is approximated by

$$d\Omega = \frac{dx\ dy}{D^2} \cos B \qquad (17)$$

where

$$D = \left| \overline{R}_{win} - \overline{R}_{ref} \right|$$

dx = width of window element
dy = height of window element
B = angle between window outward normal and ray

cos B is found from

$$\cos B = \overline{R}_{ray} \cdot \overline{W}_n ,$$

where

$$\overline{R}_{ray} = (\overline{R}_{win} - \overline{R}_{ref}) / \left| \overline{R}_{win} - \overline{R}_{ref} \right|$$

$\overline{W}_n$ = window outward normal

$$= \overline{W}_{21} \times \overline{W}_{23}$$

$$= \frac{(\overline{W}_1 - \overline{W}_2)}{\left| \overline{W}_3 - \overline{W}_2 \right|} \times \frac{(\overline{W}_3 - \overline{W}_2)}{\left| W_3 - W_2 \right|} .$$

Eq. 17 becomes exact as $\frac{dx}{D}$, $\frac{dy}{D} \rightarrow 0$, and is accurate to better than ~1% for $dx \leq D/4$, $dy \leq D/4$.

The net illuminance from the window is obtained by summing the contributions from all the window elements:

$$E_h = \sum_{\substack{\text{window}\\ \text{elements}}} L_w \, d\Omega \cos \gamma \qquad (18)$$

In performing the summation, window elements which lie below the workplane ($\cos \gamma < 1$) are omitted since light from these elements cannot reach the workplane directly.

Bare window

For the bare window case, the luminance L_w of the window element is found by projecting the ray from reference point to window element and determining whether it intersects the sky, the ground, or an exterior obstruction (local or global building shade). It is assumed that there are no internal obstructions. If L is the corresponding luminance of sky, ground, or exterior obstruction, the window luminance is

$$L_w = L\tau_{vis}(\cos B) ,$$

where τ_{vis} is the visible transmittance of the glass for incidence angle B. This transmittance is calculated from

$$\tau_{vis}(\cos B) = \frac{\tau_{vis}(\cos B=1)}{\tau_{sol}(\cos B=1)} \tau_{sol}(\cos B) , \quad (19)$$

where τ_{sol} is the glass transmittance for the total solar spectrum. This assumes that the visible transmittance has the same angular dependence as the total solar transmittance.

Window with Shade

For the window-plus-shade case, the shade is assumed to be a perfect diffuser, i.e., the luminance of the shade is independent of angle of emission of light, position on shade, and angle of incidence of exterior light falling on the shade. Closely-woven drapery fabric and translucent shades are closer to being perfect diffusers than Venetian blinds and other slatted devices, which tend to have non-uniform luminance characteristics.

The calculation of the shade luminance, L_{sh}, is described in Section 2.10 (see, in particular, Eq. 34). The illuminance contribution at the reference point from a shade element is then given by Eq. 16 with $L_w=L_{sh}$ if shade is inside the window, or $L_w=L_{sh}\ \tau_{vis}(\cos B)$ if shade is outside the window. It should be noted that at this point in the calculation the shade transmittance is taken to be 1.0. The actual shade transmittance, which can be scheduled, is accounted for in the hourly LOADS calculation.

2.8 Internally Reflected Component of Interior Daylight Illuminance

Daylight reaching a reference point after reflection from interior surfaces is calculated using the "split-flux" method (Refs. 12 and 13). In this method, the daylight transmitted by the window is split into two parts -- a downward-going flux, Φ_{FW} [lm], which falls on the floor and portions of the walls below the imaginary horizontal plane passing through the center of the window ("window midplane"), and an upward-going flux Φ_{CW} [lm], which strikes the ceiling and portions of the walls above the window midplane (see Fig. 10). A fraction of Φ_{FW} and Φ_{CW} is absorbed by the room surfaces. The remainder, the first-reflected flux, F_1, is approximated by

$$F_1 = \Phi_{FW}\,\rho_{FW} + \Phi_{CW}\,\rho_{CW} , \quad (20)$$

where ρ_{FW} is the area-weighted average reflectance of the floor and those parts of the walls below the horizontal plane through the window center, and ρ_{CW} is the area-weighted average reflectance of the ceiling and those parts of the walls above the window mid-plane.

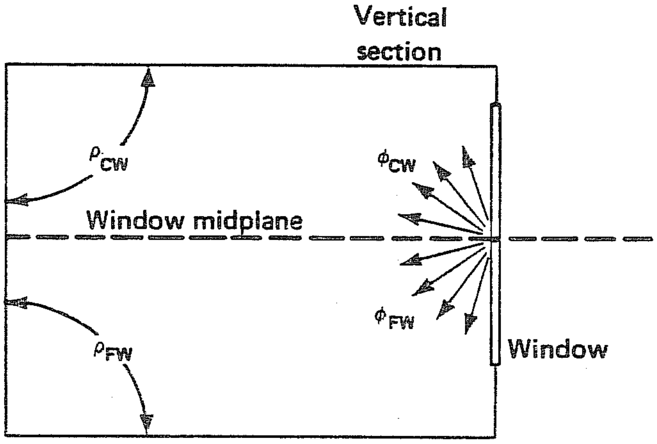

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Fig. 10. Vertical section showing up- and down-going transmitted fluxes, ϕ_{CW} and ϕ_{FW}, used in split-flux calculation of the internally-reflected component of interior illuminance.

To find the final average internally-reflected illuminance E_r on the room surfaces (which in this method is uniform throughout the room) a flux balance is used. The total reflected flux absorbed by the room surfaces (or lost through the window(s)) is $AE_r(1 - \rho)$, where A is the total inside surface area of the floors, walls, ceiling, and windows in the room, and ρ is the area-weighted average reflectance of the room surfaces, including windows. From conservation of energy,

$$F_l = A\ E_r\ (1-\rho) \tag{21}$$

Using Eq. 20,

$$E_r\ [\text{lm/unit-area}] = \frac{\Phi_{FW}\ \rho_{FW} + \Phi_{CW}\ \rho_{CW}}{A(1-\rho)} \tag{22}$$

This procedure assumes that the room behaves like an integrating sphere with perfectly diffusing interior surfaces and with no internal obstructions. It therefore works best for rooms which are close to cubical in shape, have matte surfaces (which is usually the case), and have no internal partitions. Deviations from these conditions, such as would be the case for rooms whose depth measured from the window-wall is more than three times greater than ceiling height, can lead to substantial inaccuracies in the split-flux calculation.

2.9 Calculation of Average Internal Reflectances

The average reflectances ρ_{CW} and ρ_{FW} in Eq. 22 are calculated as follows. The interior surfaces of EXTERIOR WALLs, ROOFs, INTERIOR-WALLs, UNDERGROUND-FLOORs, and UNDERGROUND-WALLs are divided into three categories according to TILT angle:

"wall" (W) : $10^\circ \leq \text{TILT} \leq 170^\circ$; floor-wall-ceiling flag = 0;

"ceiling" (C) : $0^\circ \leq \text{TILT} < 10^\circ$; floor-wall-ceiling flag = 1;

"floor" (F) : $170^\circ < \text{TILT} \leq 180^\circ$; floor-wall-ceiling flag = 2.

Then

$$\rho_{FW} = \frac{\sum_{i=1}^{N_F} \rho_{F,i}\, A_{F,i} + \sum_{i=1}^{N_W} \rho_{W,i}\, A_{W,i}\, \delta}{\sum_{i=1}^{N_C} A_{F,i} + \sum_{i=1}^{N_W} A_{W,i}\, \delta} \qquad (23)$$

$$\rho_{CW} = \frac{\sum_{i=1}^{N_C} \rho_{C,i}\, A_{C,i} + \sum_{i=1}^{N_W} \rho_{W,i}\, A_{W,i}\, (1-\delta)}{\sum_{i=1}^{N_C} A_{C,i} + \sum_{i=1}^{N_W} A_{W,i}\, (1-\delta)} \qquad (24)$$

$$\rho = \frac{\sum_{i=1}^{N_F} \rho_{F,i}\, A_{F,i} + \sum_{i=1}^{N_W} \rho_{W,i}\, A_{W,i} + \sum_{i=1}^{N_C} \rho_{C,i}\, A_{C,i}}{A} \qquad (25)$$

$$A = \sum_{i=1}^{N_F} A_{F,i} + \sum_{i=1}^{N_W} A_{W,i} + \sum_{i=1}^{N_C} A_{C,i} \qquad (26)$$

where

N_W, N_C, N_F = number of surfaces in "wall", "ceiling", "floor" categories, respectively,

$\rho_{W,i}$, etc. = inside visible reflectance

$A_{W,i}$, etc. = surface area

$\delta_{W,i}$ = fraction of wall area which lies below the window midplane (ratio of floor-to-window-center height to average floor-to-ceiling height)

The sums in Eq. 23 and 24 exclude the window-wall which is producing the incoming fluxes ϕ_{FW} and ϕ_{CW}. For walls containing windows, the $\rho_{W,i}$ is the area-weighted average reflectance of the opaque and window portions of the wall.

2.10 Calculation of Transmitted Flux from Sky and Ground (Subroutine DREFLT)

The luminous flux incident on the center of the window from a luminous element of sky, ground, or external obstruction at angular position (θ,ϕ), of luminance $L(\theta,\phi)$, and subtending a solid angle $\cos\phi d\theta d\phi$ is

$$d\Phi_{inc} = A_W L(\theta,\phi) \cos\beta \cos\phi d\theta d\phi \tag{27}$$

where A_W is the window area, and $d\Phi_{inc}$ is in lm if L is in cd/ft^2. The transmitted flux is

$$d\Phi = d\Phi_{inc} T(\beta), \tag{28}$$

where $T(\beta)$ is the window transmittance for light at incidence angle β. The value of $T(\beta)$ depends on whether or not the window has a shade and if so, whether the shade is inside or outside the window.

For a bare window, $T(\beta) = \tau_{vis}(\beta)$, the glass visible transmittance. For a window with an interior shading device, $T(\beta) = \tau_{vis}(\beta)\ \tau_{sh}$, where τ_{sh} is the visible transmittance of the shade, which is assumed to be independent of angle of incidence. For a window with an exterior shade, $T(\beta) = \tau_{sh}\tau_{vis,diff}$, where $\tau_{vis,diff}$, is the hemispherical visible transmittance of the glass for diffuse radiation. In this last case, the light transmitted by shade and incident on the glass is assumed to be diffuse, so that $\tau_{vis,diff}$ is used rather than $\tau_{vis}(\beta)$. For the calculation of daylight factors, τ_{sh} is taken to be 1.0. The actual value of the shade transmittance, which can be scheduled, is used in the hourly LOADS calculation.

For a bare window the total downgoing transmitted flux, Φ_{FW}, is obtained by integrating over the part of the exterior hemisphere seen by the window which lies above the window midplane (see Fig. 11). This gives

$$\Phi_{FW,bare} = A_w \int_{\theta_{min}}^{\theta_{max}} \int_{0}^{\pi/2} L(\theta,\phi)\cos\beta T(\beta) \quad \cos\phi d\theta d\phi \tag{29}$$

The upgoing flux is similarly obtained by integrating over the part of the exterior hemisphere which lies below the window midplane:

$$\Phi_{CW,bare} = A_W \int_{\Theta_{min}}^{\Theta_{max}} \int_{\frac{\pi}{2}-\phi_W}^{0} L(\Theta,\phi)\cos\beta T(\beta)\ \cos\phi d\Theta d\phi \qquad (30)$$

where ϕ_W is the angle the window outward normal makes with the horizontal plane.

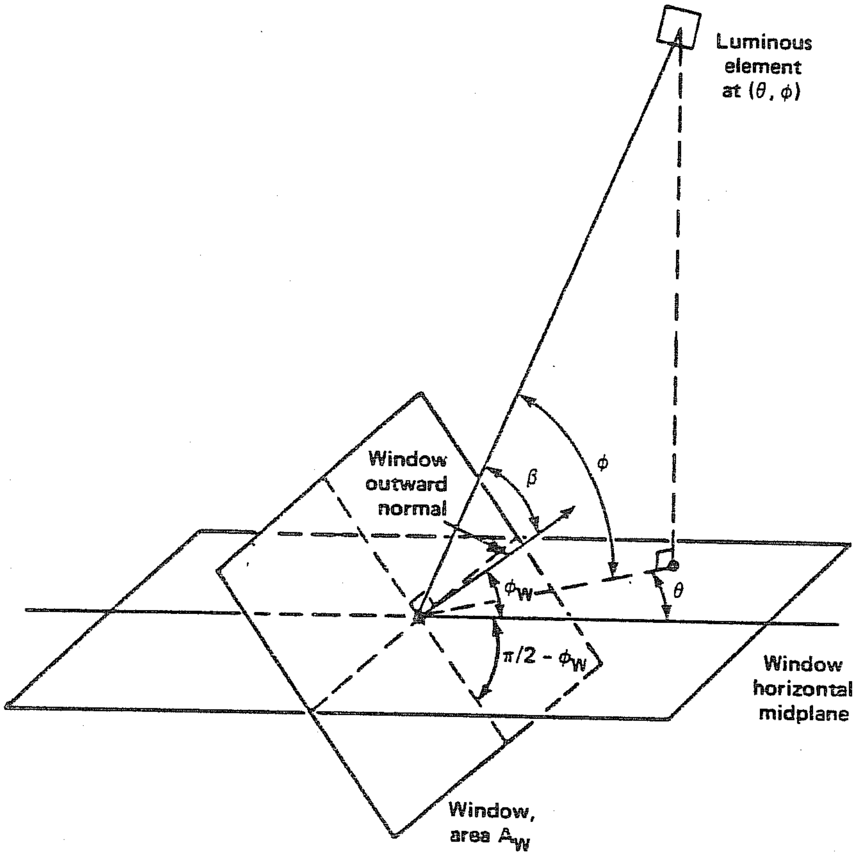

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Fig. 11. Geometry for integration over exterior luminance to obtain up- and down-going transmitted flux.

For a window with a diffusing shade, the total transmitted flux is

$$\Phi = A_W \int_{\Theta_{min}}^{\Theta_{max}} \int_{\frac{\pi}{2}-\phi_W}^{\pi/2} L(\Theta,\phi)\ \cos\beta T(\beta)\ \ \cos\phi d\Theta d\phi \qquad (31)$$

The up- and down-going portions of this flux are

$$\Phi_{FW,sh} = \Phi\ (1 - f)$$
$$\Phi_{CW,sh} = \Phi\ f$$

where f is the fraction of the hemisphere seen by the inside of the window which lies above the window midplane. In terms of ϕ_w,

$$f = 0.5 - \phi_w/\pi \qquad (32)$$

For a vertical window (ϕ_w=0), f=0.5 and the up- and down-going transmitted fluxes are equal:

$$\Phi_{FW,sh} = \Phi_{CW,sh} = \Phi/2.$$

For a horizontal skylight ($\Phi_w=\pi/2$), f = 0, giving $\Phi_{FW,sh}=\Phi$, $\Phi_{CW,sh}=0$.

The limits of integration of θ in Eqs. 29, 30, and 31 depend on φ. From Fig. 12 we have, for a window with tilt ϕ_w:

$$\sin \alpha = \sin(A-\pi/2) = \frac{\sin \phi \tan \phi_w}{\cos \phi},$$

which gives

$$-\cos A = \tan\phi \tan\phi_w ,$$

or

$$A = \cos^{-1} \left[\tan\phi \tan\phi_w\right]$$

thus,

$$\theta_{min} = -\left|\cos^{-1} (-\tan\phi \tan\phi_w)\right| , \qquad \phi < \frac{\pi}{2} - \phi_w$$

$$\theta_{max} = \left|\cos^{-1} (-\tan\phi \tan\phi_w)\right|$$

Calculation of Transmitted Flux from Direct Sun

The incident luminous flux from direct sun striking the window is

$$\Phi_{inc} = A_W E_{DN} \cos\beta (1-f_{shaded}) , \cos\beta \geq 0 \qquad (33)$$
$$= 0 , \cos\beta < 0 ,$$

where

E_{DN} = direct normal solar illuminance,
A_W = window area,
β = angle of incidence,
f_{shaded} = fraction of window which is shaded by obstructions (fins, overhangs, BUILDING-SHADEs, etc.).

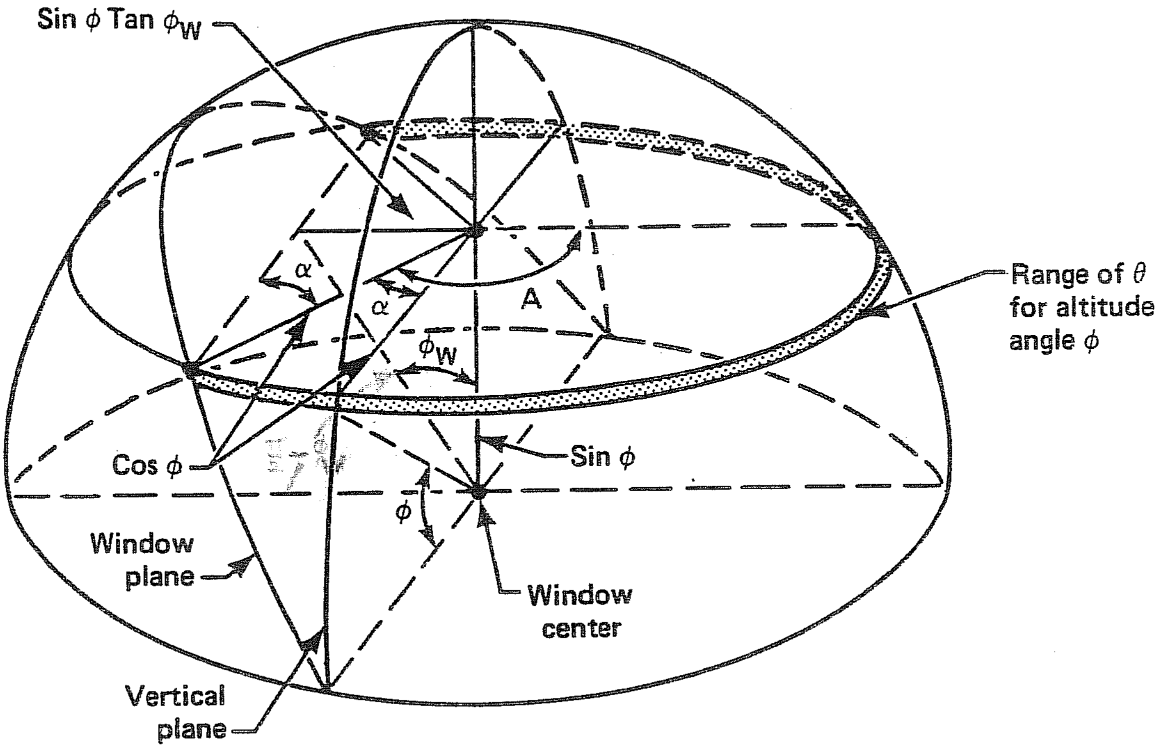

Fig. 12. Geometry for calculation of integration limits in Eqs. 29, 30, and 31.

The transmitted flux is

$$\Phi = T(\beta)\Phi_{inc},$$

where T (β) is the net transmittance of the window (plus window shade, if present). For a bare window

$$\Phi_{FW,bare} = \Phi ,$$

$$\Phi_{CW,bare} = 0 ,$$

i.e., all of the transmitted flux is downward since the sun always lies above the window midplane. For a window with a diffusing shade,

$$\Phi_{FW,sh} = \Phi\ (1-f),$$

$$\Phi_{CW,sh} = \Phi\ f ,$$

where f is given by Eq. 32.

Window Shade Luminance

Window shade luminance is determined at the same time that the transmitted flux is calculated. The shade luminance, incident flux from sky and ground (in lm/ft^2) multiplied by the shade transmittance (which gives ft-L) divided by π (which gives cd/ft^2). For a shade transmittance of 1.0, we then have (compare Eq. 29 and 30).

$$L_{sh}\ [cd/ft^2] = \frac{1}{\pi} \int_{\Theta_{min}}^{\Theta_{max}} \int_{\frac{\pi}{2} - \phi_w}^{\pi/2} L(\Theta,\phi)\cos\beta T_m \cos\phi \, d\Theta d\phi \qquad (34)$$

where

T_m = 1.0 if shade is outside window
= $T(\beta)$ if shade is inside window

2.11 Daylight Discomfort Glare

The discomfort glare at a reference point due to luminance contrast between a window and the interior surfaces surrounding the window is determined by using the Cornell-BRS "large-source" formula derived by Hopkinson (Refs. 14 and 15). This formula gives

$$G = \frac{L_w^{1.6} \ \Omega^{0.8}}{L_b + 0.07 \ \omega^{0.5} \ L_w} \qquad (35)$$

where

G = discomfort glare constant,

L_w = average luminance of the window as seen from the reference point (ft-L),

ω = solid angle subtended by window with respect to reference point,

Ω = solid angle subtended by the window, modified to take direction of occupant view into account,

L_b = luminance of the background area surrounding the window (ft-L).

By dividing the window into N_x by N_y rectangular elements, as is done for calculating the direct component of interior illuminance (Sec. 2.7), we have

$$L_w = \frac{\sum_{j=1}^{N_y} \sum_{i=1}^{N_x} L_w(i,j)}{N_x \ N_y} , \qquad (36)$$

where $L_w(i,j)$ is the luminance of element (i,j) as seen from the reference point.

Similarly,

$$\omega = \sum_{j=1}^{N_y} \sum_{i=1}^{N_x} d\omega\,(i,j)$$

where $d\omega(i,j)$ is the solid angle subtended by the $(i,j)^{th}$ element with respect to the reference point.

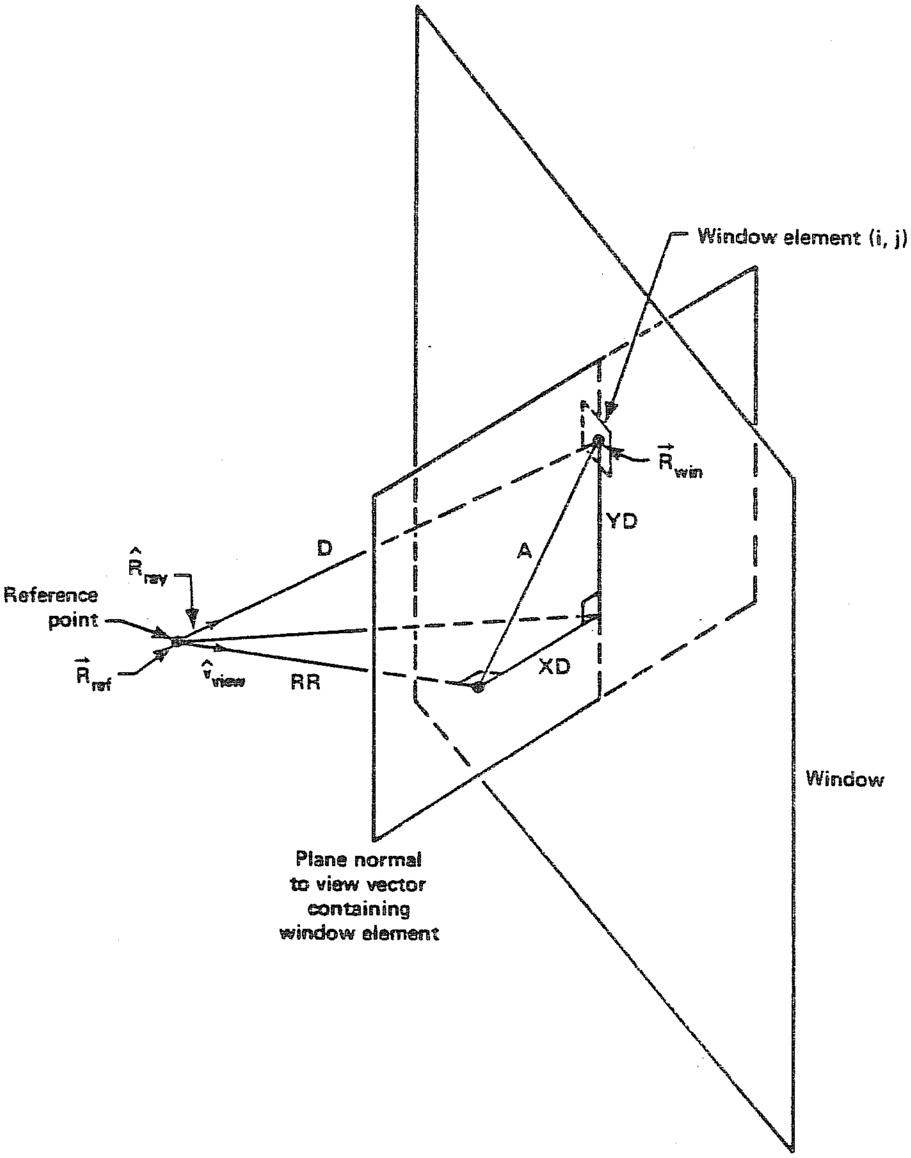

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Fig. 13. Geometry for calculation of displacement ratios used in Cornell-BRS glare formula.

The modified solid angle, Ω, is

$$\Omega = \sum_{j=1}^{N_y} \sum_{i=1}^{N_x} d\omega\,(i,j)\; p(x_R,y_R) \tag{37}$$

where p is a "position factor" (Ref. 16) which accounts for the decrease in visual excitation as the luminous element moves away from the line of sight. p depends on the horizontal and vertical displacement ratios x_R and y_R shown in Fig. 13, which are given by

$$x_R\;(i,j) \;=\; \left| A^2 - YD^2 \right|^{1/2} / \; RR$$

$$y_R\;(i,j) \;=\; \left| YD \;/\; RR \right| \;,$$

where

$RR = D\,\vec{R}_{ray} \cdot \hat{v}_{view}$,
$A^2 = D^2 - RR^2$,
$YD = \overline{R}_{win}(3) - \overline{R}_{ref}(3)$.

p can be obtained from graphs given by Petherbridge (Ref. 16) or it can be calculated from tabulated values of p_H, the Hopkinson position factor (Ref. 17), since $p=p_H^{1.25}$. The values resulting from the latter approach are given in Table 5. Interpolation of this table is used in DOE-2 to evaluate p at intermediate values of x_R and y_R.

Table 5.

Petherbridge Position Factor
for Cornell-BRS Glare
Calculation

		x_R : horizontal displacement factor							
		0	.5	1.0	1.5	2.0	2.5	3.0	>3.0
	0	1.00	.492	.226	.128	.081	.061	.057	.0
y_R:	.5	.123	.119	.065	.043	.029	.026	.023	.0
Vertical	1.0	.019	.026	.019	.016	.014	.011	.011	.0
Displacement	1.5	.008	.008	.008	.008	.008	.006	.006	.0
Factor	2.0	.0	.0	.003	.003	.003	.003	.003	.0
	>2.0	.0	.0	.0	.0	.0	.0	.0	.0

The background luminance, L_b, is determined by the illuminance E_b and the average reflectance ρ_b of, the floor, wall, and ceiling in the area surrounding the window:

$$L_b = E_b \rho_b$$

ρ_b is taken to be equal to the average interior surface reflectance, ρ, of the entire room. (see Sec. 2.9)

E_b is not explicitly calculated by DOE-2. It is approximated by

$$E_b = \max (E_r , E_s) ,$$

where

E_r = total internally-reflected component of daylight illuminance produced by all the windows in the room (footcandles),

E_s = the illuminance setpoint at the reference point at which glare is being calculated (footcandles).

A precise calculation of E_b is not required since the glare index (see next section) is logarithmic. A factor of two variation in E_b generally produces a change of only 0.5 to 1.0 in the glare index.

2.11.1 Glare Index

The net daylight glare at a reference point due to all of the windows in a room is expressed in terms of a "glare index", G_I, which is given by

$$G_I = 10\log_{10} \sum_{i=1}^{N_W} G_i \tag{38}$$

where

G_I = glare constant at the reference point due to the i^{th} window,

N_W = number of windows.

The recommended maximum values of G_I, for different situations are given in Table 6 (Ref. 17).

Table 6

Recommended Maximum Daylight Glare Index Values for Different Situations

Location or Building Type	Maximum Daylight Glare Index
Factories	
Rough Work	28
Engine Assembly	26
Fine Assembly	24
Instrument Assembly	22
Laboratories	22
Museums	20
Art Galleries	16
Offices	
General	22
Drafting	20
School Classrooms	20
Hospital Wards	18

2.12 Detailed Description of Preprocessor Subroutine DCOF

The following steps are carried out by DCOF:

1. Set length LWDC of daylight-factor block for each window/reference point combination.

   LWDC = (Number of daylight factors) * (number of clear sky sun positions + number of overcast sky sun positions),

   = 6 * (NPHS * NTHS + 1),

   = 6 * (4 * 5 + 1) = 126,

   where NPHS and NTHS are, respectively, the number of clear-sky solar altitude and azimuth values.

2. First space loop. For each daylit space (DAYLIGHTING=YES):

   a. Check that reference points and zone fractions (fractions of a thermal zone controlled by a reference point) are properly specified for each daylit space. Print error message if:

    (1) One or more coordinates of the first reference point are not specified.
    (2) Some, but not all, the coordinates of the second reference point are specified.
    (3) Sum of zone fractions exceeds 1.0.
    (4) Second reference point is specified, but corresponding zone fraction not specified.

  b. Find NRF, the total number of reference points (NRF = 1 or 2). Find NWTOT, the number of windows with area greater than 0.1 ft^2 (English input) or 0.1 m^2 (metric input). Print error message if NWTOT = 0.

  c. Get space in AA array for daylight factors. The number of words required for each space is

$$LDCTOT = NRF * NWTOT * LWDC \qquad (39)$$

  d. End of first space loop.

3. Get space in AA array for global building-shade luminance blocks. Length of each block is 2*NPHS*NTHS+1.

4. Get space for shadow calculation arrays.

5. Calculate SOLIC(M), the extra-terrestrial direct normal solar illuminance for the first day of each month (Refs. 5 and 6):

   SOLIC(M) [footcandles] =

$$92.9\ [126.82 + 4.248 \cos(OMJ) + 0.0825 \cos(2*OMJ) - 0.00043 \cos(3*OMJ) + 0.1691 \sin(OMJ) + 0.00914 \sin(2*OMJ) + 0.01726 \sin(3*OMJ)]$$

   where

   M = number of month

   OMJ = $(2\pi/366) * (1+ (M-1) * 30.5)$.

6. For each sun position calculate, for reference month (M=5):

  a. Clear sky zenith luminance (subroutine DZENLM)

  b. exterior horizontal luminance from sky and from sun for clear and overcast sky (subroutine DHILL)

  c. shadow ratios (subroutine SHADOW)

  d. global shade luminances for clear and overcast sky (subroutine DSHDLU)

7. Calculate daylight factors. The remainder of the DCOF preprocessor consists of a nested set of 7 loops in the sequence:

   - space
   - reference point
   - exterior wall
   - window
   - window x-element
   - window y-element
   - sun altitude
   - sun azimuth

   a. Begin Daylit-Space Loop

   Find area and average reflectance of inside surfaces of space for use in split-flux calculation of inter-reflected illuminance (subroutine DAVREF). See Section 2.9.

   b. Begin Reference Point Loop

   Transform reference points from space coordinate system to building coordinate system (BCS).

   c. Begin Exterior Wall Loop

   (1) Skip wall if a Trombe wall or if wall has no windows.

   (2) Find azimuth of glare view vector in building coordinate system. If this azimuth was not specified, make view vector parallel to first window in space (specifically, set view vector azimuth equal to window azimuth plus 90°).

   (3) Recalculate net area and area*reflectance sum of ceiling, wall, and floor categories with this exterior wall removed.

   d. Begin Window Loop

   (1) Print warning message if window multiplier is not 1.0. Use of a multiplier puts multiple windows all at the same location, which produces erroneous illuminance results.

   (2) Get diffuse transmittance TSOLDF and transmittance at normal incidence TSOLNM for solar radiation.

   TSOLDF = <CAM9>

   TSOLNM = <CAM1> + <CAM2> + <CAM3> + <CAM4>,

   where the <CAMn> are transmission coefficients for the window glass set in subroutine GLYTPO of LDL.

   (3) Print error message if a window-shade has been specified [i.e., WIN-SHADE-TYPE = MOVABLE-INTERIOR, MOVABLE-EXTERIOR, FIXED-INTERIOR, or FIXED-EXTERIOR] but a corresponding visible transmittance schedule (VIS-TRANS-SCH) and shading schedule (SHADING-SCHEDULE) have not been specified.

(4) Print error message if window has VIS-TRANS-SCH or SHADING-SCHEDULE, but WIN-SHADE-TYPE = NONE (the default).

(5) Get W1, W2, and W3, the vertices of the window (in BCS) numbered clockwise starting at upper left as viewed from inside of room (see Fig. 9).

(6) Get

W21 = unit vector from W2 to W1,
W23 = unit vector from W2 to W3,
WC = center point of window in BCS,
REFWC = vector from reference point (RREF) to WC,
WNORM = unit vector normal to window, pointing away from room,
ALF = absolute value of perpendicular distance between reference point and window plane.

(7) Choose the number of window x-divisions (NWX) and y-divisions (NWY) so that the solid angle subtended by any of the elements with respect to the reference point can be approximated to 1% or better as dA_n/D^2, where dA_n is the projected area of the element and D is the distance from element to reference point. This requires that

$$NWX = \text{int}\ (4 * WW/ALF)\ , \qquad (40)$$

$$NWY = \text{int}\ (4 * HW/ALF)\ ,$$

where WW and HW are the height and width of the window, respectively. An absolute upper limit of 40 is chosen for NWX and NWY to avoid excessive computation time. This yields

NWX = min [40, max(DAY-X-DIVISION, int(4*WW/ALF))]
NWY = min [40, max(DAY-Y-DIVISION, int(4*HW/ALF))]

For example, if WW=40, HW=5, ALF=10, DAY-X-DIVISION=8 (default), and DAY-Y-DIVISION=8 (default),

NWX = min [40, max(8,16)] = 16
NWY = min [40, max(8,2)] = 8

If NWX or NWY from Eq. 40 exceeds 80, a warning message is printed which suggests to the user that the window should be subdivided into two separate windows.

(8) Calculate altitude angle, PHWN, and azimuth angle, THWN, of window outward normal.

(9) For split-flux inter-reflectance calculation (Sec. 2.8 and 2.9):

(a) find ETA, the ratio of floor-to-window center height to average floor-to-ceiling height.

$$ETA = \max\left[0, \min(1, \frac{WC(3) - \langle ZZ\rangle}{\langle ZVOL\rangle / \langle ZFLRAR\rangle}) \right] ,$$

where

WC(3) = z-coordinate of window center in BCS,

<ZZ> = z-coordinate of space in BCS,

<ZVOL> = volume of space,

<ZFLRAR> = floor area of space.

Note that for a horizontal skylight in the ceiling of a rectangular space, ETA=1.

(b) find average inside reflectance, RHOCW, of incident light moving up across window midplane:

$$RHOCW = \frac{(A\rho)_{walls} \; (1-ETA) + (A\rho)_{ceiling}}{A_{walls} \; (1-ETA) + A_{ceiling} + \epsilon} \tag{41}$$

where

$(A\rho)_{walls}$ = sum of area * reflectance of all walls, excluding surface that window is in,

$(A\rho)_{ceiling}$ = area * reflectance of ceiling, excluding surface that window is in,

A_{walls} = total area of all walls, excluding surface that window is in,

$A_{ceiling}$ = area of ceilings, excluding surface that window is in,

$\epsilon = 10^{-5}$, added to prevent zero/zero for a skylight in a rectangular room.

In Eq. 41, $A_{walls}(1-ETA)$ and $(A\rho)_{walls}(1-ETA)$ are the area and area * reflectance of those parts of the walls lying above the window midplane.

(c) find average inside reflectance, RHOFW, of incident light moving down across window midplane:

$$RHOFW = \frac{(A\rho)_{walls} \; ETA + (A\rho)_{floor}}{A_{walls} \; ETA + A_{floor}}$$

(d) find, FRUP, the fraction of light from a window-shade which goes up to the ceiling and part of the walls above window midplane:

$$FRUP = 0.5 - PHWN/\pi$$

For a vertical window (PHWN = 0), FRUP = 0.5, i.e. half of the light transmitted by the shade goes up, and half goes down. For a horizontal skylight (PHWN = $\pi/2$), FRUP = 0, i.e., all of the light transmitted by the shade goes down.

(10) Initialize to zero:

EDIRSK (I,J,K) = sky-related component of direct illuminance at reference point (footcandles),

EDIRSU (I,J,K) = sun-related component of direct illuminance at reference point (footcandles),

AVWLSK (I,J,K) = sky-related component of average window luminance as seen from reference point (cd/ft^2),

AVWLSU (I,J,K) = sun-related component of average window luminance as seen from reference point (cd/ft^2),

where

I = sky condition index: I=1 for clear sky, I=2 for overcast sky;

J = shading device index: J=1 for bare window, J=2 for window covered by shading device;

K = sun position index:
=1 for $\phi_{sun}=10^\circ$, $\theta_{sun}=290^\circ$;
=2 for $\phi_{sun}=10^\circ$, $\theta_{sun}=235^\circ$;
=3 for $\phi_{sun}=10^\circ$, $\theta_{sun}=180^\circ$;
etc.

(11) Initialize to zero:

<OMEGA> = solid angle subtended by window with respect to reference point,

<OMEGAW> = position-factor-weighted solid angle subtended by window.

e. <u>Begin Window x-element Loop</u> (IX=1, NWX)

f. <u>Begin Window y-element Loop</u> (IY=1, NWY)

(1) Find center of window element in BCS:

$$RWIN(I) = W2(I) + (IX - .5) * W23(I) * DWX + (IY - .5) * W21(I) * DWY, \quad I=1,3$$

(2) Find length of ray between reference point and center of window element:

$$DIS = \left[\sum_{I=1}^{3} (RWIN(I) - RREF(I))^2 \right]^{1/2}$$

(3) Construct unit vector along ray pointing from reference point to window element:

$$\mathrm{RAY(I)} = (\mathrm{RWIN(I)} - \mathrm{RREF(I)})/\mathrm{DIS}, \quad \mathrm{I}=1,3$$

(4) Calculate cosine of "incidence angle", i.e. of angle between ray and window outward normal:

$$\mathrm{COSB} = \overline{\mathrm{WNORM}} \cdot \overline{\mathrm{RAY}}$$

(5) If COSB < 0, light from the window element cannot reach the reference point directly. Skip remaining calculations for this window element.

(6) Find altitude and azimuth of ray in BCS:

$$\mathrm{PHRAY} = \sin^{-1}(\mathrm{RAY}(3)) \ , \ -\pi < \mathrm{PHRAY} < \pi/2$$
$$\mathrm{THRAY} = \tan^{-1}(\mathrm{RAY}(2),\mathrm{RAY}(1)) \ , \ -\pi < \mathrm{THRAY} < \pi$$

(THRAY=0 is along x-axis of BCS; PHRAY is measured from x-y plane of BCS).

(7) Find solid angle subtended by window element

$$\mathrm{DOMEGA} = \mathrm{DWX} * \mathrm{DWY} * \mathrm{COSB} \ / \ \mathrm{D}^2$$

Increment solid angle subtended by window:

$$\langle\mathrm{OMEGA}\rangle = \langle\mathrm{OMEGA}\rangle + \langle\mathrm{DOMEGA}\rangle$$

(8) Find POSFAC, the position factor used in the glare calculation:

(a) Initialize POSFAC to zero.

(b) Find distance RR from reference point to point where glare view vector intersects the plane passing through the window-element center which is normal to the view vector:

$$\mathrm{RR} = \mathrm{DIS} * (\overline{\mathrm{RAY}} \cdot \overline{\mathrm{VIEWVC}})$$

(c) Find square of distance from intersection point in (b) to window element:

$$\mathrm{ASQ} = \mathrm{DIS}^2 - \mathrm{RR}^2$$

(d) Find vertical displacement of window element with respect to reference point:

$$\mathrm{YD} = \mathrm{RWIN}(3) - \mathrm{RREF}(3)$$

(e) Find horizontal and vertical displacement ratios:

$$\mathrm{XR} = |\mathrm{ASQ} - \mathrm{YD}^2|^{1/2}/\mathrm{RR}$$

$$\mathrm{YR} = |\mathrm{YD}/\mathrm{RR}|$$

(f) Get position factor via call to function DPFAC:

POSFAC = DPFAC (XR, YR)

(g) Increment modified solid angle

<OMEGAW> = <OMEGAW> + DOMEGAW * POSFAC

(9) Find variable transmittance of glass, TVISB

TVISB = (VIS-TRANS/TSOLNM) *
[<CAM1> + <CAM2> * COSB + <CAM3>
* COSB^2 + <CAM4> * COSB^3]

(10) Determine if ray from reference point to window element hits a local or global building-shade after passing through window (subroutines DHITSH and DPIERC).

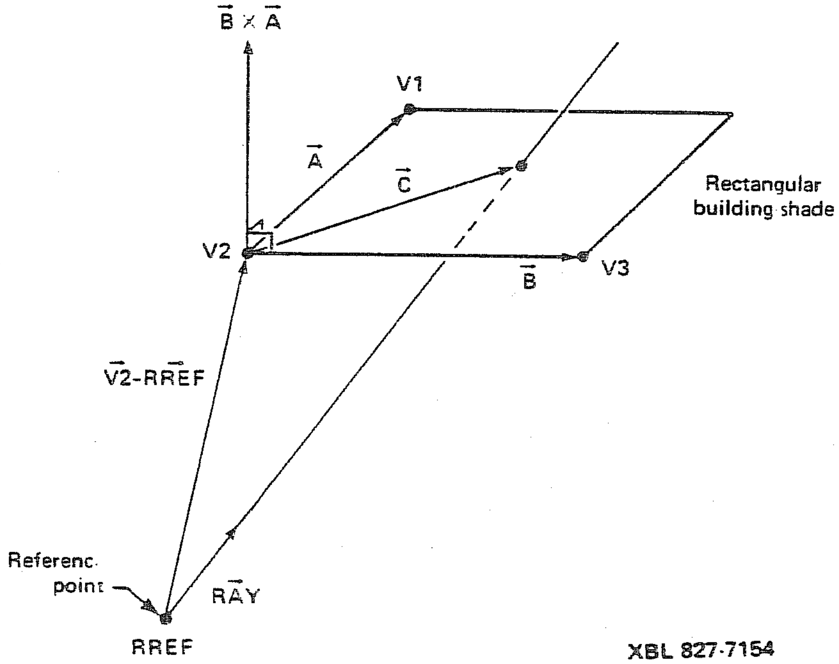

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Fig. 14. Geometry for determining if ray from reference point intersects a shading surface (subroutine DPIERC).

From Fig. 14 a ray with a unit vector $\overline{RAY}$ from reference point $\overline{RREF}$ intersects a rectangle with vertices $\overline{V1}$, $\overline{V2}$, and $\overline{V3}$ if

$0 < \overline{C} \cdot \overline{B} < \overline{B} \cdot \overline{B}$,

and

$0 < \overline{C} \cdot \overline{A} < \overline{A} \cdot \overline{A}$,

where

$\overline{C}$ = vector from V2 to point that ray intersects the plane of the rectangle,

$\overline{A} = \overline{V1} - \overline{V2}$,
$\overline{B} = \overline{V3} - \overline{V2}$.

$\overline{C}$ is given by

$$\overline{C} = \overline{RAY} \quad \frac{(\overline{B} \times \overline{A}) \cdot (\overline{V2} - \overline{RREF})}{(\overline{B} \times \overline{A}) \cdot \overline{RAY}} \quad - \quad (\overline{V2} - \overline{RI})$$

g. Begin Sun Altitude Loop (IPHS = 1,NPHS)

(1) Get altitude of sun in degrees (H) and radius (PHSUN)

H = PHSMIN + (IPHS - 1) * PHSDEL
PHSUN = H / 57.3

(2) Find clear sky zenith luminance for this solar altitude (subroutine DZENLM).

h. Begin Sun Azimuth Loop (ITHS = 1, NTHS)

(1) get azimuth of sun in BCS

THSUN = (THSMIN - 90 + ITHS * THSDEL) / 57.3 + BAZIM,

where
BAZIM = building azimuth
(THSUN = 0 is along x-axis of BCS)

(2) Calculate sun position index, IHR:

IHR = ITHS + NTHS * (IPHS - 1)

(3) At first step in window element loop (IWX=1, IWY=1) find inter-reflected components of illuminance at reference point, EINTSK and EINTSU, and window shading device luminance, WLUMSK and WLUMSU (subroutine DREFLT).

(4) Add contribution of window element to direct illuminance at reference point and to window luminance:

(a) bare window, building shade not hit
For PHRAY > 0, ray sees sky; therefore for PHRAY > 0,
add DSKYLU * DOMEGA * RAY(3) * TVISB to EDIRSK (I,1,IHR),
add DSKYLU * TVISB to AVWLSK (I,1,IHR),
where DSKYLU is the clear-sky luminance (cd/ft^2) for I=1, and the overcast-sky luminance (cd/ft^2) for I=2.

For PHRAY < 0, ray sees ground; therefore,
Add TVISB * GILSK (I,IPHS) * GNDREF / π to AVWLSK (I,1,IHR),
Add TVISB * GILSU (I,IPHS) * GNDREF / π to AVWLSK (I,1,IHR),

where GILSK and GILSU are the illuminances on the ground due to sky and sun, respectively, in cd/ft^2. Note that EDIRSK does not appear in this case since light from the ground cannot directly reach the horizontal workplane.

(b) bare window, building shade hit

Add TVISB * (building shade luminance, sky) to AVWLSK (I,1,IHR) for I=1, clear sky; and 2, overcast sky (IHR = 1 only).

Add TVISB * (building shade luminance, sun) to AVWLSU (I,1,IHR) for I=1, clear sky.

If PHRAY > 0, add (building shade luminance, sky)
*DOMEGA*RAY(3)*TVISB to EDIRSK (I,1,IHR) for I=1,2

add (building shade luminance, sun)
*DOMEGA*RAY(3)*TVISB to EDIRSU (I,1,IHR) for I=1,2

In this last case, window elements which lie below the horizontal plane containing the reference point (and therefore have PHRAY < 0) are excluded since light from these elements cannot reach the reference point directly.

(c) Window with shade

In this case, the luminance of the window element is equal to the shade luminance (times the glass transmittance if the shade is on the outside of the window).

- Set transmittance multiplier:
    TVIS1 = 1.0 if shade inside window,
    = TVISB if shade outside window.
- Add WLUMSK (I,INR) * TVIS1 to AVWSLK (I,2,IHR) for I=1, clear sky; and 2, overcast sky (IHR=1 only)
- Add WLUMSU (I,INR) * TVIS1 to AVWSLU (I,2,IHR) for I=1, clear sky; and 2, clear sky (IHR=1 only),

where

WLUMSK is the luminance of the shade (cd/ft^2) due to light directly from sky or light from sky reflected from ground or building shades; and WLUMSU is the corresponding sun-related luminance. Note that at this stage the shade transmittance is taken to be 1.0. Correction for the actual transmittance, which is a scheduled quantity, is done in the hourly calculation.

If PHRAY > 0,

- Add WLUMSK (I,IHR) * DOMEGA * RAY(3) * TVIS1 to EDIRSK (I,2,IHR) for I=1, clear sky; and for I=2, overcast sky (IHR=1 only).
- Add WLUMSU (I,IHR) * DOMEGA * RAY(3) * TVIS1 to EDIRSU (I,2,IHR) for I=1, clear sky.

i. <u>End of Sun Azimuth Loop.</u>

j. <u>End of Sun Altitude Loop.</u>

k. <u>End of Window y-element Loop.</u>

l. <u>End of Window x-element Loop.</u>

m. Loop again over sun positions and calculate the sky- and sun-related daylight factors by adding direct and inter-reflected illuminance components, then dividing by the exterior horizontal illuminance.

The illuminance factors are:

$$\text{DFACSK [fc/fc]} = \frac{\text{EDIRSK (I,J,IHR) + EINTSK (I,J,IHR)}}{\text{GILSK (I,IPHS)}} ,$$

$$\text{DFACSU [fc/fc]} = \frac{\text{EDIRSU (I,J,IHR) + EINTSU (I,J,IHR)}}{\text{GILSU (I,IPHS)}} .$$

The window luminance factors are:

$$\text{SFACSK [ft-L/fc]} = \frac{\text{AVWLSK (I,J,IHR)} * \pi \text{ /(NWX * NWY)}}{\text{GILSK (I,IPHS)}} ,$$

$$\text{SFACSU [ft-L/fc]} = \frac{\text{AVWLSU (I,J,IHR)} * \pi \text{ /(NWX * NWY)}}{\text{GILSU (I,IPHS)}} .$$

The window background-luminance factors are:

$$\text{BFACSK [ft-L/fc]} = \frac{\text{EINTSK (I,J,IHR) * RHOAV}}{\text{GILSK (I,IPHS)}} ,$$

$$\text{BFACSU [ft-L/fc]} = \frac{\text{EINTSU (I,J,IHR) * RHOAV}}{\text{GILSU (I,IPHS)}} ,$$

where RHOAV is the area-weighted average inside surface reflectance of the space.

n. Print daylight factor summary report (LV-L) for this space-window-reference point combination. Note that if a window-shade is defined, it is assumed in this report to have transmittance=1.0.

o. Store daylight factors in AA array after packing the pairs (DFACSK, DFACSU), (BFACSK, BFACSU), and (SFACSK, SFACSU) to save space.

p. End of window loop.

q. End of exterior wall loop.

r. End of space loop.

3. Hourly Daylighting Calculation

3.1 Overview

An hourly daylighting calculation is performed each hour that the sun is up for each space with DAYLIGHTING=YES. The exterior horizontal illuminance from sun and sky is calculated theoretically for the current-hour sun position and cloud amount, or is determined from solar irradiance data if present on the weather file. The interior illuminance at each reference point is found for each window by interpolating the illuminance factors calculated by the preprocessor. By summation, the net illuminance and glare due to all the windows in a space are found. If glare exceeds MAX-GLARE, window shading devices are deployed, if present, to reduce glare. Finally, the illuminance at each reference point for the final window-shade configuration is used by the lighting control system simulation (subroutine DLTSYS) to determine the electric lighting power required to meet the illuminance setpoint at each reference point.

3.2 Calculation Sequence

The following calculations are performed if there is at least one daylit space.

3.2.1 Exterior Daylight Availability Calculation

1. Integrate over sky luminance distribution to find exterior horizontal illuminance in footcandles from standard CIE clear sky (CHILSK), and from standard CIE overcast sky (OHILSK). Find direct solar CIE horizontal illuminance (CHILSU). These calculations use the current-hour sun position and are performed only on the first day of each month using the appropriate monthly value of atmospheric moisture and turbidity as entered with the ATM-MOISTURE and ATM-TURBIDITY keywords (subroutines DAVAIL, DHILL, DSKYLU, DNSOL, DZENL).

2. If weather file has measured solar irradiance data, find lumens/watt conversion factors for direct and diffuse radiation from CIE clear sky (CDIRLW, CDIFLW, respectively) and from CIE overcast sky (ODIFLW) (subroutines DAVAIL, DLUMEF).

3. For the current sky condition, which will be either clear, partly-cloudy, or overcast, the sky is divided into a fraction ETACLD which has the CIE clear sky luminance distribution for the current sun position, and a fraction 1-ETACLD which has the CIE overcast sky luminance distribution. ETACLD is a function of CR, the fraction of the skydome covered with clouds (obtained from the weather file).

   The form chosen for ETACLD vs CR, shown in Fig. 15, gives a clear sky luminance distribution for the whole sky for CR $\leq$ 0.2, which assumes that, for low cloud amounts, reflection of sunlight from the clouds will, on the average, give a cloud luminance which is comparable to that of the sky. As CR increases above 0.2, the average cloud luminance is assumed to become progressively closer to the CIE overcast sky luminance.

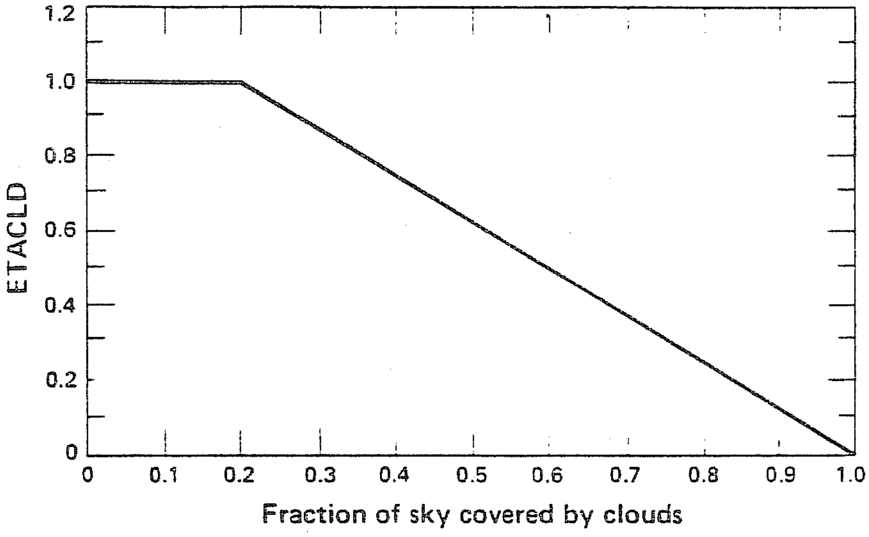

Fig. 15. ETACLD factor.

We have then:

CHISKF[footcandles] = exterior horizontal illuminance due to fraction of sky which has clear sky luminance distribution
= ETACLD * CHILSK (IHR)

OHISKF[footcandles] = exterior horizontal illuminance due to fraction of sky which has overcast sky luminance distribution
= (1-ETACLD) * OHILSK (IHR)

HISUNF[footcandles] = average direct solar exterior horizontal illuminance for the current hour
= (1-CR) * CHILSU (IHR)

If the weather file has measured solar radiation data, the above direct solar illuminance is replaced by

HISUNF = RDNCC * 0.292875 * CDIRLW * RAYCOS(3)

where

RDNCC = measured direct normal solar irradiance [Btu/ft^2-h],

0.292875 = conversion factor for Btu/ft^2-h to w/ft^2,

CDIRLW = luminous efficacy of direct solar radiation for current hour [lm/w],

RAYCOS = cosine of angle of incidence on the horizontal.

In addition, CHISKF and OHISKF are adjusted so that their sum equals the measured horizontal diffuse irradiance, SDIFH, times the luminous efficacy. Thus

$$\text{CHISKF} \rightarrow \text{CHISKF} * \text{ALFAD}$$
$$\text{OHISKF} \rightarrow \text{OHISKF} * \text{ALFAD}$$

where

$$\text{ALFAD} = \frac{\text{SDIFH} * (\text{CDIFLW}*\text{ETACLD} + \text{ODIFLW}*(1-\text{ETACLD}))}{\text{CHISKF} + \text{OHISKF}}$$

3.2.2 Luminous Efficacy of Solar Radiation

If solar radiation values are present on the weather file, the luminous efficacy in lumens/watt is calculated for direct solar radiation, clear sky diffuse solar radiation, and overcast sky diffuse solar radiation.

Luminous Efficacy, Direct Solar Radiation

The luminous efficacy of direct solar radiation as parameterized by Dogniaux (Refs. 5 and 6) is

$$K_s\ [\text{lm/W}] = K_o\, e^{-mT(\bar{a}_R - \bar{a}_s)} \tag{42}$$

where
K_o = 93.73 lm/W, the extraterrestrial luminous efficacy,
m = optical air mass, given by Eq. 11,
T = atmospheric turbidity, given by Eq. 6,
$\bar{a}_R$ is given by Eq. 10,

and

$$\bar{a}_s = 1.4899 - 2.1099 \cos \phi_{sun} + 0.6322 \cos 2\phi_{sun} + 0.0252 \cos 3\phi_{sun} - 1.0022 \sin \phi_{sun} + 1.0077 \sin 2\phi_{sun} - 0.2606 \sin 3\phi_{sun}$$

K_s is plotted as a function of solar altitude for selected values of turbidity coefficient, β, and atmospheric moisture, w, in Fig. 16. The rapid fall-off in K_s for solar altitudes $\leq$30% is primarily due to the λ^{-4} wavelength dependence of Rayleigh scattering.

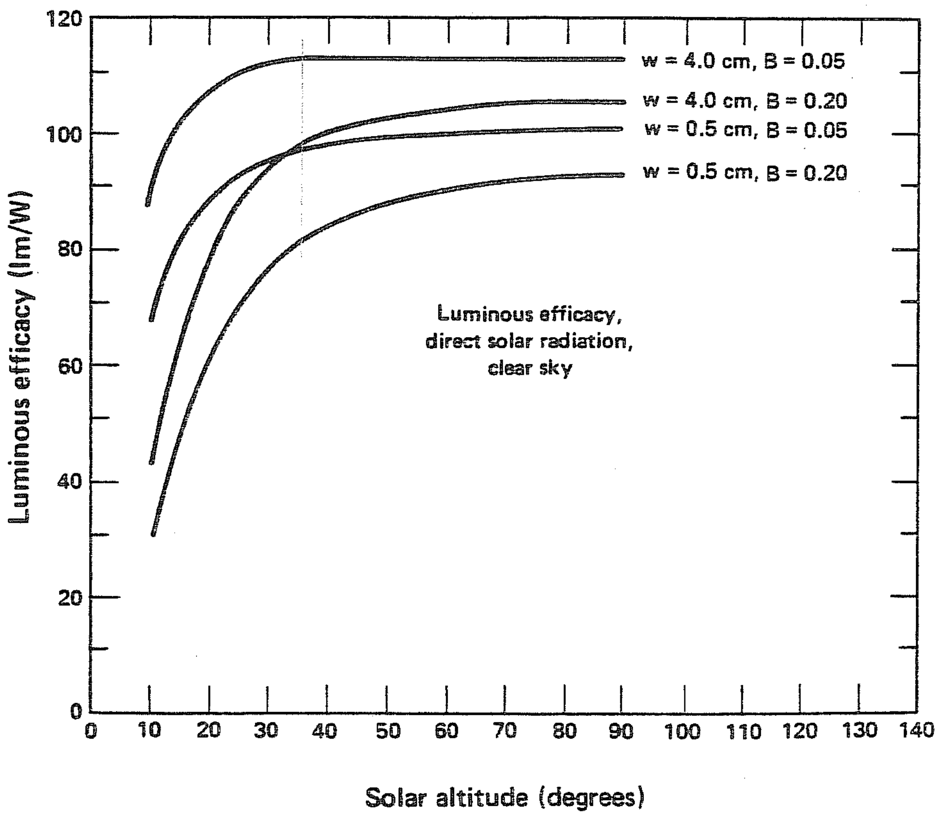

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Fig. 16. Luminous efficacy of direct solar radiation for clear sky conditions, for selected values of atmospheric moisture, w and decadic turbidity coefficient, B ($B \cong 1.07\ \beta$).

Luminous Efficacy, Diffuse Solar Radiation, Clear Sky

Figure 17, which is based on Table 4 of Aydinli, Ref. 19, shows the luminous efficacy, K_{cl}, of clear sky diffuse radiation as a function of β, w, and solar altitude. Aydinli's values are based on calculations (Refs. 18 and 20) taking into account the spectral distribution of extraterrestrial solar radiation, Rayleigh scattering, aerosol scattering and absorption by water vapor and ozone. The figure shows that K_{cl} varies from 115 to 135 lm/w, with a mean value of 125.4 lm/w and standard deviation of 6.1 lm/w. Because of the relatively small standard deviation in K_{cl} (~±5%) the mean value of K_{cl} is used in DOE-2.

Luminous Efficacy, Diffuse Solar Radiation, Overcast Sky

A constant value of 110 lm/w (Ref.6) is used for the luminous efficacy of diffuse solar radiation from an overcast sky.

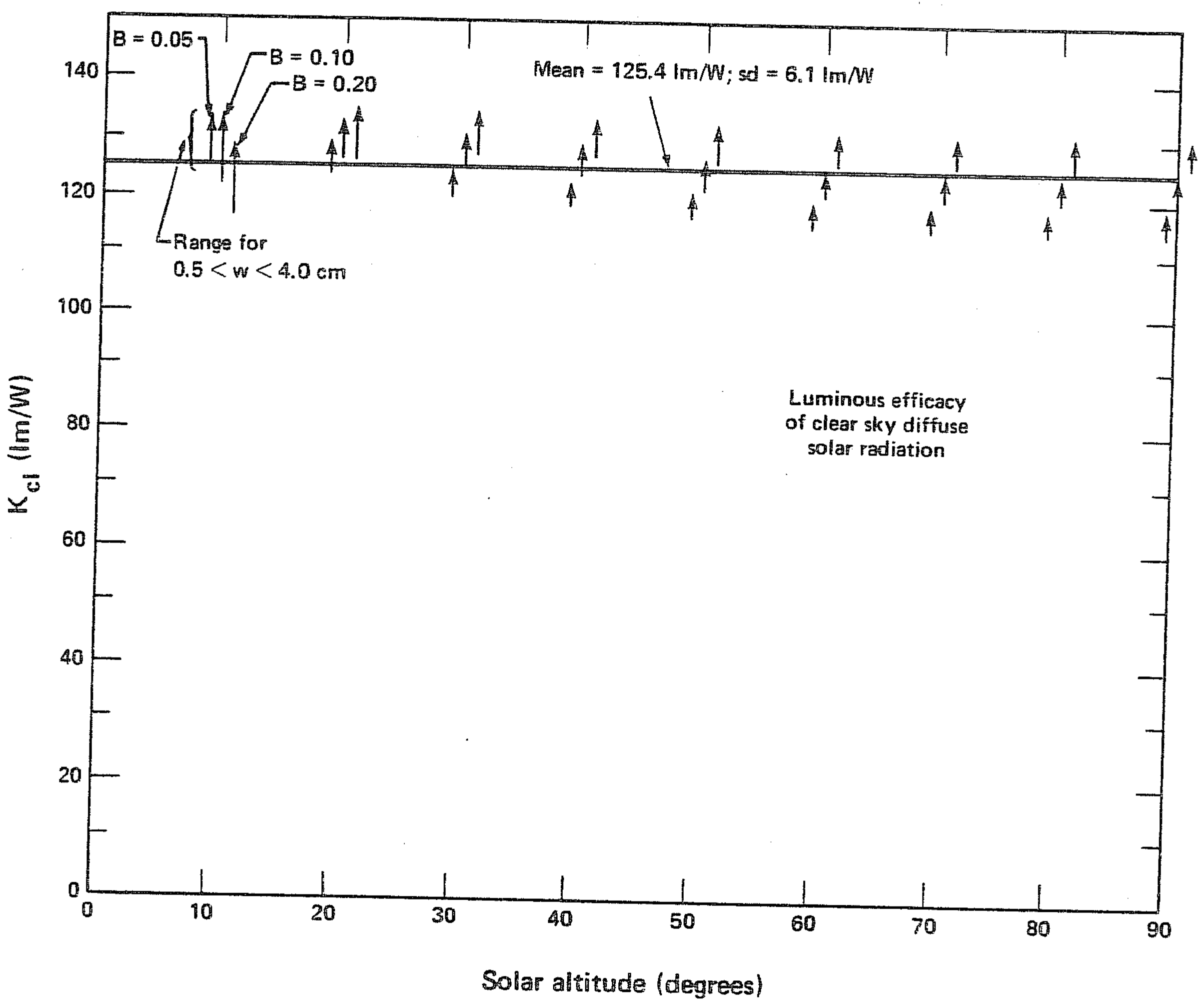

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Fig. 17. Luminous efficacy of clear sky diffuse solar radiation as a function of solar altitude, decadic turbidity factor, B (B ≅ 1.07 β), and atmospheric moisture, w. Based on Aydinli [Ref. 19].

3.2.3 Interior Illuminance Calculation (Subroutine DINTIL)

The following calculations are performed for each daytime hour for each daylit space.

1. Begin first window loop. Get shade transmittance, TAU, of window shading device.

2. Begin first reference point loop. Using current-hour sun position, unpack and interpolate stored daylight factors to obtain

DFSKHR (I,IS) = sky-related illuminance factor [fc/fc]
DFSUHR (I,IS) = sun-related illuminance factor [fc/fc]
BFSKHR (I,IS) = sky-related window-background luminance factor [ft-L/fc]
BFSUHR (I,IS) = sun-related window-surround luminance factor [ft-L/fc]
SFSKHR (I,IS) = sky-related window luminance factor [ft-L/fc]
SFSUHR (I,IS) = sun-related window luminance factor [ft-L/fc]

Here I = 1 for clear sky
2 for overcast sky
IS = 1 for bare window
2 for window with shading device

3. Multiply above daylight factors by exterior horizontal illuminance (and by shading device transmittance for shaded-window case) to obtain interior illuminance due to this window, <ILLUMW>; window background luminance, <ILLUMW>; and average window luminance, <SLUMW>:
BLUMW

$$\langle \mathrm{ILLUMW}\rangle_{IL,IS} = [\mathrm{DFSUHR}(1,IS) * \mathrm{HISUNF} + \mathrm{DFSKHR}(1,IS) * \mathrm{CHISKF} + \cancel{[}\mathrm{DFSKHR}(2,IS) * \mathrm{OHISKF}] * \mathrm{TAU1}$$

$$\langle \mathrm{BLUMW}\rangle_{IL,IS} = [\mathrm{BFSUHR}(1,IS) * \mathrm{HISUNF} + \mathrm{BFSKHR}(1,IS) * \mathrm{CHISKF} + \cancel{[}\mathrm{BFSKHR}(2,IS) * \mathrm{OHISKF}] * \mathrm{TAU1}$$

$$\langle \mathrm{SLUMW}\rangle_{IL,IS} = [\mathrm{SFSUHR}(1,IS) * \mathrm{HISUNF} + \mathrm{SFSKHR}(1,IS) * \mathrm{CHISKF} + \cancel{[}\mathrm{SFSKHR}(2,IS) * \mathrm{OHISKF}] * \mathrm{TAU1}$$

where IL = 1,2 is the reference point index
TAU1 = 1 for IS=1 (bare window)
= TAU, the shade transmittance, for IS=2 (window with shading device)

4. End of first reference point loop.

5. End of first window loop.

6. Find total interior illuminance and background luminance due all windows in the space. At this point, a shading device covers a window only if (a) a fixed shading device has been defined (WIN-SHADE-TYPE=FIXED-INTERIOR or FIXED-EXTERIOR), or (b) the user has specified solar gain control by inputting a MAX-SOLAR-SCH for the window, and the direct solar radiation transmitted through the window this hour (calculated in subroutine CALEXT) exceeds the MAX-SOLAR-SCH value, and the sun control probability tests passes.

The total interior illuminance at reference point IL is then

$$\langle \mathrm{DAYLIGHT\text{-}ILLUM}\rangle_{IL} = \sum_{\mathrm{windows}} \langle \mathrm{ILLUMW}\rangle_{IS,IL} ,$$

where IS = 1 if window is bare
= 2 if shading device covers window

The total background luminance is

$$\mathrm{BACLUM}(IL) = \sum_{\mathrm{windows}} \langle \mathrm{BLUMW}\rangle_{IS,IL}$$

3.2.4 Glare Index Calculation

Find glare index GLRNDX(IL) at each reference point via call to subroutine DGLARE. This yields

$$\text{GLRNDX(IL)} = 10 \log_{10} \sum_{\text{windows}} \frac{\langle \text{SLUMW} \rangle_{\text{IS,IL}}^{1.6} \ \langle \text{OMEGAW} \rangle_{\text{IL}}^{0.8}}{\text{BACL} + 0.07 \langle \text{OMEGA} \rangle_{\text{IL}}^{0.5} \langle \text{SLUMW} \rangle_{\text{IL,IS}}} \tag{43}$$

where

$\langle\text{OMEGAW}\rangle_{\text{IL}}$ = weighted solid angle subtended by window
$\langle\text{OMEGA}\rangle_{\text{IL}}$ = solid angle subtended by window
BACL = background luminance
= max (BACLUM(IL), RHOAV * SETPNT(IL))

In the last relationship, the background luminance is approximated as the larger of the background luminance from daylight, and the average background luminance which would be produced by the electric lighting at full power if the illuminance on the room surfaces were equal to the setpoint illuminance, SETPNT(IL). In a more detailed calculation, where the luminance of each room surface is separately determined by a multi-surface flux balance, BACL would be better approximated as an area-weighted luminance of the surfaces surrounding a window, taking into account the luminance contribution from the electric lights.

3.2.5 Glare Control Logic

If glare at either reference point exceeds <MAX-GLARE>, close shading devices one by one in an attempt to bring the glare at both points below <MAX-GLARE>. (Each time a shading device is closed, the glare and illuminance at each reference point is recalculated.) The following logic is used:

1. If there is one reference point, close a shade if it decreases the glare, even if it does not decrease the glare below MAX-GLARE.

2. If there are two reference points:

    (a) if glare is too high at both points, close a shade if it decreases glare at both points.

    (b) if glare is too high only at the first point, close a shade if the glare at the first point decreases, and the glare at the second point stays below MAX-GLARE.

    (c) if glare is too high only at the second point, close a shade if the glare at the second point decreases, and the glare at the first point stays below MAX-GLARE.

3. A shade is left open if the glare-control probability test fails, i.e., if a random number between 0 and 1 is greater than GLARE-CTRL-PROB. For example, if GLARE-CTRL-PROB=0.8, there is a 20% chance the shade will remain open even if closing it reduces glare.

4. Shades are closed in the order of window input until glare at both points is below MAX-GLARE, or until there are no more shades.

3.2.6 Lighting Control System Simulation (Subroutine DLTSYS)

1. For each reference point, calculate the fractional electric lighting output power, FP, required to meet the illuminance setpoint, SETPNT. FL, the fractional light output required to meet the setpoint, is given by

$$\text{FL} = \frac{\text{SETPNT(IL)} - \langle\text{DAYLIGHT-ILLUM}\rangle_{\text{IL}}}{\text{SETPNT(IL)}},$$

where
IL = reference point index
$\langle\text{DAYLIGHT-ILLUM}\rangle_{\text{IL}}$ = daylight illuminance (fc) at reference point IL

If $\langle\text{DAYLIGHT-ILLUM}\rangle_{\text{IL}} > \text{SETPNT(IL)}$, FL=0.

2. For a continuously-dimmable control system, it is assumed that FP is constant equal to MIN-POWER-FRAC for FL < MIN-LIGHT-FRAC and that FP increases linearly from MIN-POWER-FRAC to 1.0 as FL increases from MIN-LIGHT-FRAC to 1.0 (see Fig. 18a). This gives

$$\begin{aligned} \text{FP} &= \text{MIN-POWER-FRAC for FL} \le \text{MIN-LIGHT-FRAC} \\ &= \frac{\text{FL} + (1-\text{FL})(\text{MIN-POWER-FRAC}) - (\text{MIN-LIGHT-FRAC})}{1-(\text{MIN-LIGHT-FRAC})} \quad \text{for} \\ &\qquad \text{MIN-LIGHT-FRAC} \le \text{FL} \le 1 \end{aligned}$$

3. For a stepped control system, FP takes on discrete values depending on the range of FL and the number of steps, LIGHT-CTRL-STEPS (see Fig. 18b). (Note that LIGHT-CTRL-STEPS is the number of steps in FP excluding FP=0). This gives:

$$\begin{aligned} \text{FP} &= 0,\ \text{if FL} = 0 \\ &= \frac{\text{int}\,[(\text{LIGHT-CTRL-STEPS}) * \text{FL}] + 1}{\text{LIGHT-CTRL-STEPS}} \quad \text{for } 0<\text{FL}<1 \\ &= 1,\ \text{if FL} = 1 \end{aligned}$$

To simulate the uncertainty involved with manual switching of lights, FP is set one level higher a fraction of the time equal to 1-(LIGHT-CTRL-PROB). Specifically, if FP<1,

FP → FP + 1/(LIGHT-CTRL-STEPS)

if a random number between 0 and 1 exceeds LIGHT-CTRL-PROB. The default value of 1 for LIGHT-CTRL-PROB implies automatic switching with no probabilistic element.

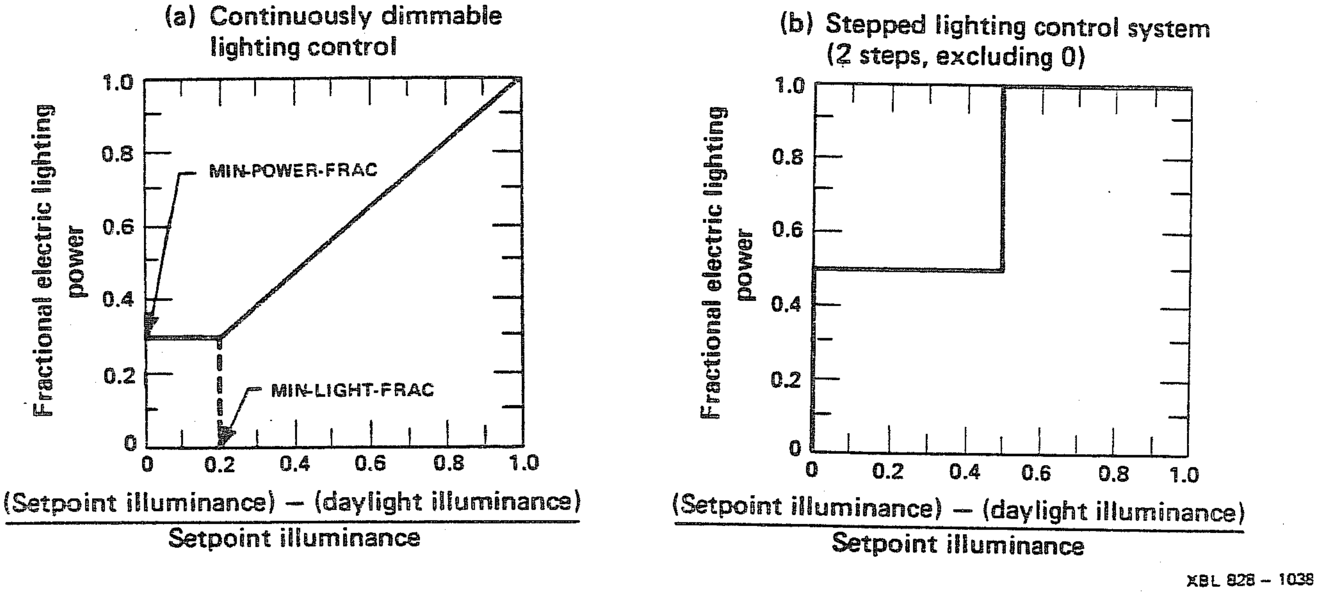

Fig. 18. Lighting control curves for (a) continuously dimmable system and (b) stepped system.

4. FP is corrected for the fraction, FSUNUP, of the hour that the sun is up (FSUNUP=1 if sun is up for the entire hour; FSUNUP<1 for sunrise and sunset hours.)

   FP → FP * FSUNUP + 1.0 * (1-FSUNUP)

   It is assumed that the exterior illuminance before sunrise is zero.

5. Using the value of FP at each reference point, and the fraction ZFRAC of the space controlled by the reference point, the net lighting power multiplier for the entire space is calculated:

$$\text{<POWER-RED-FAC>} = \sum_{\text{ref.pts.}} \text{FP*ZFRAC} + 1.0 * \left[1 - \sum_{\text{ref.pts.}} \text{ZFRAC} \right]$$

   In this expression, the term on the right in parentheses corresponds to the fraction of the space not controlled by either reference point. For this fraction, which is generally zero, the electric lighting is unaffected and the power multiplier is 1.0.

   Note that the fractional <u>reduction</u> in lighting power due to daylighting is 1-<POWER-RED-FAC>.

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