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Skylight Design: Photometric Characteristics

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Abstract

This study analyzes the photometric performance of a sample of commercially-available 4' by 4' skylights, of the type commonly used to light warehouses, grocery stores and big box retail stores. Though skylight photometry has been measured earlier on scale model and residential sized skylights,^{1,2} this study is the first time that the luminous distribution of commercial sized skylights has been measured and recorded in the IESNA LM-63-95 photometric file format.³ These files are freely available at www.h-m-g.com. An innovative goniophotometer⁴ was used to take measurements under real skies in both clear and overcast conditions.

This paper analyses the measured photometric data to investigate the way in which skylight efficiency and light distribution are influenced by common design variables such as skylight shape, glazing material properties, light well depth and light well surface reflectance. These variables determine not only the luminous performance of the skylight (as described by its luminous efficiency, the degree of asymmetry of the light, and the uniformity of illuminance in the building beneath) but also its uniformity over time, since the light distribution of some skylights changes significantly during the course of the day while others have a fairly unchanging distribution.

The idea of an “ideal” skylight that would produce a reasonably constant level of illumination under a wide variety of sky conditions is discussed. The tested skylights do not approach this ideal performance; this paper describes a framework within which skylight manufacturers could improve and test their existing products.

Types of Skylight Tested

Three shapes of skylight were tested: dome, pyramid and compound arch (see Figure 1). The dome and compound arch shapes are formed by blow forming or stretching over a frame a heat-softened flat plastic sheet, while the pyramid shape is formed by joining four or more flat sheets. The plastics we tested included: acrylic, structured polycarbonate, PET (polyethylene tetrachloride) and fiberglass insulating panels. Some of the glazings diffused light via the use of pigments, refraction due to surface and shape of the glazing cross section and others used fibers. Transparent plastic and glass skylights were also tested.



Figure 1 - The three shapes of skylight tested: dome, pyramid and compound arch

Each skylight was tested on top of a generic non-splayed square light well 1.2 m (4') in width and length, and either 0.3m (1'), 0.9m (3') or 1.8m (6') in depth. The walls of the light well were lined with either white-painted sheetrock or highly specular aluminum.

Photometric Test Method

To measure the photometric distribution of a skylight, a large photometer with unobstructed access to daylight was required. Since no existing device of this type could be found, one was specially constructed

for this project (see Figure 2), and has been described in detail in a previous paper⁵ that also discusses sources of error. The photometer resembles a small room with a 2' by 2' (0.6m by 0.6m) square aperture on top and a series of fixed mirrors and photocells inside. Skylights that were 2' by 4' or 4' by 4' could be tested one section at a time. The skylight photometer is subject to all the sources of error of a regular photometer, and to several further sources of error incurred by the inherent variability of the light source.

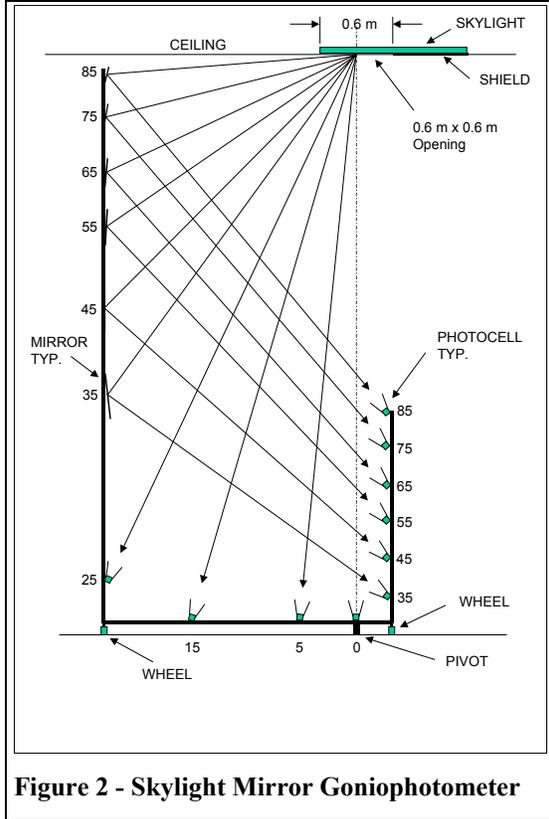


Figure 2 - Skylight Mirror Goniophotometer

Sources of Experimental Error

Measurements were taken under real skies that are non-uniform and that change constantly; this induces two types of error.

Firstly, the condition of the sky was slightly different from one set of measurements to another. We intended to conduct the tests under perfectly overcast or perfectly clear skies, since these are extreme conditions of the sky, and many other sky conditions can be approximated as a combination of overcast and clear. Also, overcast and clear are fairly common sky conditions in many climates. Unfortunately, real skies are almost never either perfectly overcast or perfectly clear, so to ensure that the skies under which measurements were taken were as close as possible to ideal conditions, one of two criteria for sky ratio had to be met before measurements were taken. Sky ratio is the ratio of diffuse horizontal illuminance to global (diffuse plus direct solar) horizontal illuminance. Sky ratio had to be less than 0.25 for clear skies and greater than 0.85 for overcast skies. However, cloud locations may have varied during each test cycle such that the sky ratio criterion may not have been met for the entire duration of each cycle. Furthermore, 0.25 does allow some degree of cloudiness in a mainly clear sky (see Figure 3). Although sky ratio was

much less than 0.25 during most of the measurements, the measurements taken at low sun angles had sky ratios that approached 0.25 because the horizontal illuminance from the sun is proportional to the sine of solar elevation. For future measurements, a more robust criterion for sky clearness might be the ratio of normal beam illuminance to diffuse illuminance. A threshold value for this ratio would have to be chosen to ensure both that there is an unobstructed view of the sun, and that cloud cover is not more than a few percent.

Secondly, sky conditions change constantly; during the course of one set of measurements the sun moves a short distance across the sky, and the pattern of luminance of an overcast sky may change. To minimize the resulting error, the time taken for the measurements had to be as short as possible, so the number of measurements taken was reduced to the bare minimum: 22.5 degree increments of azimuth and 10 degree increments of elevation were used. These increments are larger than the 15 degree increments of azimuth and 5 degree (or 2.5 degree) increments of elevation typically used in luminaire photometry. Other sources of error are more fully described in Domigan et al.⁶



Figure 3 – Clear skies that meet the criterion for 0.25 sky ratio may still have clouds that might obscure the sun and compromise photometric measurements

Possibly the largest source of error is due to the interaction between the collimated or partially collimated light from the skylight and the “grid” of measurement points defined by the shape and size of the photometer. The reflected path that the light must travel between the goniophotometer opening in the center of the photometer is 17 feet (5.2 m) so at 45 degrees elevation, the 22.5 and 15 degree horizontal measurement increments correspond to a horizontal measurement spacing of 4.7 ft (1.4m). Since the skylight aperture under test was only 2 ft (0.6m) wide, a patch of sunlight falling through this aperture could easily have fallen between measurement points, leading to a significant underestimate of the efficiency of the skylight, and a completely incorrect luminous intensity distribution. This may have been a major source of error for the photometric measurements of flat non-diffusing glass skylights that admit significant amounts of collimated light. The only way to reduce this error would be to increase the number of measurement points to ensure that the measurement grid is substantially smaller than the patch of collimated light. An integrating sphere (or its equivalent, a grid of photocells across the neck of the light well, as described in an earlier report¹¹) would produce a more accurate measurement of the total number of lumens leaving the skylight, but this value could not be used to “scale up” the goniometric intensity values, as this would lead to inaccurate values for the diffuse portion of the skylight’s output.

In an attempt to quantify the magnitude of these errors, a comparison was made between the two sets of efficiency data recorded for each skylight – one set in the morning and one set in the evening. In theory, the morning and evening results should be identical since the solar elevation and solar azimuth are symmetrically equal. Any difference should be due to variations in weather conditions, or to shafts of collimated light either just missing or just hitting particular photocells. The average magnitude of the ratio of the morning and evening efficiencies are shown in Table 1. The fact that most transparent materials (flat glass and clear structured polycarbonate) have the highest magnitude errors suggests that collimated light may be the most significant source of error with this experimental apparatus. The magnitude of the errors for diffusing skylights is of the order of 10%.

Skylight Shape	Glazing	Average error between AM and PM efficiency
White acrylic dome	single glazed	0.1
	double glazed	0.11
Flat glass	double glazed	0.21
Compound arch, ridges N-S	single-glazed white PET	0.05
	double-glazed prismatic acrylic	0.04
Pyramid	double-glazed clear structured PC	0.20
	double-glazed crystal fiberglass	0.08

Table 1 – Average magnitude of the ratio of morning to evening efficiency values for various skylights. All have 1' white light wells.

The outdoor photocell used in the experiment was found to have degraded by 19% during the period over which measurements were taken. An attempt was made to compensate the results to take account of the decay; a mathematical model was created that used measured daily illuminance data and assumed that the sensitivity of the outdoor photometer decayed exponentially over time, from initial accurate measurement to recording only 81% of actual measurements at the end of the measurement period.

The shape of this outdoor photometer sensitivity decay curve comes from three sources: the photometer was calibrated at the initiation of the measurement period, the error of the photometer was established at the end of the measurement period and the time in between was compared against the IESNA clear sky model over each day and as a further check compared against data from a nearby weather station managed by the Arizona State climatologist. Weather data included global horizontal irradiance and dewpoint temperature. Global horizontal irradiance was decomposed into its horizontal diffuse and direct beam components via the Boes correlation with respect to kT, the ratio of global horizontal irradiance to extraterrestrial irradiance.⁷ Luminous efficacies of diffuse and direct beam sunlight can be calculated by means of the Perez et al.⁸ correlation to irradiance, Zenith angle, air mass and dewpoint temperature. Multiplying these calculated efficacies by their corresponding components of irradiance yields direct beam and diffuse ambient illuminance.

As shown in Figure 4, the IESNA clear sky model estimated that on the first day of testing, recorded measurements were higher than the real ambient light levels, whereas the weather station data and the Perez model estimated that recorded measurements were lower than real ambient light levels. This discrepancy lasted over the course of the test period. Both the clear sky model and the weather station data were normalized (multiplied by a constant) so they matched the first day's recorded measurements with the outdoor photometer used with the goniophotometer. An exponential decay curve was fitted to the Boes/Perez and IES clear sky data, and had coefficients as shown in (1).

$$\text{Ratio of measured illuminance to predicted illuminance} = 0.812 + 0.188e^{-0.28(\text{daynumber})} \quad (1)$$

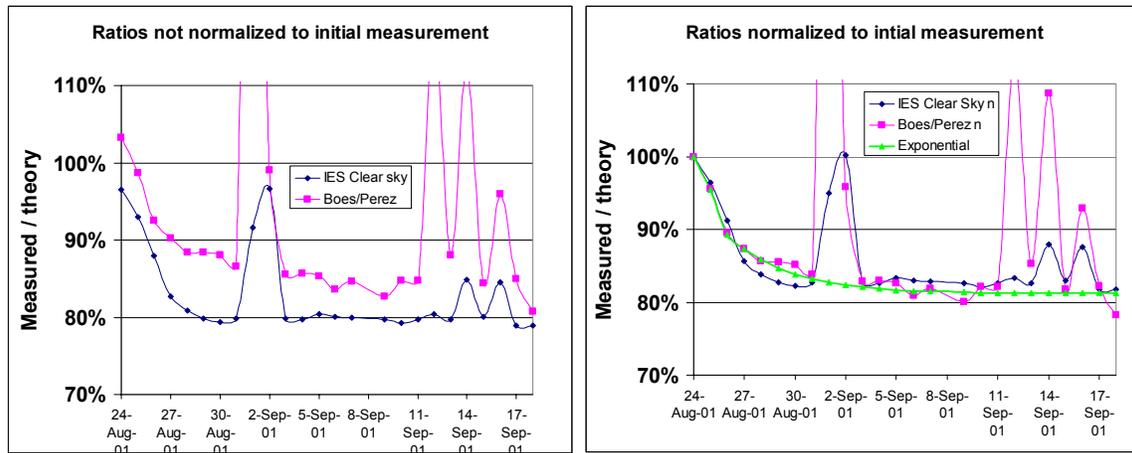


Figure 4 - Ratios of measured illuminance to IESNA Clear Sky Model or local weather and Perez model and the resulting exponential correction factor

We think that the discrepancy between the exponential best fit curve and the data in the two predicted curves is related to tests being conducted under partly cloudy skies – at such times reflected light from clouds can increase ambient light levels and weather station irradiance data taken on an hourly increment may be reduced by clouds passing across the sun.

Skylights tested during these periods of discrepancy between the exponential decay function and the models are: the compound arch when rotated 90° ribs of arches face E-W, the single glazed white acrylic dome over a 3 foot tall specular light well and over a 6 foot specular light well, a single measurement at solar noon of a structured polycarbonate pyramid over a 1 foot white light well. The overall efficiency (fraction of transmitted light) of these test results should be questioned. However, the photometric distributions in terms of relative intensities are not affected by this error. Thus the shape of polar plots from these tests could be accurate while the scale or magnitude may be incorrect. Because the physical processes described in the previous paragraph could explain the discrepancy, other comparisons are needed to determine whether these tests should be removed from the library of skylight photometrics.

Although shadowing from surrounding buildings was minimal, it may have reduced the interior light measurements especially for the shorter light wells. See Figure 3 for the “fish-eye” view of the sky from the test apparatus.

Lastly, only a certain range of solar azimuth angles were tested for each skylight. For dome skylights it might be anticipated that azimuth would not significantly affect the measured efficiency or intensity distribution, but for pyramid and compound arch skylights azimuth might affect results significantly.

Limitations of the Results Obtained

The photometric data was collected under real sky conditions at a single location over a period of a few weeks. Consequently, for each angle of solar elevation, there is only a very small variation in solar azimuth. To make the results more indicative, it would be desirable to test the skylights at different times of year to obtain measurements under a wider range of azimuth angles. We took goniophotometric measurements of a small subset of skylight and light well configurations in the winter to investigate how sensitive the photometric distribution is to azimuthal angle.

Similar to luminaire photometric tests, the results do not include any consideration of dirt appreciation on the top of the skylights. Similar to electric lighting design, dirt depreciation should be calculated as part of the design process.

Results: Effect of Light Well Design on Photometrics

White Light Wells

White pigmented acrylic dome skylights produce a near-Lambertian (cosine) distribution of light under an overcast sky (see Figure 5). As the depth of the light well increases, this distribution becomes narrower. These plots are for a light well with 80% reflective matte white paint.

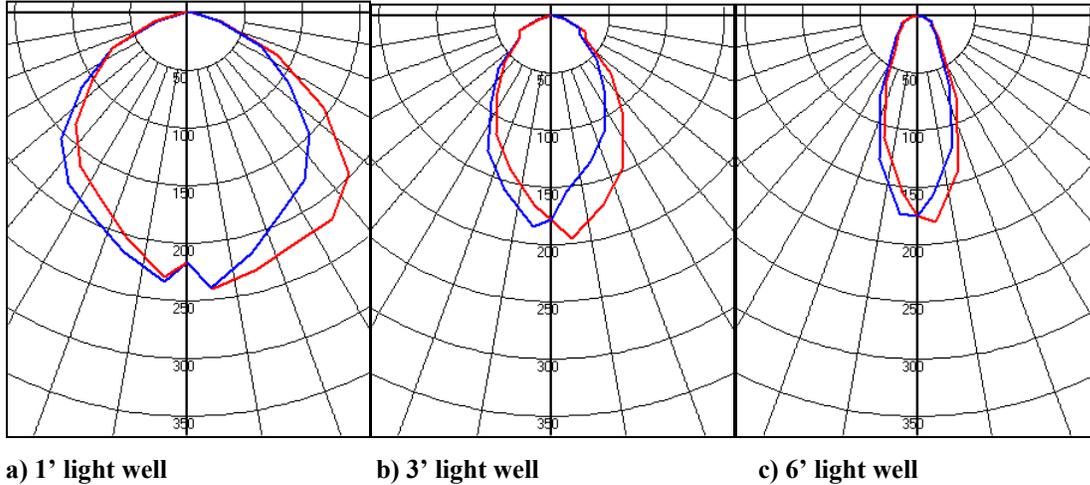


Figure 5 - White acrylic dome skylight with 1', 3', and 6' white light well under overcast sky

As the light well depth increases, the overall efficiency of the skylight drops (see Table 2); this follows an approximately exponential decay with increasing length. The percentage reduction would be less for larger diameter light wells, and for splayed light wells.

Light well depth	1'	3'	6'
Skylight efficiency	45%	30%	19%

Table 2 – Average efficiency over all sun angles of white acrylic dome skylights with white light wells.

The intensities at the nadir for these skylights are, with increasing light well height, 216, 178 and 176 cd/klm (the intensities are normalized per 1,000 lumens, since the actual intensity leaving the bottom of the light well is proportional to the number of lumens of daylight incident on the skylight opening). The values reduce because the skylight dome itself moves further away from the photometer's photocell as the well height increases. Photometers measure illuminance; intensity values are then calculated from these values (using $I=E.d^2$), based on the assumption that the skylight is a point source at a fixed distance from the photocell. This assumption is not true because the skylights with deeper light wells were further from the photocell than skylights with shallow light wells, hence they were further from the photometric center and their apparent intensity decreased. This reduction is itself influenced by increases in light reflected from the side walls of the well. Measured intensity values are subtly affected by the length of the light path in each particular photometer; the decrease in nadir intensity would be less for a larger photometer, and would tend to zero for an infinitely large photometer.

Specular Light Wells

Matte white light wells cause a narrowing of the polar curves as the light well becomes deeper, but highly specular light wells do not show this tendency (see Figure 6). Note the difference in scale on the two plots. A similar reduction in the nadir intensity is found in the 6 foot well as was found for the white light well. Thus we are deviating somewhat from the assumption that the source is at the geometric center of the goniometer.

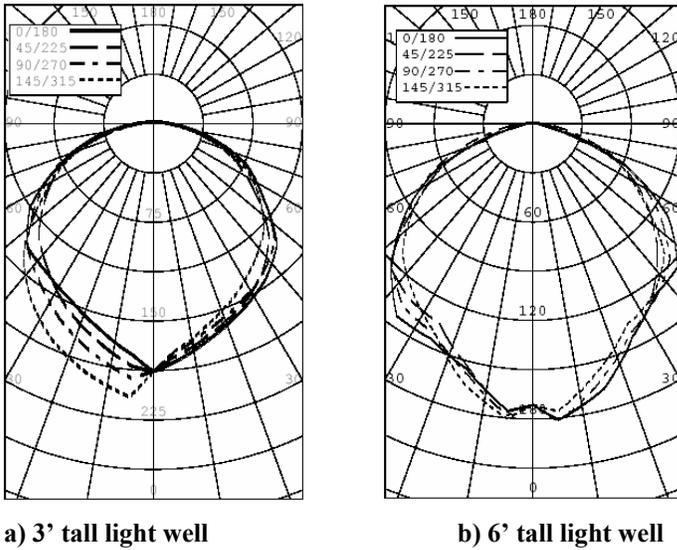


Figure 6 - White dome skylight with 3' and 6' specular light well under overcast sky

Furthermore, it would be expected that the reduction in efficiency with light well depth would not be so pronounced for specular light wells as for white light wells, due to the higher reflectance of the specular materials used, and the absence of light being scattered back up the well from diffusely reflecting light well walls. As shown in Table 3, the overall efficiency the white skylighting over a 3' specular light well is 37%. This is 23% more light than the skylight and light well efficiency of 30% for the same skylight over a 3' white light well. Note that increasing the light well depth to 6' has little impact on the overall system efficiency. This would indicate that here is great benefit to making use of specular surfaces when it is necessary to have a deep light well.

Light well depth	1'	3'	6'
Skylight efficiency	No data	37%	34%

Table 3 – Average efficiency over all sun angles of white acrylic dome skylights with specular light wells.

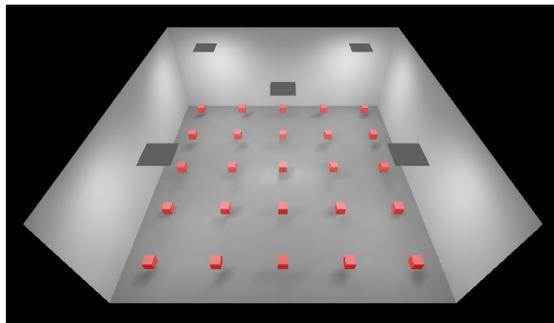
Presence of Diffusers at the Base of Light Wells

Diffusers at the bottom of the light well can make the light emitted from the light well both more uniform and less uniform, depending on the type of uniformity sought. One common measure of uniformity is the “spacing criterion” - a calculated value for how far apart two light sources can be spaced as a fraction of mounting height while providing the same illuminance half-way between those sources as is found directly underneath a single source.⁹

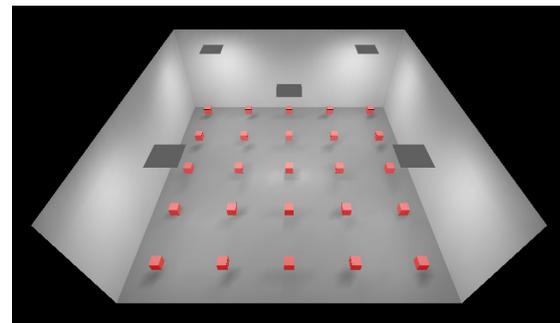
	3’ specular light well	3’ specular light well with diffuser
overcast	1.2, 1.2	1.1, 1.1
Clear sky, 10° solar elevation	1.3, 1.3	1.2, 1.4
Clear sky, 20° solar elevation	1.4, 1.6	1.3, 1.5
Clear sky, 30° solar elevation	1.3, 1.5	1.2, 1.4
Clear sky, 40° solar elevation	1.3, 1.5	1.4, 1.4
Clear sky, 50° solar elevation	1.4, 1.4	1.3, 1.3
Clear sky, 10° solar elevation	1.4, 0.9	1.3, 1.1
Average	1.34	1.29
Standard deviation of spacing criterion values	0.17	0.13

Table 4 - Minimum spacing criteria for a white acrylic skylight [parallel (N-S), perpendicular (E-W)]

The spacing criterion is usually the considered the maximum distance apart fixtures can be spaced while maintaining uniformity. Diffusers tend to slightly reduce the spacing criteria of vertical (non-splayed) specular light wells (see Table 4), although the effect is small and does not make much difference to the appearance of the space as a whole (see Figure 7). The reduction in spacing criterion is not consistent; it does not occur for all sky conditions, or necessarily for both directions of measurement (parallel and perpendicular to N-S axis). Nonetheless diffusers are almost always used with specular light wells to control glare.



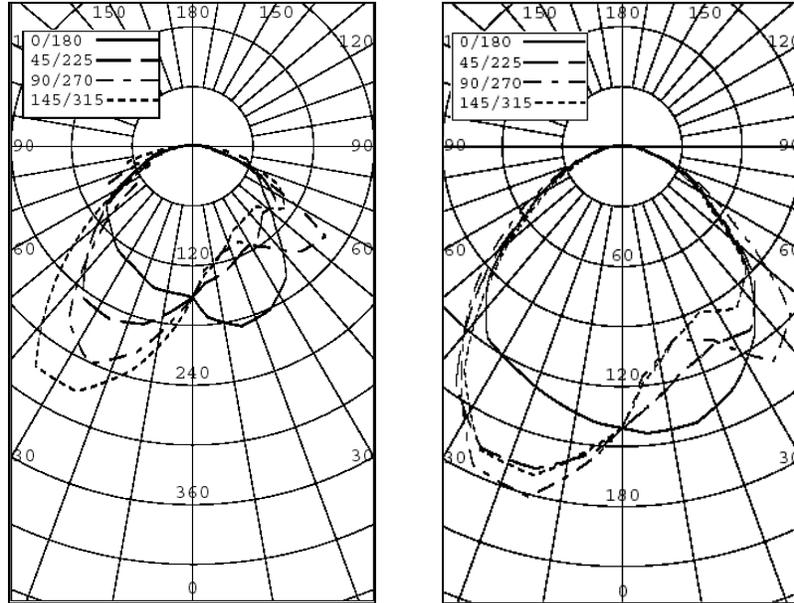
a) 3’ Specular light well



b) 3’ Specular light well and bottom diffuser

Figure 7 - Lumen-Micro visualization of space lit by white acrylic dome skylights without and with a bottom prismatic lens under an overcast sky

Another measure of the limited effect of the diffusers that were tested is the shape of the polar curve. If the diffusers were highly effective they would randomize the light passing through them and produce a polar curve that had the same values in each azimuthal plane. However, the polar curves of the diffusers that were tested show significant variations in intensity with azimuth under clear sky conditions (see Figure 8). The presence of a diffuser does broaden the polar plot showing that the diffuser does spread the light but is far from a Lambertian transmitter.



a) Photometric distribution without diffuser

b) Photometric distribution with diffuser

Figure 8 - White acrylic dome skylight in 3' specular light well without and with diffuser under clear sky with sun at 20 degree elevation. Note scale change between plots

Note that the use of spacing criterion as a design variable is only valid for spaces in which there are no large obstructions above the floor cavity. In real, cluttered spaces (for instance those with high racks) skylights have to be more closely spaced to achieve adequate uniformity. In many of these cases horizontal uniformity is not a relevant design criterion.

In other senses, the presence of a diffuser leads to increased uniformity. When viewed from below, a specular light well with a diffuser will appear more uniform than one without a diffuser, i.e., the aperture will be more uniformly luminous, and the luminance of the aperture will not alter quickly as the viewer walks around. Distraction effects can be a source of glare, so consequently a diffuser can be an effective anti-glare device even though it might cause the calculated glare index or glare rating of the space to increase.

The effect of diffusers may be summarized as follows:

- Little impact on uniformity; spacing criterion tends to be reduced
- Reduction in glare
- 20-30% Reduction in overall light level

Consequently, if glare control is the main goal and the light well is not too deep, it might be more efficient to use a white light well, or strategies borrowed from luminaire design such as reflected light on the ceiling, or the use of a translucent trim around the base of the light well.

Results: Effect of Solar Elevation on Photometrics

Typical Efficiency Curves

Each type of skylight has a characteristic curve relating solar elevation to overall efficiency, and the shape of these curves can be logically deduced. Here, efficiency is calculated by dividing the total number of lumens of light that leave the bottom of the light well by the number of lumens that would be incident on the 1.2 m by 1.2 m (4 ft by 4 ft) skylight aperture, were the skylight not present (note that the number of lumens falling on the skylight is often larger (but never smaller) than this value, because the skylights project upward from the aperture plane and ‘catch’ more sunlight than the aperture alone would). Measuring efficiency in this way provides a flat playing field for comparison of the effectiveness of different skylight shapes. The number of lumens transmitted down into the space is calculated by integrating the measured photometric intensity values of the skylight over the downward half-sphere, and the number of incident lumens is calculated by multiplying the measured external horizontal illuminance by the area of the skylight. The efficiency is therefore the proportion of lumens that are transmitted through the skylight, irrespective of where those lumens are directed.

Flat Glass Skylights

The efficiency of flat glass skylights should be described by the physical equations for the amount of light reflected and transmitted when an incident beam hits a partially reflective surface with a known refractive index. These would be modified by the path length of each incident beam through the glass, and would yield a curve that shows a steady increase in transmittance with solar angle. Theoretical predictions showing this increase in transmittance through multi-layer glazings were developed in the 19th century by Stokes.¹⁰

Figure 9 shows a comparison between light transmittance values calculated in three different ways: from the goniophotometric measurements; from a grid of 16 photometers placed directly beneath the 1.2 m by 1.2 m (4 ft by 4 ft) opening of the light well; and from the angular glazing transmittance value predicted by the Window 4.1 window properties calculation program (using Stokes’ equations). It should be noted that the grid measurements were taken at a different time as part of calorimetric measurements of skylights and light wells. See McHugh et al.¹¹ for more details.

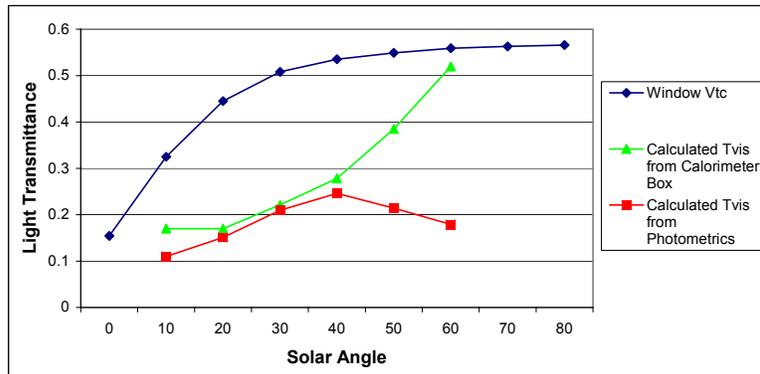


Figure 9 - Comparison of T_{vis} over varying solar angles - Window 4.1 software vs. calculations from calorimeter box and photometric testing. For a flat glass skylight with a 3' white light well.

For skylights that admit collimated light, the grid method is expected to produce smaller errors in the calculated skylight and light well efficiency than the goniophotometric measurements, because the patch of collimated light is less likely to “slip through” the measurement grid (see earlier discussion of errors). The grid measurement has 16 measurement points across a 16 sq foot opening (1 sq ft per measurement point) whereas the photometer has 73 measurement points around a hemisphere with a surface area of 1816 sq ft (on average 25 sq ft per measurement point). A patch of collimated light less than 4 sq ft in area in the goniophotometer is more likely to miss a sparse grid of photocells that cover 25 sq ft each than the 16 sq ft

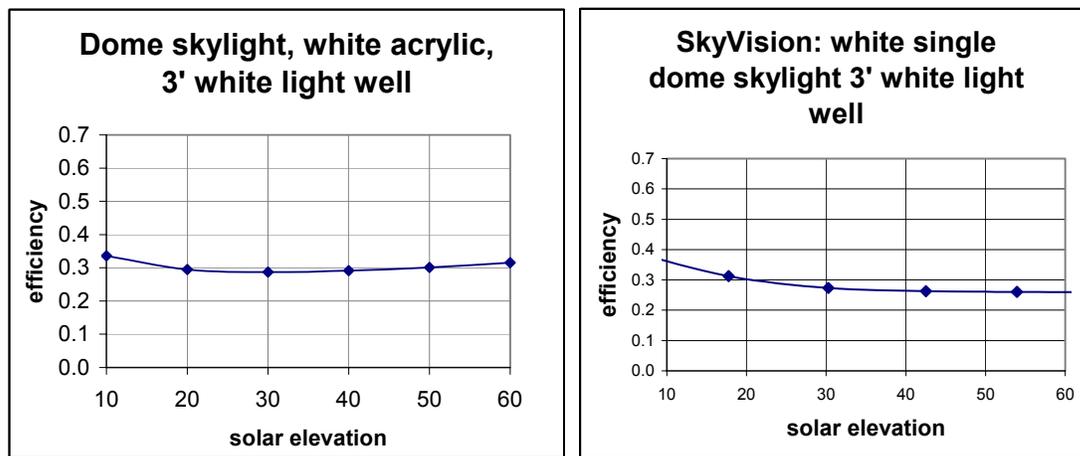
patch of light in the calorimeter will not be correctly characterized by a dense grid of photocell that cover only 1 sq ft each.

Measurements were made for a glass skylight over a 3 foot white light well using the skylight goniophotometer and the grid measurements in the calorimeter box. The resulting luminous flux exiting the bottom of the light well was divided by the ambient luminous flux on the skylight opening to yield a combined skylight and light well efficiency. So that this information could be compared with the Window 4.1 estimates of glazing transmittance, the combined skylight and light well efficiency was divided to by the well efficiency to yield the Skylight Tvis either measured using the grid in the calorimeter box or the skylight goniophotometer.

As shown in Figure 9, at low sun angles, the Tvis of both the photometer and the grid measurements match fairly well. It is hypothesized that at low sun angles, the light is mostly reflected by the light well and the distribution of light is diffuse and is therefore subject to less error. As the sun climbs higher in the sky, more collimated light is directly transmitted into the space and the spacing of measurement points becomes more important. However, both measurement methods have fairly large errors as compared to the theoretical calculations as contained in the Window 4.1 program.

White Acrylic Domed Skylights

These skylights have a very broad U-shaped curve that is almost flat relating their efficiency to the elevation angle of the sun (see Figure 10). The curve is essentially flat with a little increase in efficiency at both low and high sun angles.



a) Efficiency from photometric measurements

b) Efficiency calculated from SkyVision

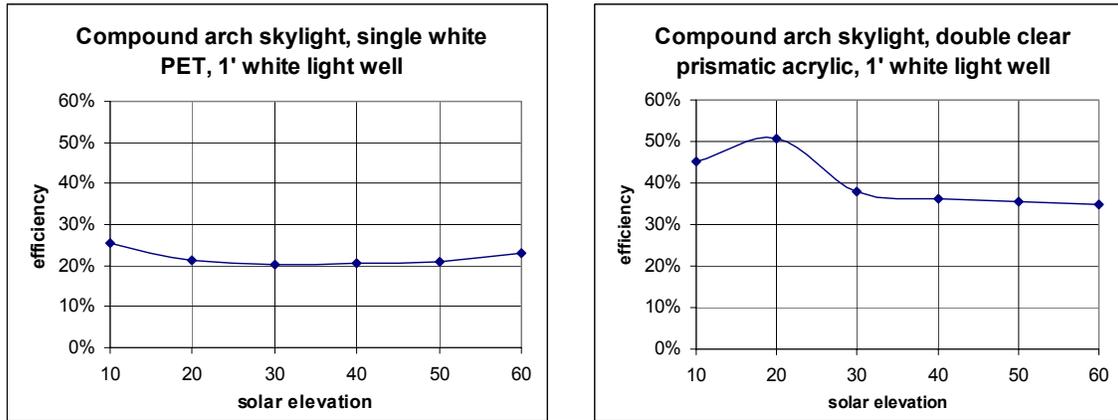
Figure 10 - Dome skylight, white acrylic with 3' white light well.

Due to its near-hemispherical shape, a dome-shaped skylight is effective at collecting incident sunlight even at low angles of solar elevation. This accounts for its high efficiency when the sun is at 10° elevation. However, the amount of sunlight collected does not increase significantly when the sun rises to 20°, yet the measured external horizontal illuminance does increase quite quickly (following a sine curve). Therefore, since the efficiency is related to the ratio of the collected light to the incident light, the efficiency of the skylight falls from 10° to 20°. However, in parallel with this decrease, the illuminance from daylight is increasing at a greater rate, so the actual amount of light transmitted down into the space at 20° is likely to be greater than that at 10°. As shown in Figure 10, this flat curve with higher efficiency at low sun angles matches well the analytical calculation of dome skylight effective visible transmittance developed by Laouadi and Atif, as implemented in the SkyVision skylight simulation software distributed by National Research Council Canada.¹² The SkyVision results match even better the more accurate efficiency calculations that result from grid measurements taken in the skylight calorimeter.

Compound Arch Skylights

These skylights are similar in shape to white acrylic dome skylights, but have flat sides intended to maximize light admission at low solar elevations. The compound arch skylights tested came in two materials: white PET and clear prismatic acrylic.

The efficiency curves of the white PET compound arch skylights are very similar to that of white dome skylights but with a slightly greater curvature. Efficiencies at middle solar elevations drop off, but the efficiencies are relatively flat (see Figure 11a).



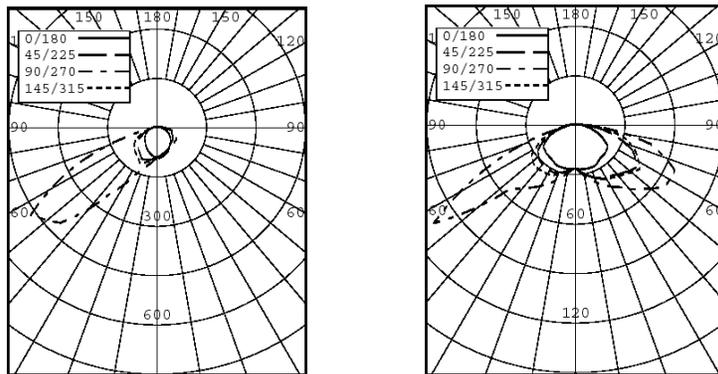
a) White single glazed PET

b) Double clear prismatic acrylic

Figure 11 - Compound arch white PET skylight and clear prismatic skylights with 1' white light well

The clear prismatic acrylic compound arch skylights have highest efficiency at low solar elevations and maintain relatively constant efficiencies at solar elevations higher than 30 degrees (see Figure 11b).

The reason for this is clear from the highly directional light distribution evident in the polar curves; the prismatic acrylic does not significantly scatter incident sunlight (see Figure 12), and consequently the polar curves are very similar to those of flat glass skylights. This may be because the prismatic material is insufficiently deep in profile, or because heating during the manufacturing process rounds off the edges and points of the prismatic material, or because the prisms are deformed during the bending process. It should be noted that a popular version of the prismatic compound arch skylight is clear prismatic over high white prismatic glazing to further increase diffusion.



a) Arch double prismatic acrylic

b) Flat double glass

Figure 12 - Compound arch prismatic acrylic skylight and flat glass skylight over 1' white light well, 20° solar elevation after noon. Note change in scale.

Other Skylights

Square pyramidal skylights were also tested, and they showed similar variations between steadily decreasing, steadily increasing, and check-shaped curves.

Results: Effect of Skylight Shape on Photometrics

Isolating the Effect of Shape

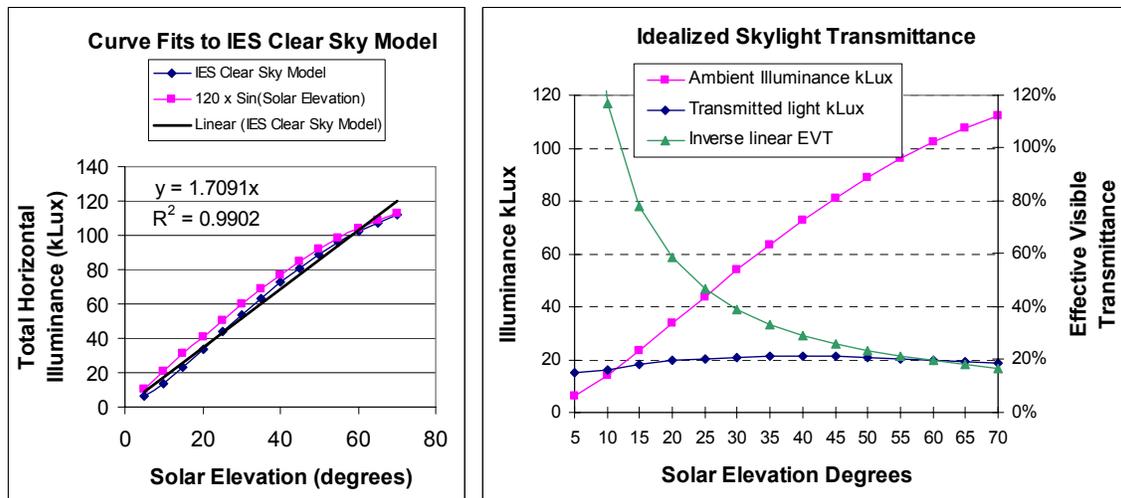
The effect of shape is of interest since several skylight manufacturers claim that particular shapes improve performance; several skylights are marketed on the basis that their shape admits light more efficiently at low solar angles than at higher solar angles, and therefore that their efficiency curves come closer to the “ideal” shape described below.

By comparing skylights that use similar diffusing materials, it is possible to isolate the effect of skylight shape (for instance, dome or compound arch) on efficiency at different angles of solar elevation. The diffusing materials used have different inherent visible light transmittance (VLT) values, so by scaling each efficiency graph up or down to normalize VLT at an arbitrary value (0.5 in this case), graphs can be directly compared; any differences should be due to shape only (see the graphs for the “dome” and “compound arch” skylights in Figure 14).

“Ideal” Efficiency Curves

For many applications, such as offices, retail stores and warehouses, the “ideal” skylight would provide a constant level of illumination throughout the day, irrespective of the sky condition or external horizontal illuminance. Providing too little illuminance would cause the lights to be switched on, thus wasting electricity, while providing too much illuminance brings no benefit and increases cooling loads.

In this paper, skylight efficiency curves are plotted for clear sky conditions as a function of solar elevation. Efficiency is defined with respect to global horizontal illuminance. Therefore to achieve constant illuminance under clear sky conditions at all elevations, an ideal skylight would have an efficiency curve that would follow the inverse of the global illuminance available at each solar elevation. Equations that describe typical values of global illuminance as a function of solar elevation¹³ have been used to derive the curves shown in Figure 13.



a) IES Clear Sky Model

b) Skylight EVT to yield constant transmitted light

Figure 13 IES Clear Sky Illuminance Model and ideal skylight effective transmittance (EVT)

The shape of the ambient solar illumination profile with respect to sun position is needed to identify the ideal shape of a skylight transmittance curve with respect to sun position. Figure 13(a) plots the total

(combined beam and diffuse) horizontal illuminance values of the IES clear sky model with respect to solar elevation. The global horizontal illuminance of the clear sky model can be simplified to a linear curve fit with 99% R^2 of the form:

$$\text{Horizontal illuminance klux} = 1.71 \times \text{Solar elevation (degrees)} \quad (2)$$

An alternate curve fit is:

$$\text{Horizontal illuminance klux} = 120 \times \sin(\text{solar elevation}) \quad (3)$$

A skylight that was able to transmit a constant amount of light into a space would have a transmittance that is the inverse of the clear sky function. In Figure 13(b), an example of the “ideal” angular effective visible transmittance is given by:

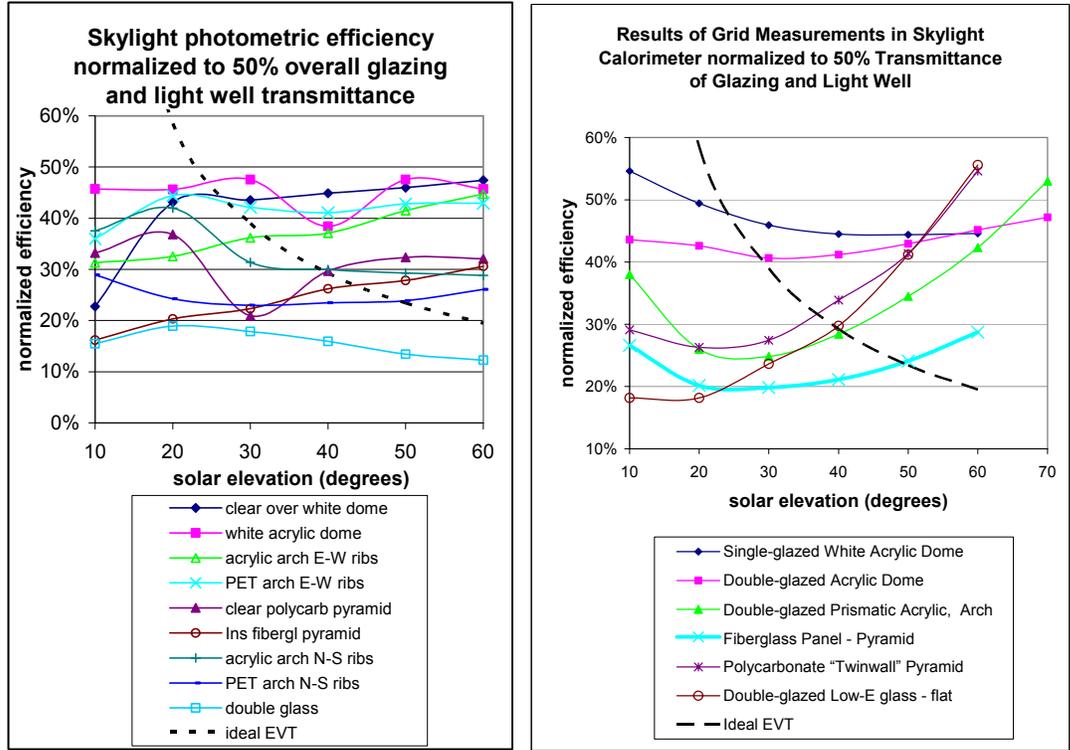
$$EVT = \frac{20}{1.71 \times \text{Solar Elevation (degrees)}} \quad (4)$$

The transmitted light by the skylight is the product of the ambient illuminance and the effective visible transmittance of the skylight; in this case yielding a nearly constant 20 Klux of transmitted light through the day. Thus the ideal skylight for clear sky climates will transmit significantly more light at low sun angles than at high sun angles. As shown in Laoudi & Atif⁴, dome skylights can have effective visible transmittances greater than 100% at low sun angles because they are intercepting significantly more light than their horizontal opening without a skylight.

Skylight efficiency under overcast skies is a constant value, and does not vary as a function of solar elevation. Overcast skies are also a less critical issue than clear skies because they do not radiate as much heat into the building and, in most climates, overheating is not likely on overcast days. Skylight efficiency under overcast skies should therefore be as high as possible.

Effect of Shape on Efficiency

Unfortunately only two of the skylight types tested (dome and compound arch) used highly diffusing materials. From this small sample it is impossible to draw general conclusions, but Figure 14(a) shows that the compound arch skylight, with its ridges oriented north-south, approaches closer to the ideal efficiency curve than the dome skylight does: its efficiency is higher at lower solar elevations, but when the solar elevation reaches 40° its efficiency falls sharply while the efficiency of the dome skylight continues to increase. When oriented in the other direction, the compound arch skylight performs in almost exactly the same way as the dome skylight. This improvement in performance with north-south orientation is in line with manufacturers' claims, and appears to make a difference of the order of 10-15% at low sun angles. This data is subject to significant errors, so this improvement in performance should not be regarded as proven.



a) Efficiency from goniophotometer

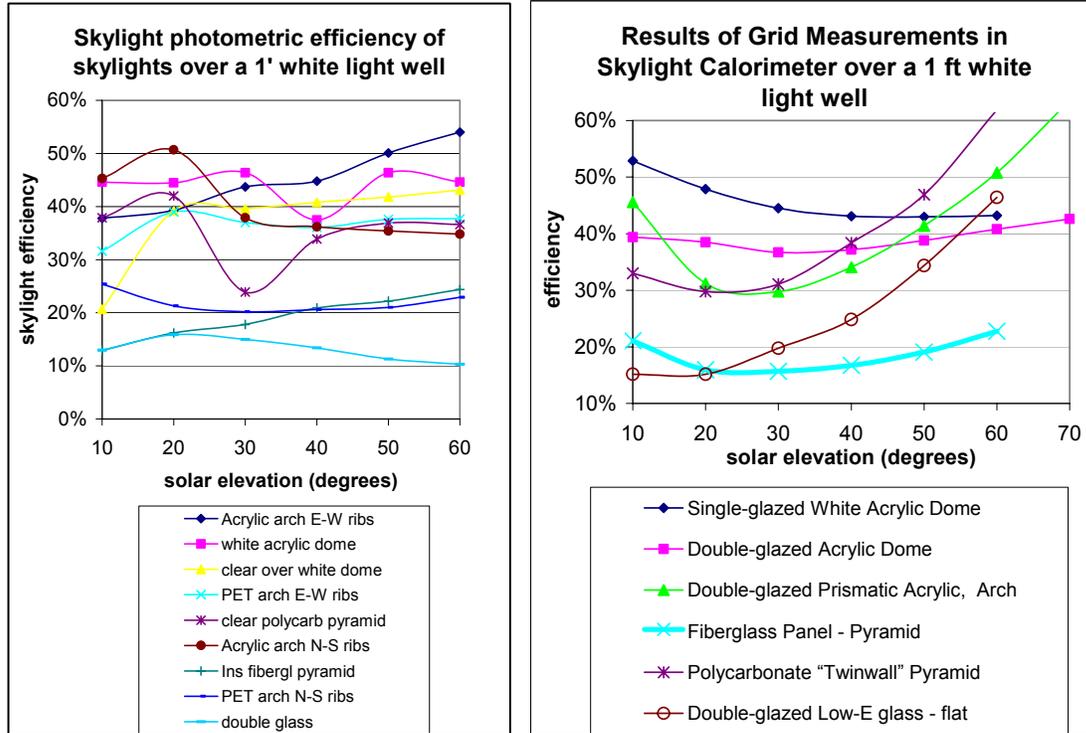
b) Efficiency from grid measurements

Figure 14 - Relative clear sky efficiency of various skylights with respect to solar elevation. Values have been weighted as if all skylights had the same visible light transmittance (0.5)

Note that some variations in efficiency may be due to azimuthal effects; for instance, the distinct drop in efficiency of the pyramid skylight above 40 degrees solar elevation (72 degrees azimuth) may occur because at 50 and 60 degrees elevation the sun was close to 45 degrees azimuth and therefore the incident light was striking the panels of the pyramid at an oblique angle and “bouncing off”.

Also note that both prismatic acrylic and white PET compound arches captured more light when the “ribs” or the peaks of the arches were oriented East-West rather than North-South. However, both types of arched skylights caught relatively more light in the morning when the ribs were aligned North-South and would reduce the variability of transmitted light.

The results of the same analysis performed for those skylights that had grid measurements taken in the skylight calorimeter are shown in Figure 14(b). As described earlier we believe the grid measurement to provide a more accurate estimate of the light that has been transmitted. The results for pigmented domes match quite well between the two analyses. The fluctuation is not found in the efficiency of pyramidal skylight in the grid measurements but these measurements were taken at different times and thus azimuthal angles may be different. The grid analysis would indicate that the domes have the closest to ideal performance with pyramids and arched skylights having similar U-shaped curves and flat glass (mounted horizontally) having an efficiency curve that would accentuate the fluctuations in ambient daylight. The white PET arch skylight was not measured in the calorimeter and thus grid data is not available for comparison.



a) Efficiency from goniophotometer

b) Efficiency from grid measurements

Figure 15 - Measured clear sky efficiency of various skylights over 1 ft white light wells with respect to solar elevation

The plots in Figure 15 are the measured skylight efficiencies with respect to solar elevation. The shapes are the same as those in Figure 14 except that the materials actually do have different transmittances and thus this shifts the plots up and down relative to their true efficiency so one can make note of the overall impact of shape and glazing transmittance.

Conclusions: Comparative Performance of Typical Skylights

Comparative Performance

This study deals with the photometric and energy performance of skylights, but it should be remembered that skylights are often designed to achieve specific visual goals such as contact with the outside, admission of sunlight at particular times, or the minimization of glare, along with specific mechanical goals such as control over ventilation, or a particular U-factor. Several other factors such as watertightness, strength, weatherability, etc. make a critical difference to the overall performance of a skylight, so the performance of a skylight can only be properly judged in its full architectural context.

Comparative Efficiency

It is not necessarily true that a skylight with a higher photometric efficiency is a more efficient skylight; the thermal conductivity (U-value) and the solar heat gain coefficient (SHGC) of a skylight are important variables not considered in this paper. A full appraisal of the energy balance created by the skylight in situ requires an annual energy simulation that accounts for daylight, electric lighting controls and the interaction of heat flows through skylights with the rest of the building energy characteristics.¹⁵

The variability of the factors involved makes it impossible to define the "perfect" skylight; nevertheless, at any given location and time, the most efficient skylight for providing general uniform illumination would closely follow an ideal efficiency curve as described above.

Dome skylights were found to have relatively close to ideal efficiencies with respect to solar elevation when measured on the goniophotometer and with the grid method on the calorimeter. The white compound arch skylights were also found to have efficiency profiles that were beneficial as measured on the goniophotometer.

Additional design methods besides skylight shape may be used to boost low angle skylight efficiency. The methods described in the paper can be used to investigate and quantify these improved designs.

Use of Skylight Photometric Data

This project has made it possible for any lighting designer with rudimentary lighting software to model daylighting with skylights in the same manner that they would model electric lighting with luminaires. Results obtained from these calculations (such as average illuminance levels) can be directly compared with the levels obtain from electric lighting calculations. Of course, several calculations would typically be run, each modeling the light distribution at a particular time of day.

As part of this project, other useful quantities such as coefficients of utilization and spacing criteria have also been calculated, so that lighting designers can think about skylights more readily as luminaires with certain defined, albeit varying, intensity distributions.

The use of skylights is likely to increase significantly in the wake of the 2005 revision to California's Title 24, which includes skylighting as a prescriptive measure for large indoor spaces. It is possible that national energy codes will soon follow this model. The widespread availability of .ies files (LM-63 formatted photometric data files) for skylights should make these code changes more successful by giving designers the tools they need to optimize skylight energy performance and aesthetics.

This paper has identified that some of the PIER photometric data is imperfect, primarily due to fairly large increments of horizontal and vertical angles used in collecting the data. Those files for skylights that admit mostly collimated light have not been posted for public access as they would likely be used without the user knowing their shortcomings. However, skylight photometric files for diffusing skylights have been posted by the PIER program. Many lighting software programs can more appropriately model clear glass skylights without the use of photometric files.

Recommendations

These recommendations follow from the lessons we learned during this project

- Photocells must be calibrated between tests to assure equipment accuracy is maintained
- Sky ratio is not the ideal metric to judge sky clearness. A threshold value for this ratio would have to be chosen to ensure both that there is an unobstructed view of the sun, and that cloud cover is not more than a few percent.
- Many skylights, including flat glass and prismatic skylights, admit light that is still somewhat collimated. When these skylights are tested, the number of vertical and horizontal angle measurements must be increased to ensure sufficient accuracy.
- The automated goniophotometer already developed for this project could be modified to achieve a sufficient density of measurement points. The less diffusing the skylight glazing, the more measurement points are needed.
- A comparison of the skylight efficiency calculated from tightly spaced grid measurements can be compared to the efficiency resulting from goniometric measurements. If the two calculations of

skylight efficiency diverge sufficiently it would indicate the goniometric measurements need to be taken at smaller increments of vertical and horizontal angles.

Future Work

This report is a small part of a more extensive project to quantify and improve the performance of skylights in conjunction with skylight manufacturers. The ultimate goal of the project is not only improved skylight designs, but an expanding library of photometric data available to designers, that will enhance their ability to design attractive, energy efficient, luminous spaces with skylights. Since this work has shown that not all skylights are alike, building designers should demand that measured photometrics are provided for diffusing skylights when accurate prediction of daylighting is required.

As more sophisticated skylight designs become available, they can be tested against existing designs to gain further insight into their characteristics and performance, especially in regard to the effect of shape on efficiency.

The data from this study could be used to make daylighting analysis software more accurate. The daylighting models in DOE-2, Energy Plus and SkyCalc by default assume that skylights are flat pieces of glass and assume that visible transmittance increases as solar elevation increases. For domes, the model would be much improved if transmittance was kept constant with solar elevation. The effective transmittances contained in the SkyVision software match reasonably well the results from the grid measurements. Ideally these algorithms will be applied to whole building energy models so that designers have better tools to optimize overall energy and cost savings benefits of skylights.

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