A procedure for calculating the potential savings in lighting energy from the use of skylights

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A step-by-step procedure is presented for determining the lighting energy trade-offs between artificial lighting and skylighting based on the ability of each to provide average horizontal footcandles on a work plane.

Introduction

This paper explains a procedure for calculating the lighting energy that can potentially be saved by turning off some or all of the artificial lighting in a room that has skylights. It is not a procedure for designing a skylighting installation, although it contains many of the elements of skylighting design. It is not a procedure for determining the total energy balance within a space, although it could be extended to do so by including heating and air conditioning considerations and the thermal losses of skylights. Rather it is a procedure for determining the lighting energy trade-offs between artificial lighting and skylighting based on the ability of each to provide average horizontal footcandles on a work plane.

The procedure is presented in a step-by-step manner, but in order to keep the paper to a reasonable length, several tables and graphs in the IES "Recommended practice of daylighting" (IES RPD)[1] are not reproduced in the paper but rather are simply referred to.

Step 1. The number of watts of artificial lighting required to produce a desired average footcandle level within a room is calculated. The procedure used is the customary lumen zonal-cavity method, as covered in the *IES Lighting Handbook,* Fifth Edition.[2] Calculations are based on average maintained footcandles. Thus the four light loss factors discussed in the IES Handbook, namely room surface dirt depreciation (RSDD), lamp burnouts (LBO), luminaire dirt depreciation (LDD), and lamp lumen depreciation (LLD), are charged to the artificial lighting.

Step 2. The horizontal footcandles incident on the skylights are determined. A great deal of data, mostly old, are presented in the IES RPD,[1] and in various other references, giving footcandle and footlambert levels to be expected from overcast skies, clear skies, and solar illumination (direct sunlight) at various latitudes, dates of the year and times of day.* These data are in some cases incomplete and are sometimes conflicting between a given pair of observers. The author has found that by plotting all of the data *vs.* solar altitude, rather than *vs.* latitude, date and time, a single curve for each of the three conditions—overcast sky, clear sky, and direct sunlight—results. Use of these three universal curves and a table that displays solar altitude as a function of latitude, date and time permits a quick determination of sky luminance and solar illumination values and considerably reduces the number of tables and graphs required for skylighting calculations.

Step 3. The transmission factors of the skylights are calculated. Here one must be concerned with both direct and diffuse transmission; with shape, thick-

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* The IES has developed definitions of clear sky, overcast sky, and solar illumination for daylighting calculations. Clear sky implies less than 30 percent cloud cover. Overcast sky means 100 percent cloud cover with no sunlight visible and with luminous intensity independent of azimuth but not of altitude. Solar illumination is the light coming directly from the sun and excludes light from the sky. Thus, on a clear sky day, it is necessary to add direct sunlight to clear sky light to obtain the total illumination on a skylight.

ness, and material of the dome; with the average angle of incidence of direct sunlight; with the distribution of sky luminances on overcast and clear days; and with the effect of any light well and frame present. Data on such transmission factors is confusing in the literature.[3-8] In this paper it is assumed that the skylight domes are segments of spheres with a four-to-one width-to-height ratio, that a nine-inch well is present, that skylight transmission is independent of angle of incidence out to 60 to 70 degrees, and that equivalent uniform sky luminance values can be used for both overcast and clear sky conditions in place of the nonuniform luminance distributions that actually exist.

Step 4. The average horizontal footcandles on the work plane are calculated. The method used is the lumen method of toplighting described in the IES RPD. This procedure is similar to the lumen zonal-cavity method of artificial lighting design in that it integrates the room and luminaire (in this case the skylight) characteristics into a single coefficient of utilization. The illumination on the work plane is then found from

$$E_S = E_H \times \frac{A_S}{A_W} \times K_U \times K_M \qquad (1)$$

where E_S is the work plane illumination from skylighting, E_H is the horizontal illumination on the skylight, A_S is the area of the skylights, A_W is the area of the work plane, K_U is the coefficient of utilization and K_M is the maintenance factor.

Step 5. With the average horizontal footcandles on the work plane due to skylighting calculated, the BTU-per-hour savings can be determined. To illustrate how this is done, assume a certain skylighting installation provides 30 footcandles on the work plane at a specified latitude, date, time, and sky condition. Further assume that the artificial lighting provides 50 footcandles. Then, if the artificial lighting can be switched on and off in parts, it is possible to turn off 60 percent of the artificial lighting under the assumed conditions. If the entire artificial lighting installation, including ballasting, consumes P watts, then 0.6P watts can be saved. Since each watt represents 3.413 BTU-per-hour, the saving is 2.048P BTU-per-hour.

If, on another day, it is found that the skylighting produces 60 footcandles, then all of the artificial lighting can be turned off and the saving is 3.413P BTU-per-hour. In this latter case, there is more illumination in the room space than required, but credit can only be taken for the first 50 footcandles.

In the remainder of the paper, each of these steps will be explained in detail and an example will be worked.

Step 1: Calculation of artificial lighting

Interior lighting design by the lumen zonal-cavity method is a straightforward and well-documented procedure.[2] Thus only the salient features will be given here in the form of an example.

Consider an office area 40 feet by 30 feet with a 10-foot ceiling. Assume typical reflectance values: ceiling 75 percent, walls 50 percent, and floor 20 percent. It is desired to light this office to an average maintained level of 50 footcandles with 40-watt cool-white fluorescent lamps, using conventional prismatic wraparound two-lamp luminaires (unit number 30, page 9–24, Reference 2). Work plane height is 2½ feet and the luminaires are flush mounted on the ceiling.

Proceeding through the calculations, a coefficient of utilization (CU) of 0.60 and a light loss factor (LLF) of 0.69 are found. The total initial lumens (ϕ) required are obtained from

$$\phi = \frac{E_A \times A_W}{CU \times LLF} \qquad (2)$$

where E_A is the work plane illumination from artificial lighting. The result is ϕ = 145,000 lumens which requires 23 luminaires at 92 watts-per-luminaire. Thus the total wattage consumption by the artificial lighting is 2116 watts.

Step 2: Determination of illumination on skylights

Data for overcast skies. An overcast sky does not have constant luminance with viewing angle. Rather its luminance is generally 2½ to 3 times as great directly overhead as near the horizon, and its luminance distribution pattern depends on the altitude of the sun above the horizon.

In daylighting design, it has become customary to assign a single value of equivalent uniform sky luminance to represent an entire overcast sky at a certain date and time. The assumption is that a sky with this single uniform luminance will produce the same illumination level as the actual nonuniform luminance sky.

Values of equivalent overcast sky luminance as a function of latitude, date, and time are given in Table IX of the IES RPD. These have been plotted in Fig. 1 as a function of solar altitude and a single average curve has been drawn through the points. To use Fig. 1, it is necessary to relate solar altitude to latitude, date, and time. This is done in Table I. For example,

Figure 1. Overcast sky: equivalent sky luminance *vs.* solar altitude.

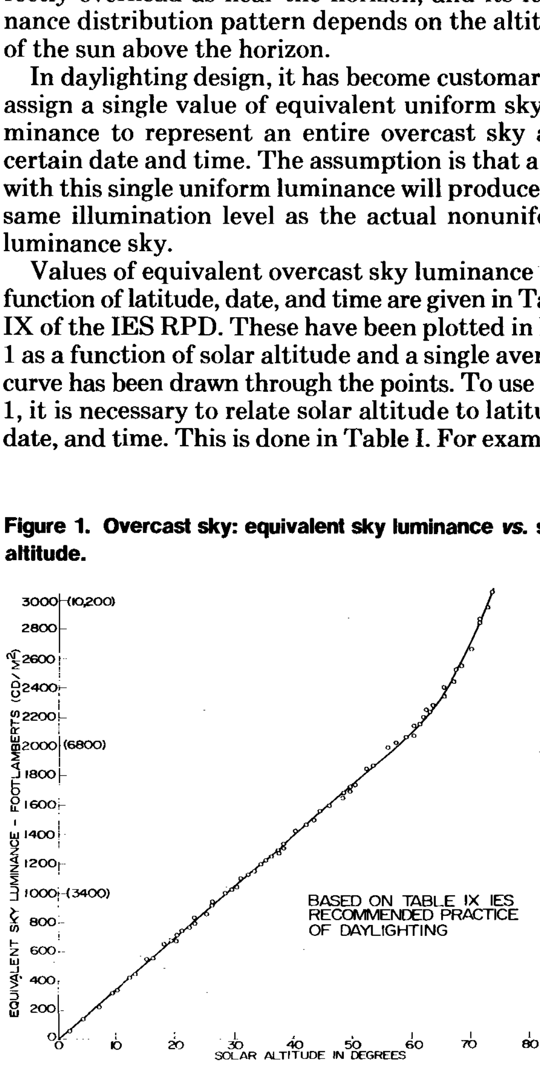


Table I—Degrees of solar altitude *vs.* latitude, date, and time

Latitude	Date	A.M. 6 / P.M. 6	7 / 5	8 / 4	9 / 3	10 / 2	11 / 1	noon / noon
30°N	June 21	12	24	37	50	63	75	83
	Mar-Sept 21		13	26	38	49	57	60
	Dec 21			12	21	29	35	37
34°N	June 21	13	25	37	50	62	74	79
	Mar-Sept 21		12	25	36	46	53	56
	Dec 21			9	18	26	31	33
38°N	June 21	14	26	37	49	61	71	75
	Mar-Sept 21		12	23	34	43	50	52
	Dec 21			7	16	23	27	28
42°N	June 21	16	26	38	49	60	68	71
	Mar-Sept 21		11	22	32	40	46	48
	Dec 21			4	13	19	23	25
46°N	June 21	17	27	37	48	57	65	67
	Mar-Sept 21		10	20	30	37	42	44
	Dec 21			2	10	15	20	21

if we desire the equivalent overcast sky luminance on March 21 at 30 degrees north latitude and 10 am, it is found from Table I that the solar altitude is 49 degrees. Entering Fig. 1 an equivalent uniform sky luminance of about 1720 footlamberts is obtained. The horizontal illumination in footcandles is equal to this value.

Data for clear skies. Values of equivalent clear sky luminance as a function of latitude, date, and time are presented in Table X of the IES RPD. Four luminances, one for each of the four compass directions, are given for each latitude, date, and time entry. The four luminances have been averaged and plotted *vs.* solar altitude in Fig. 2. An average curve has been drawn through the plotted points. Use of Table I with Fig. 2 yields equivalent clear sky luminance for a given latitude, date, and time. As in the overcast sky case, horizontal illumination in footcandles and clear sky luminance in footlamberts are numerically equal.

The concept of equivalent luminance for clear skies is more suspect than it is for overcast skies. First, a clear sky is brighter near the horizon than overhead, by as much as 12 to 1 for low sun angles. Second, clear sky luminance distributions are more nonuniform than those for overcast skies. Last, because of these nonuniform distributions, it is difficult to know how to weight the data for the four directions so as to obtain a single luminance value for each latitude, date, and time. The equal weighting of the four luminances, which is done here, may not be best.

These concerns may be somewhat laid to rest when it is realized that on a clear sky day, the contribution of direct sunlight to the horizontal illumination exceeds the contribution of the clear sky luminance for solar altitudes greater than 15 degrees. Thus errors in clear sky luminance tend to be reduced in significance when the values of horizontal illumination from clear sky plus direct sunlight are calculated.

Data for solar radiation. Horizontal illumination from solar radiation as a function of latitude, date, and time is given in Table XII of the IES RPD. These data are replotted as a function of solar altitude in Fig. 3 and a curve is drawn through the points. Figure 3 and Table I may be used together to find the horizontal illumination due to direct sunlight for a given latitude, date, and time.

Step 3: Calculation of dome transmission factors

There are two transmission factors to consider when dealing with skylights. One is the direct transmission factor, which is somewhat dependent on the angle of incidence of the incoming radiation. It is this factor that must be used in obtaining the transmitted footcandles due to direct sunlight impinging on a skylight. The second is the diffuse transmission factor, which is largely independent of the angle of incidence. This factor is used in obtaining the transmitted footcandles due to overcast and clear sky luminances, because these luminances are assumed to be uniformly distributed throughout the sky hemisphere.

Consider the diffuse transmission first. It is as-

Figure 2. Clear sky: equivalent sky luminance *vs.* solar altitude (direct sunlight excluded).

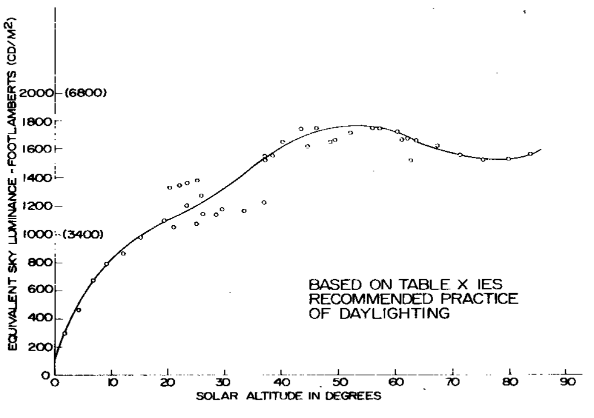
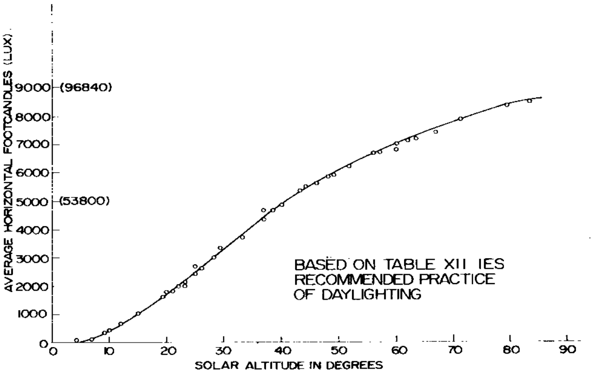


Figure 3. Average solar illumination *vs.* solar altitude.



sumed that the clear and overcast sky luminance distributions may each be replaced by equivalent uniform sky luminances, which are independent of angle of observation. Thus a single transmission factor, independent of angle, will suffice for both these cases. This is called the diffuse transmission factor and is given the symbol T_d.

Values of T_d vary from reference to reference. For transparent acrylic material, the range is from 0.79 to 0.85. For translucent acrylic material, it is from 0.46 to 0.57. Conservative figures are chosen, and T_d values of 0.79 for transparent skylight domes and 0.46 for translucent skylight domes are used. (The skylight dome is the light transmitting part of the skylight. Later, the effect of the skylight well and frame also will be included.)

Direct transmission factors, which are needed for direct solar radiation, are not as easy to resolve. These do depend on the angle of incidence that the sun makes with the skylight and thus they vary with latitude, date, and time. Depending on which reference one reads, a transparent flat acrylic sheet transmits 86 to 92 percent of the light striking it normally. Using the 92-percent figure, which seems the more prevalent, four percent of the light is reflected at each surface and virtually no light is absorbed if the sheet thickness is less than one inch. Thus the sheet has a direct normal transmission (T_{DN}) of 92 percent.

As the angle of incidence of the source increases from zero degrees, a greater percentage of the light is reflected at each surface and the net direct transmission (T_D) decreases. However, it is reasonably constant (within ten percent) for angles of incidence less than 50 degrees but falls rapidly at higher angles. For translucent sheets, the result is essentially the same except that transmissions are less at all angles. Values of T_{DN} for 3/16-inch translucent acrylic sheets vary from 0.42 to 0.52 in the literature, with the 0.52 figure being the more prevalent.

When domes are considered instead of flat sheets, three changes occur.[4,5] First, doming decreases sheet thickness at the center of the dome to about 77 percent of its flat-sheet value. This increases T_{DN} at the center of the dome by as much as 15 to 20 percent. Second, the angle of incidence of the sunlight varies over the dome surface, unlike the flat-sheet case, and at low sun angles portions of the dome will receive no direct sunlight. Last, the dome, because it extends above the plane of the roof, has greater light-gathering surface area than a flat sheet.

The integration of these three effects for translucent domes shows that direct dome transmission is constant within ten percent for all sun elevation angles greater than about 18 degrees. Relating this to latitude, date, and time, it is found that only in the winter in the early morning and late afternoon does direct dome transmission vary significantly with sun elevation. Thus it is assumed that $T_D = T_{DN}$ for all angles of interest, and the previously listed values of 92 percent for transparent domes and 52 percent for translucent domes are used, with a footnote that the latter factor should be increased by 10 to 20 percent when dealing with the early morning or late afternoon in December.

Table II—Transmission factors of typical transparent and translucent domes

	T_D	T_d
Transparent Dome	.92	.79
Translucent Dome	.52*	.46
Double Dome-Transparent over Translucent	.50*	.41

*These values should be increased by 10-20% for calculations in the early morning or late afternoon in winter.

It remains to consider double domes, particularly the case of a transparent dome over a translucent dome. Pierson[4] presents the following formula for calculating the overall direct transmission through two flat sheets:

$$T_D = \frac{T_1 T_2}{1 - R_1 R_2} \quad (3)$$

where T_1 and T_2 are the direct normal transmission factors of the transparent and translucent domes, and R_1 and R_2 are their total reflection factors. For the two materials previously considered

$$T_D = \frac{0.92 \times 0.52}{1 - 0.08 \times 0.48} = 0.50$$

This formula ignores angle effect and is valid only for angles of incidence of 60 degrees or less. It also ignores doming effect.

Pierson does not discuss how to compute the overall diffuse transmission for the double dome case. We will assume here that his formula in Equation (3) remains valid, with diffuse transmissions replacing direct normal transmissions. The result is

$$T_D = \frac{0.79 \times 0.46}{1 - 0.21 \times 0.54} = 0.41$$

The transmission factors established in this discussion are presented in Table II.

Step 4: Calculation of average horizontal footcandles on the work plane from skylighting

Knowing the external daylighting levels and the dome transmission factors, it is possible to proceed with the calculation of interior horizontal footcandle levels produced by skylighting. The procedure to be used is the lumen method of toplighting, as described in the IES RPD. The procedure uses Equation (1) as its basis, and our major task is to determine K_U, the coefficient of utilization.

Calculation of room ratio. The measure of room dimensions is in terms of room ratio. Room ratios for toplighting are given in Table V in the IES RPD. For the office area initially considered in Step 1, the room ratio is 2.3.

Number and size of skylights. For reasonable uniformity of illumination within the room interior, the spacing between skylights generally should not exceed 1.5 times the ceiling height of the room. Thus for the room being considered, the maximum spacing is 15 feet and six skylights are the minimum requirement.

Normally, the next step in a skylighting design (which this procedure is not) is to determine the dome size to produce a given footcandle level for the type of dome and number of domes selected. It is assumed that a certain percentage of the ceiling area is devoted to skylights and from that figure skylight size can be obtained. The room considered has a ceiling area of 1200 square feet. If three-foot by three-foot units are used, then 4.5 percent of the ceiling area will be devoted to skylights, a not unreasonable percentage by industry standards.

Determination of net skylight transmission. To calculate the net transmission of a skylight, it is necessary to include the effect of the light well. For this purpose, a well index given by

$$WI = \frac{H(L + W)}{2LW} \tag{4}$$

must be obtained, where H, L, and W are the height, length, and width of the light well. From the previous step, L = W = 3 feet. A nine-inch curbing is assumed and thus H = 0.75 feet (a height-to-width ratio of one to four). This gives a well index of 0.25.

Knowing the well index, the well efficiency N_w can be obtained, if the reflectance factor of the well wall is known. This information is presented in Fig. 36 of the IES RPD. Assuming 60 percent well-wall reflectance, a well efficiency of 0.79 is obtained.

One other factor must be determined before net skylight transmission can be obtained. This is the ratio of net to gross skylight area (R_a). A skylight has a rim to hold the dome in place and this rim detracts from the net light-transmitting area of the dome. Assuming that a three-by-three skylight has a net light transmission area of 2.75 feet by 2.75 feet, the ratio of net to gross areas is 0.84.

The net transmission of the skylight is given by

$$T_S = T \times N_w \times R_a \tag{5}$$

where T is taken from Table II and is T_d for diffuse transmission and T_D for direct transmission.

Using Equation (5) and Table II, the net transmissions for the given domes, well efficiencies, and area ratios can be calculated. The results are given in the first two columns in Table III as T_{SD} (net direct transmission) and T_{Sd} (net diffuse transmission).

Determination of coefficients of utilization. Table VI in the IES RPD is used to determine the coefficient of utilization K_U. The room considered has a room ratio of 2.3. It has 75 percent ceiling reflectance and 50 percent wall reflectance. The net transmission factors are listed in Table III.

Entering the K_U table, and interpolating where necessary, the last two columns in Table III are arrived at, a set of coefficients of utilization for direct (K_{UD}) and diffuse (K_{Ud}) transmissions for the domes of interest.

Determination of maintenance factor. Of the four light loss factors involved in artificial lighting, only two are applicable in daylighting calculations, namely RSDD (room surface dirt depreciation) and LDD (luminaire dirt depreciation). The latter should be retitled skylight dirt depreciation (SDD) in this situation.

Table III—Net transmission and coefficients of utilization of skylights

	T_{SD}	T_{Sd}	K_{UD}	K_{Ud}
Transparent	.61	.52	.52	.45
Translucent	.34*	.31	.30	.27
Transparent over Translucent	.33*	.27	.29	.23

*These values should be increased by 10-20% for calculations in the early morning or late afternoon in winter.

An RSDD factor of 0.95 is used, implying a clean room which is cleaned annually. To determine SDD, refer to Table IV in the IES RPD. Unfortunately this table does not list a maintenance factor for glass installed horizontally in an office (clean) area and does not include maintenance factors based on once a year cleaning. However, through extrapolation and interpolation of the data that is given, an SDD factor of 0.72 based on cleaning once annually can be gotten. Then the maintenance factor is

$$K_M = 0.95 \times 0.72 = 0.68$$

Calculation of average horizontal footcandles on work plane. Equation (1) may now be employed in the calculation of horizontal footcandle levels produced by skylighting. The coefficients of utilization are assembled in Table III and the ratio A_S/A_W is 54/1200 = 0.045. For overcast day calculations, the diffuse coefficient of utilization is used. For clear sky plus solar radiation calculations both the diffuse and direct coefficients of utilization are used. In equation form, for overcast days

$$E_{SO} = E_{HO} \times \frac{A_S}{A_W} \times K_{Ud} \times K_M \tag{6}$$

where the "O" denotes overcast. For clear sky plus solar radiation days,

$$E_{SCR} = E_{HC} \times \frac{A_S}{A_W} \times K_{Ud} \times K_M + E_{HR} \times \frac{A_S}{A_W} \times K_{UD} \times K_M \tag{7}$$

where CR denotes clear sky plus solar radiation, C denotes clear sky, and R denotes solar radiation. For the cases of interest,

$$\begin{aligned}
&\text{Transparent:} && E_{SO} = 0.014\, E_{HO} \\
& && E_{SCR} = 0.014\, E_{HC} + 0.016\, E_{HR} \\
&\text{Translucent:} && E_{SO} = 0.0083\, E_{HO} \\
& && E_{SCR} = 0.0083\, E_{HC} + 0.0092\, E_{HR} \qquad (8) \\
&\text{Transparent over translucent:} && E_{SO} = 0.0070\, E_{HO} \\
& && E_{SCR} = 0.0070\, E_{HC} + 0.0089\, E_{HR}
\end{aligned}$$

It must now be decided what latitudes, dates, and

Table IV—Horizontal footcandles for selected latitudes, dates, and times

		June 21			March-Sept 21			December 21		
		8am	10am	12noon	8am	10am	12noon	8am	10am	12noon
Overcast	34°	1300	2200	--	880	1610	1950	330	900	1150
Sky	38°	1300	2150	--	810	1510	1820	250	810	980
	42°	1330	2100	2850	780	1400	1680	150	680	880
Clear	34°	1530	1680	1530	1200	1720	1760	790	1220	1410
Sky	38°	1530	1700	1520	1160	1680	1770	700	1160	1270
	42°	1570	1710	1560	1130	1620	1740	510	1090	1210
Direct	34°	4450	7200	8450	2450	5600	6650	400	2650	3800
Sunlight	38°	4450	7050	8150	2100	5250	6300	150	2100	2950
	42°	4600	7000	7950	2000	4900	5850	0	1550	2450

To obtain lux, multiply each footcandle value by 10.76.

times are of interest and values must be obtained for E_{HO}, E_{HC} and E_{HR}. For purposes of illustration, 34, 38, and 42 degrees are chosen as the three latitudes of interest, and 8 am, 10 am and 12 noon as the three times of interest, realizing that data for 8 am and 4 pm are the same, as are data for 10 am and 2 pm. For dates, the two solstices, June 21 and December 21, and the two equinoxes, March 21 and September 21, will be chosen. With these choices made, Table I can be used and Figs. 1, 2, and 3 can be entered to obtain values of horizontal footcandles from overcast skies, clear skies and direct sunlight. These are presented in Table IV.

Using the values in Table IV and Equations (8), Table V can be composed, the average horizontal footcandles on the work plane in the chosen room from skylighting for transparent, translucent, and double domes. To illustrate how the entries in Table V are obtained, it is noted that the 19-footcandle value for the transparent dome is obtained from $E_{SO} = 0.014 \times 1330 = 18.62 \approx 19$ and the 96-footcandle value from $E_{SCR} = 0.014 \times 1570 + 0.016 \times 4600 = 21.98 + 73.60 = 95.58 \approx 96$.

Determination of BTU-per-hour savings

With the footcandle levels of Table V in hand, the BTU-per-hour savings obtainable by turning off a fraction of the artificial lighting within the room can be calculated. Recall that with all the fluorescent lamps turned on, an average level of 50 footcandles on the work plane was achieved and 2116 watts were consumed. The maximum saving obtainable is $3.413 \times 2116 \approx 7200$ BTU-per-hour. This will occur whenever the skylights provide 50 footcandles or greater of work plane illumination. For skylight footcandle levels less than 50 footcandles, a fraction of 7200 BTU-per-hour is saved. The BTU-per-hour savings corresponding to the skylight footcandle levels of Table V are displayed in Table VI, where there is rounding-off to the nearest 100 BTU's.

What Table VI says is that, for example, on June 21 at 42 degrees north latitude with an overcast sky, the average horizontal footcandles from skylighting with a translucent dome at 10 am are such that 33 percent of the artificial lighting can be turned off with a saving of 2400 BTU-per-hour. With a clear day plus direct sun situation under the same conditions, 100 percent of the artificial lighting can be turned off and 7200 BTU-per-hour can be saved.

Conclusion and critique

The procedure outlined in this paper should help those concerned with skylighting to obtain estimates

Table V—Average horizontal footcandles on work plane from skylights

		June 21			March-Sept 21			December 21		
		8am	10am	12noon	8am	10am	12noon	8am	10am	12noon
					Transparent Dome					
Overcast	34°	18	31	--	12	23	27	5	13	16
Sky	38°	18	30	--	11	21	25	4	11	14
	42°	19	29	40	11	20	24	2	10	12
Clear	34°	93	139	157	56	114	131	17	59	81
Sky Plus	38°	93	137	152	50	108	126	12	50	65
Sun	42°	96	136	149	48	101	118	7	40	56
					Translucent Dome					
Overcast	34°	11	18	--	10	14	15	7	10	12
Sky	38°	11	18	--	10	14	15	6	10	11
	42°	11	17	24	9	13	14	4	9	10
Clear	34°	54	80	90	33	66	76	10	35	47
Sky Plus	38°	54	79	88	29	62	73	7	29	38
Sun	42°	55	79	86	28	59	68	4	23	33
					Double Dome - Transparent over Translucent					
Overcast	34°	9	15	--	6	11	14	2	6	8
Sky	38°	9	15	--	6	11	13	2	6	7
	42°	9	15	20	5	10	12	1	5	6
Clear	34°	50	76	86	30	62	72	9	32	44
Sky Plus	38°	50	75	83	27	58	68	6	27	35
Sun	42°	52	74	82	26	55	64	4	21	30

To obtain lux, multiply each footcandle value by 10.76.

Table VI—BTU-per-hour savings with skylights

		June 21			March-Sept 21			December 21		
		8am	10am	12noon	8am	10am	12noon	8am	10am	12noon
					Transparent Dome					
Overcast	34°	2600	4500	--	1700	3900	3900	700	1900	2300
Sky	38°	2600	4300	--	1600	3000	3600	600	1600	2000
	42°	2700	4200	5800	1600	2900	3500	300	1400	1700
Clear	34°	7200	7200	7200	7200	7200	7200	2400	7200	7200
Sky Plus	38°	7200	7200	7200	7200	7200	7200	1700	7200	7200
Sun	42°	7200	7200	7200	6900	7200	7200	1000	5800	7200
					Translucent Dome					
Overcast	34°	1600	2600	--	1400	2000	2200	1000	1400	1700
Sky	38°	1600	2600	--	1400	2000	2200	900	1400	1600
	42°	1600	2400	3500	1300	1900	2000	600	1300	1400
Clear	34°	7200	7200	7200	4800	7200	7200	1400	5000	6800
Sky Plus	38°	7200	7200	7200	4200	7200	7200	1000	4200	5500
Sun	42°	7200	7200	7200	4000	7200	7200	600	3300	4800
					Double Dome - Transparent over Translucent					
Overcast	34°	1300	2200	--	900	1600	2000	300	900	1200
Sky	38°	1300	2200	--	900	1600	1900	300	900	1000
	42°	1300	2200	2900	700	1400	1700	100	700	900
Clear	34°	7200	7200	7200	4300	7200	7200	1300	4600	6300
Sky Plus	38°	7200	7200	7200	3900	7200	7200	900	3900	5000
Sun	42°	7200	7200	7200	3700	7200	7200	600	3000	4300

of average lighting energy savings that can result from the use of skylights in providing horizontal illumination in room interiors. But the procedure is by no means a panacea, and additional data need to be gathered and analysis and design procedures need to be refined. Following are several comments and suggestions for future work.

(1) Current data on the illumination from clear skies are inconsistent. Clear sky luminance distributions are very nonuniform and the assignment of an equivalent sky luminance is questionable and should be reviewed.

(2) The definition of *overcast* needs to be spelled out quantitatively before one can develop confidence in the use of overcast sky luminance data. Also, overcast sky data for solar latitudes greater than 73 degrees need to be obtained.

(3) Most days are neither completely overcast nor completely clear. Sky luminance data are needed for such situations.

(4) The daylight industry should decide what sky and sun data it needs—latitudes, dates, times, averages over time.

(5) A standardized procedure for measuring the diffuse transmission factors of domes is needed. Such a procedure should take into account dome shape and should also allow for the fact that dome thickness varies from edge to peak, whereas flat-sheet thickness does not. It should also require a standard light source, probably a uniform luminance hemisphere, and should allow for source polarization.

(6) A standardized procedure for measuring the direct transmission factors of domes is needed. Here angle of incidence is a key factor. The procedure in this paper of using a constant direct transmission factor for angles up to 70 degrees needs to be tested.

(7) The room ratio table in the IES RPD needs to be reexamined and expanded. For example, the table does not permit one to calculate the illumination from skylights for a large factory area of say 100 feet by 100 feet with a 30-foot ceiling.

(8) In determining net skylight transmission, several factors such as well-height, well-wall reflection factor and the dimensions of the hardware around the edges of the dome must be taken into account. Reliable standardized data on these parameters should be published.

(9) The coefficient of utilization table for skylighting in the IES RPD needs to be expanded to include floor reflectances and additional ceiling reflectances and wall reflectances.

(10) A study of maintenance factors of skylighting installations should be done. This factor should include dome dirt depreciation, room surface dirt depreciation and loss of transmission of a dome due to aging.

(11) It is desirable to include ESI in skylighting design.

(12) The use of flat acrylic or glass lens plates, possibly polarized, at the sky dome ceiling openings for reduction of glare, veiling reflections, and sky dome luminances should be investigated.

References

1. Committee on Daylighting of the IES, "Recommended practice of daylighting," ILLUMINATING ENGINEERING, Vol. 57, No. 8, August 1962, p. 517 (also available as a reprint, IES RP-5).
2. J. E. Kaufman and J. F. Christensen (editors), *IES Lighting Handbook*, Fifth Edition, New York: Illuminating Engineering Society of North America, 1972.
3. L. F. Schutrum and N. Ozisik, "Solar heat gains through domed skylights," *ASHRAE Transactions*, Vol. 67, August 1961, p. 465.
4. O. L. Pierson, "Acrylics for the architectural control of solar energy," in *Technical Papers, Vol. 9*, presented at the Nineteenth Annual Technical Conference (ANTEC) of the Society of Plastics Engineers, Inc., Los Angeles, Ca., February 26–March 1, 1963, Session No. 7, Paper No. 2. (Similar engineering design information is found in O. L. Pierson, "Control of solar energy transmission with acrylic construction panels," *SPE Journal*, Vol. 19, No. 10, October 1963, p. 1085.)
5. E. Linforth, "Daylighting," ILLUMINATING ENGINEERING, Vol. 53, No. 9, September 1958, p. 475.
6. "Daylighting characteristics of acrylic dome skylights," *Rohm and Haas Bulletin PL-586* (available from Rohm and Haas, Independence Mall West, Philadelphia, Pa. 19105).
7. "Plexiglas design and fabrication data," *Rohm and Haas Bulletin PL-927a* (available from Rohm and Haas, Independence Mall West, Philadelphia, Pa. 19105).
8. "Systems analysis for skylight energy performance," A report to the skylighting industry from the Center for Industrial and Institutional Development, University of New Hampshire, October 1976.

DISCUSSION

D. L. DILAURA:* The author has performed a service by culling together some of the literature on daylighting and applying it to the question of lighting energy savings from skylight use. The result is a straightforward procedure for determining horizontal illumination from skylights that allows a resultant savings in artificial lighting to be determined. There seems to be little room for comment on any particular aspect of the procedure itself, save to question the need for the detailed consideration of skylight transmittance, given the crude nature of the calculations implicit in the zonal-cavity system and the "Recommended practice for daylighting." Is not such detail lost in the overall *slippage* when using such procedures as the zonal-cavity system?

The importance of the author's statement that the paper "is not a procedure for determining the total energy balance within a space" must be emphasized. He rightly indicates that it only provides for lighting energy trade-offs based on average horizontal illuminance levels, one possible aspect of the entire energy question in buildings. The narrowness of these considerations must be made clear. The information in this paper is of little value unless coupled with skylight heat-loss/heat-gain analyses. I am not aware of any significance of "savings in lighting energy." Energy savings are meaningful *only* when, as the author points out, the overall balance is considered. In this regard, it would be a serious omission to leave out the word "lighting" from the paper's title.

There are several questions regarding the underlying assumptions of the procedure. I believe that justification must be made for making linear trade-offs between lighting systems (artificial or otherwise) based only on average horizontal illuminance levels. A trade-off, even within a scope limited to lighting systems' comparison, must be made on a precisely equivalent basis if it is to be linear. By linear is meant the equivalence relation of watts or lumens (in this case) produced in one system in a particular range of levels to watts or lumens produced by another system, possibly in another range of values. The use to which most lighting systems are put does not allow the equivalence relation of average horizontal illuminance levels since average horizontal illuminance does not necessarily track or correlate with visibility or visual

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Table D1 —Heat loss/gain comparisons between typical roof and skylights

Component	"U" Factor (conservative)	BTU/Hour /° F for 54 square feet	Denver Conditions			
			Design Winter ΔT 80°	BTU/Hour Summer ΔT 20°	Year D.D. 5905 x 24 hours BTU	Cooling Hours for 450 hours/year
Typical roof	0.15	8.1	648	162	1,149,000	72,900
Skylights						
Clear with diffuser (double layer)	0.45	24.3	1944	485	3,444,000	218,250
Clear or translucent	0.75	40.5	3240	810	5,740,000	364,500

performance, and the purpose of most lighting systems is to produce visibility or visual performance.

Based on average horizontal illuminance *alone,* one cannot simply substitute a certain amount of daylighting for the same amount of artificial lighting: In some cases the daylight is far more efficacious than artificial lighting and should not be traded on a one-to-one basis. In other cases, the converse is true. Zonal-cavity techniques simply cannot supply the required information.

The issue is not the trading of daylighting for artificial lighting, but the assumption of linearity. I submit that the trade-off the author assumes can be made is not possible in most environments unless we use ESI. In that regard, I concur with the author's conclusion remarking on the need to use ESI in daylighting analysis.

A. W. LANGE AND C. M. PELANNE:† Architects and engineers over the past several decades have frequently been intrigued by the possibility of electrical energy savings by using daylight instead of electrical illumination for certain types of buildings, but experience shows that:

(1) The multistory structure is more efficient and economical for owning and operating costs, and land costs; and this would eliminate all but the top floor of such a structure from daylighting considerations.

(2) When the top floor of a multistory structure, or a single level building is analyzed for total energy requirements and total-operating-costs per square-foot per year, it becomes evident that the savings in energy by using daylighting are to a large degree offset by losses during the heating season, heat gain during cooling season requiring air conditioning, air infiltration, and the many ancillary maintenance problems experience proves crop up during the life of the structure: (a) maintenance of the skylight (washing, cleaning); (b) snow buildup; and (c) repair costs due to rain and snow melt leakage.

The paper is, as stated in the introduction, limited to the lighting considerations. The author states that he has not included the effects of the skylights on the heating and cooling loads of the example building. These factors should be taken into account if one is to make a reasonable judgment on the merits of skylights. While our investigation has been limited, we must comment on several factors that are significant.

First, the heat loss or gain (air to air) on the basis of the substitution of the skylights into the roof increases by a factor of three to five, depending on the type of skylight, over a conventionally insulated roof. Table D1 shows the effect of this substitution for the example cited by Dr. Murdoch—54 square feet of skylight. The data is presented for Denver, Colorado, conditions (winter/summer design, degree day and cooling hour basis). It must be stated that these data represent only "U" value heat flow rates but do not include the effects of added air infiltration that can be a very significant factor. In some instances it has been found to be one-third of the total building heat loss. These data are only intended to illustrate one aspect of the problem, and do not show the whole picture.

A second important aspect is the solar heat load. In the winter the heat gain during a clear sunny day may be an added benefit which may partially compensate for the heat loss throughout the day and night dependent on outside temperatures. In the summer, however, the problem is much more significant since it adds to the

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Table D2—Heat load (BTU) on sunny day (based on nine-hours lighting)

	Solar Heat Load	Transmitted Heat Load (additional) ΔT 20° F	Total Additional Load (BTU/day)
Square feet	1,937	108*	2,045
54 square feet	104,598	5,832	110,430

*("U" - "U" skylight roof) x ΔT x hours = heat load BTU per square foot
(0.75 - 0.15) x 20° F x 9 hours = 108 BTU per square foot

air conditioning load. Tables in *Heating and Ventilating Engineering Databook* by Strock indicate the heat gain in BTU-per-hour per square-foot, through skylights.

When we combine these two heat loads, solar radiation and transmitted heat, we obtain an increased heat load on the air conditioning amounting to more than 110,000 BTU-per-day (see Table D2). Air conditioners have about a 2.5 to 1 efficiency factor; thus, to remove this heat load will require 44,000 BTU of electrical energy. Our assumptions have been based on a nine-hour lighting day, thus the applicable per day savings is nine times the 7200 BTU-per-hour stated by the author. The net savings in energy on a single summer day is, therefore, (64,800 minus 44,000 or) 20,800 BTU-per-day or only 2300 BTU-per-hour net savings.

These examples of factors affecting the heat balance of the building are only intended to point out that these factors are not negligible. Only a complete, complex analysis of the problem can provide the necessary information for a sound decision. A complete analysis would have to include the changing solar load as a function of time of year and cloud cover, the changing transmitted load as a function of temperature difference plus the influence of infiltration which will depend on wind velocity.

The author does a service in presenting this paper at a time of concern for energy conservation, and the entire subject certainly merits further study. Our discussion is intended only to remind us all that skylights have been around in some form nearly as long as buildings have, and that the savings in lighting energy are offset to an appreciable extent by these thermal considerations.

AUTHOR: I wish to thank the discussers for taking the time to comment on this paper. I think I might best respond to the comments of Mr. Lange and Mr. Pelanne by reviewing briefly some of the results of our overall study of skylights, of which the lighting study in my paper is only one part. The rest of the study did indeed involve consideration of the heating and cooling energy aspects of skylighting.

Without going into too much detail here, what we considered was an interior lunchroom 30 feet by 40 feet by 10 feet lighted artificially to an average maintained level of 30 footcandles (1290 watts). The room was in use from 6 am to 12 midnight seven days a week. We used six four-foot by four-foot double dome skylight units (8 percent of the roof area). Heating was electric and an inside design temperature of 65° F was assumed, with the heating system being on from October 21 through March 21. During that period of time we assumed that all the lights would be on—thus *no* lighting energy savings would result from skylighting.

Cooling was provided by mechanical refrigeration during the period March 21 through October 21. An inside design temperature of 80° F was assumed. For the cooling period we determined an average number of hours-per-day during which the artificial lighting could be off and still have 30 footcandles.

Calculations were made for six cities. I will summarize the results for one of these—Oklahoma City.

Cooling season: lights off an average of 7¾ hours-per-day.
Lighting energy saved: 7,390,000 BTU-per-year.
Increase in cooling system energy: 3,042,000 BTU-per-year.
Increase in heating system energy: 1,430,000 BTU-per-year.
Net energy savings: 2,918,000 BTU-per-year.
Only one of the six cities examined showed an energy loss

(slight) from the use of skylights. Three cities showed a greater energy saving than was achieved in Oklahoma City. As a result of this study, I feel it is quite fair to say that properly designed and insulated double dome skylights usually result in overall energy savings, even though those total savings are significantly less than the lighting energy savings, as Mr. Lange and Mr. Pelanne point out.

I will consider Mr. DiLaura's comments in the order in which they are presented. I don't really care for his philosophy that one should not bother to improve one facet of a design or analysis procedure because some other facet may be "crude." One should then improve both facets. The fairly wide variations in flat-sheet transmission in the literature, the uncertainties regarding effects of doming, and the lack of quantitative methods for dealing with double domes are matters that I feel should be addressed.

I fully agree that the word "lighting" must be in the title of the paper, and it has been from the outset. I don't agree that the information in the paper "is of little value" unless coupled with the heat gain/loss analyses. The skylighting industry indicated a need to us for a procedure to calculate the potential lighting energy savings from the use of skylights. They were interested in both the procedure and the potential lighting energy savings, for they wished to assess whether their own skylighting design procedures were valid and complete.

The issue of "linear trade-offs" between lighting systems is a good one, although I'm not convinced that trade-offs must be on a "precisely equivalent basis." After all, we are engineers and not physicists. It seems to me that the substitution of skylighting in a ceiling for artificial lighting located on a ceiling does not have to cause much difficulty in this linear trade-off sense. Far more serious would be comparisons of other methods of daylighting such as sidelighting, with artificial lighting. In these latter cases, I agree with Mr. DiLaura that ESI should be used in making the comparisons.