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Skylights as luminaires: PIER skylight photometric test results.

by

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Jon McHugh[1], Ian Lewin[2] and Jim Domigan[2]

Abstract

Thoughtful design of buildings using daylight can improve lighting quality, increase productivity[1] and reduce energy consumption[2]. Since over 60% of commercial building floorspace is single story or on a top floor[3], toplighting with skylights or other rooftop apertures will be the method of choice for daylighting much of the commercial building stock.

Unlike electric lighting luminaires, which have photometric files and photometric reports, skylights have little published luminous performance information. Given the above lack of information, the building designer can only crudely predict skylight system performance and has limited guidance on specifying better performing skylights.

The California Energy Commission Public Interest Energy Research (PIER) program sponsored the development of a test method, and the collection of goniometric data on 22 skylight/lightwell configurations under overcast skies and for each 10 degree increment in solar elevation for clear skies. The tests resulted in a library of public domain photometric files and photometric reports that can be used by lighting software developers, lighting designers or researchers and others to understand the dynamics of daylight delivered from skylights.

This paper will describe how this recent work on skylight photometrics impacts the lighting field in the following areas:

- development of revised Light Measurement (LM) standards
- expanding the capabilities of any lighting software that uses IESNA photometric files to model daylighting with skylights
- opportunities for lighting software developers to enhance the daylighting capabilities of their product
- modifying the electric lighting circuiting requirements under skylights in building energy efficiency standards so that energy savings are more reliable and lighting quality is enhanced
- increased information for product development of skylights and hybrid lighting systems

Introduction

The market potential for widespread application of skylights and photocontrols is dramatic. Of 686 million square feet of new commercial buildings constructed each year in the United States, it has been estimated that 46% of the total floor area is single story, 62% of total commercial floor area is directly under a roof and therefore potentially available for skylighting. The amount of low-rise construction, spreading in the suburbs, may be low visibility, but it is enormous.

Some estimates suggest that daylighting can reduce electric lighting consumption by as much as 50% to 70%[4]. A more conservative estimate is that the potential skylighting energy savings for the entire class of commercial buildings average around 1/3 of total lighting energy in the daylit zone. The lighting electricity consumption for each year's new commercial construction in the US is 4.6

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Billion kWh/yr[5]. If we consider skylighting only half of the floor area directly under a roof in new commercial buildings over the next 10 years, the technical energy savings potential on the 10th year is 4.7 Billion kWh/yr[6].

The energy savings potential of skylights is primarily in non-residential occupancies. Commercial and industrial occupancies are good targets for energy savings from skylights since they have high lighting power densities, extensive lighting use during daytime hours, and whole building energy consumption that is relatively insensitive to envelope thermal transmittance (U-factor). Residential buildings, on the other hand, are not likely to see energy savings from skylights for the opposite of all the reasons from those listed above.

Recognizing the tremendous energy savings potential from skylights, the California Energy Commission, through the Public Interest Energy Research (PIER) program, sponsored testing the energy performance of skylights in conjunction with light wells[7]. This skylight testing program includes measuring solar heat gains and nighttime heat loss through many of the same skylight/light well assemblies that were the subjects of the photometric testing described in this paper.

The hoped for outcome of this work is that photometric testing of skylights becomes commonplace. If photometric information for skylights becomes readily available, it is reasonable to expect that lighting designers can become as adept at specifying high quality skylighting systems as they are at specifying high quality electric lighting systems.

Similarities of Skylights and Luminaires

Skylights in conjunction with their light wells have these features in common with electric lighting luminaires:

- They both provide light
- They both have characteristic luminous intensity distributions
- They both have limits on how far apart they can be spaced while maintaining appropriate illuminance uniformity in the task area.

However, skylights have these differences from electric lighting:

- The light source (the sun) above the skylight changes its orientation at different times of day and year. As illustrated in Figure 1 for a white diffusing skylight, this will have some effect on the distribution of light coming from the skylight (i.e. skylights are not perfectly diffusing). This is somewhat similar to high bay fixtures, which have more than one distribution depending upon how high the lamp is mounted in the fixture.

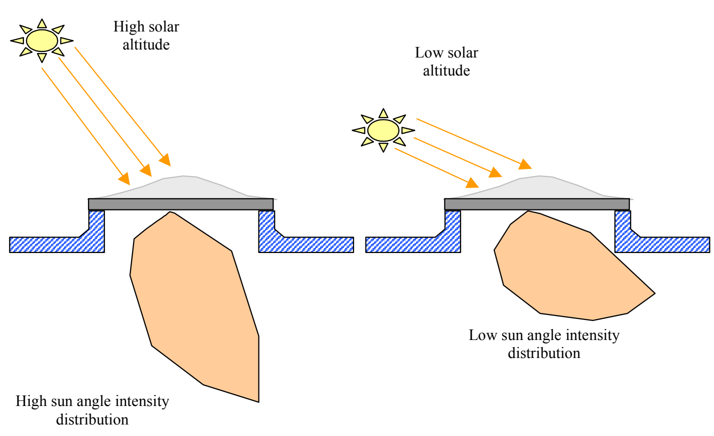

Figure 1: Impact of Sun Angle on Light Distribution from a Skylight

- The light source above the skylight can be diffused by clouds - this will also change the distribution of light coming out of the skylight.
- The luminous flux from the light source changes over the course of each day.
- Skylights are often located well above the level of the ceiling thus the light distribution into the space is affected by the light well.

From the above comparison of electric lighting luminaires and skylights, the following conclusions can be drawn:

1. To characterize the photometric distributions of skylights, one must test the skylights under different solar positions, and different sky conditions.
2. Since the luminous flux from the sun and sky varies, the photometrics of skylights should be normalized by this luminous flux. Thus the intensities measured in this project are in units of candelas per lumen incident on the skylight.
3. If the geometry or reflectance characteristics of the light well under a skylight changes, it will change the distribution of light into a space. This is particularly important to test if the light well is specular or a diffuser is added to the bottom of the light well.

Selection of Skylights and Light Wells

The primary consideration in selecting the skylights and light wells for testing was to include a broad range of configurations that are encountered in commercial buildings specifically for saving lighting energy. To this end, we focused on curb mounted unit skylights, which can be uniformly distributed in a space, instead of monumental or architectural skylights. A list of the 22 skylight/light well configurations tested are contained in Table 1.

Table 1: Skylight and Light Well Combinations Tested

Test No.	Material	Shape	Color	Glazing(s)	Tilt	Well Ht.	Well Surface	Diffuser	Rotation
1	Glass	Flat	Clear low-e	Double	Horz.	1'	Diffuse	No	
2	Glass	Flat	Clear low-e	Double	Horz.	3'	Diffuse	No	
3	Glass	Flat	Clear low-e	Double	Horz.	6'	Diffuse	No	
4	Glass	Flat	Clear low-e	Double	Horz.	6'	Diffuse	Yes	
5	Acrylic	Dome	White	Single	Horz.	1'	Diffuse	No	
6	Acrylic	Dome	White	Single	Horz.	3'	Diffuse	No	
7	Acrylic	Dome	White	Single	Horz.	6'	Diffuse	No	
8	Acrylic	Dome	White	Single	Horz.	3'	Specular	No	
9	Acrylic	Dome	White	Single	Horz.	6'	Specular	No	
10	Acrylic	Dome	White	Single	Horz.	3'	Specular	Yes	
11	Acrylic	Dome	White	Single	Horz.	6'	Specular	Yes	
12	Acrylic	Dome	White	Double	Horz.	1'	Diffuse	No	
13	Acrylic	Compound Arch	Clear Prismatic	Double	Horz.	1'	Diffuse	No	
14	Acrylic	Compound Arch	Clear Prismatic	Double	Horz.	6'	Diffuse	No	
15	Acrylic	Compound Arch	Clear Prismatic	Double	Horz.	1'	Diffuse	No	90 deg
16	Fiberglass	Pyramid	Crystal/crystal	Panel	Horz.	1'	Diffuse	No	
17	Fiberglass	Pyramid	Crystal/crystal	Panel	Horz.	6'	Diffuse	No	
18	Polycarbonate	Pyramid	Clear	Twinwall	Horz.	1'	Diffuse	No	
19	Polycarbonate	Pyramid	Clear	Twinwall	Horz.	6'	Diffuse	No	
20	Acrylic	Pyramid	Bronze	Single	Horz.	3'	Diffuse	No	
21	PET	Compound Arch	White	Single	Horz.	1'	Diffuse	No	
22	PET	Compound Arch	White	Single	Horz.	1'	Diffuse	No	90 deg

PET = Modified Polyethylene Terephthalate

The size of all the skylights in our sample was a nominal 4 ft by 4 ft. This size was chosen so that we would have geometries that are similar to the 4 ft by 8 ft size typically found in commercial buildings and yet would be small enough to fit in the thermal test chamber for other tests conducted on these same skylights. Similar photometric tests have been performed previously on one-eighth scale models.[8,9] We wanted to test full-size products because: 1) we wanted to test commercially available skylight products from a variety of manufacturers (not just manufacturers that were willing to create scale models) and 2) we wanted to develop a moderate cost photometric testing methodology that could be used in the future to create photometric files and reports for any skylight.

From discussions with skylight manufacturers, the most common type of unit skylight is the white plastic dome skylight. Given its market share, the white dome skylight was subjected to the most variation in the permutations of its light well (height, surface properties, bottom diffuser).

We also tested unit skylights with clear flat glass even though they are rarely used in commercial buildings. Flat glass skylights were included in the test sample because: the angular performance of flat glass is easy to calculate, earlier thermal testing focussed on these skylights,[10] and with clear glass we could easily measure the effect of the light well as a diffusing element.

One key trade-off in skylight design is that between visible light transmittance and diffusion. Sometimes using skylights with high transmittance plastics results in lower light levels between skylights than medium transmittance plastics because the glazing diffusion of the high transmittance product is too low. We were interested in how well competing diffusion strategies worked for maintaining light transmittance. Thus we looked at the diffusion from plastic glazing that used pigments, clear plastics that used refraction (such as prismatic glazings as well as structured "twinwall" polycarbonate glazing), and diffusion by fibers in fiberglass panels.

One might question why we bothered to test vertical light wells with diffusing paint. The calculations for light passage through a diffusing light well are pretty straightforward. However having measured photometrics of a skylight with different well heights gives a way of checking the accuracy of lighting programs – even those that are limited to orthogonal geometries. A light program should give nearly the same results from a building model with 1) the skylight photometrics from a skylight tested without a light well and the light well is simulated within the program, as from 2) the photometrics from the same skylight but tested as a combined skylight and light well assembly. We did not have the scope nor the chamber size to test splayed wells – Serres and Murdoch investigated this topic earlier on scale models of skylights and light wells.[11]

We tested prismatic glazings in two configurations: 1) a compound parabolic double dome that had two layers of formed prismatic glazing (the top layer had the prisms facing down and the bottom layer had the prisms facing up). 2) a flat prismatic diffuser placed at the bottom of the light well with the prisms facing down. All the prismatic material in both the skylight glazings and bottom diffuser were pattern 12. The reader is directed to the work of Serres and Murdoch[12] for a comprehensive comparison of a variety of prismatic lens patterns for use with skylights.

Methodology

The following is a brief discussion of the test method used to measure the photometrics of skylights under outdoor skies. See the references in the endnotes for more details.[13, 14]

Since far-field photometric testing is based on the assumption that the luminous source can be approximated as a point source, the “five times rule” is applied. To keep the error associated with measurement geometry below 2%, this rule requires that the photometric sensor is no closer than 5 times the distance of the longest dimension of the test object.[15] Since the diagonal across the opening of a 4 ft by 4 ft skylight is 5.6 ft, one would need a photometric test chamber with a 28 foot height and a 56 foot diameter. One member of our team had developed a test methodology and apparatus that would fit in a 17 ft tall cube. This was accomplished by blocking off three of the four quadrants and testing the skylight one 2 ft by 2 ft quadrant at a time. The results from the four quadrants are summed. Further space economy was accomplished by "folding" the path of light from the skylight opening to the photocell by the use of mirrors. This rotating goniometer, as shown in Figure 2, collected luminous intensity information for 10 vertical angles (spaced at the midpoint of each 10 degree increment and the nadir) simultaneously. This goniometer design substantially reduces the real estate and thus costs associated with testing skylights. This more affordable test method translates into a test method that industry is more likely to adopt.

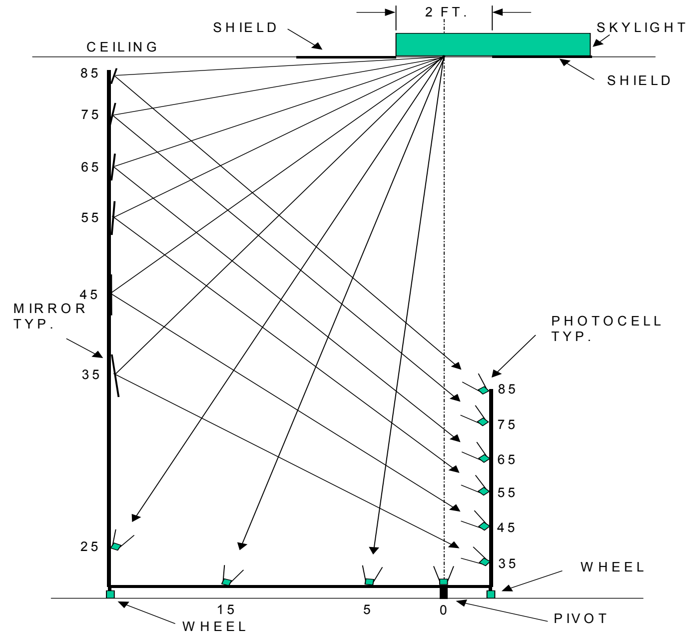

Figure 2: Schematic of Skylight Goniometer

While luminous intensity readings were collected under the skylight, outdoor total horizontal illuminance was collected at the same time. Effective lumens hitting the surface of the skylight are calculated by multiplying the total horizontal illuminance by the horizontal projection of the glazing area. Thus luminous intensities from the skylights can be normalized and reported in terms of candelas per 1,000 lumens of outdoor light.

Both global horizontal and diffuse horizontal ambient illuminance measurements are taken at the beginning of each set of skylight measurements so the goniometric measurements of skylights are taken only under the correct sky conditions. Clear sky measurements for a given sun angle and skylight configuration are taken only when the sky ratio (ratio of diffuse to total horizontal illuminance) is less than 25%. Overcast sky measurements are taken only when the sky ratio is greater than 85%.

The glazing materials of all of the plastic skylights were also tested on a Byk Gardner Haze Gard (Cat. #4725) for visible transmittance, haze and clarity. The transmission haze is the ratio of the diffuse only transmittance to total transmittance. Clarity is the characteristic of a transparent material, whereby distinct images may be observed through it. Clarity is the ratio of light directly transmitted to the total light scattered within 2.5° normal to the sample. Thus, the overall transmittance characteristics of the skylight glazing are known for the skylights in our test sample.

It should be noted that the skylights tested were new. The comparison between skylights may diverge as different glazing materials degrade at different rates.

Results

Clear sky photometric measurements were collected for each ten-degree increment in solar elevation as well as at solar noon under clear skies. Given that measurements were taken in the morning as well as in the evening (two files for each solar elevation) on the twenty-two skylight and light well combinations there are over 270 skylight complete goniometric measurements. These measurements have been converted into photometric files in IESNA LM63-1995 format and photometric reports. This represents a great increase in the amount of information available on the measured photometrics of skylights. This information is freely available on the Heschong Mahone Group website (www.h-m-g.com) and over the long term will be freely available on the New Buildings Institute (www.newbuildings.org/pier/index.html) and the California Energy Commission (www.energy.ca.gov/pier/index.html) PIER websites.

Photometric Reports

The photometric reports contain polar plots of intensity, zonal lumen summaries, the optical efficiency of the skylight, the parallel and perpendicular spacing criterion, and the coefficients of utilization. These reports will quickly help the lighting designer determine:

- the maximum spacing of skylights
- the distribution of light from a skylight
- a quick estimate of the average footcandles in the room (after calculating ambient horizontal fc and multiplying by skylight glazing area)

LM63-1995 Compatible Photometric Files

The IESNA formatted photometric files allow the lighting designer to perform detailed calculations of skylighting design that have not been possible previously. A designer can now load these photometrics into lighting software and calculate horizontal and vertical illuminance, display this as isolux graphs and even visualize a space with skylights. Figure 3 shows such a visualization of a warehouse space with evenly spaced skylights.

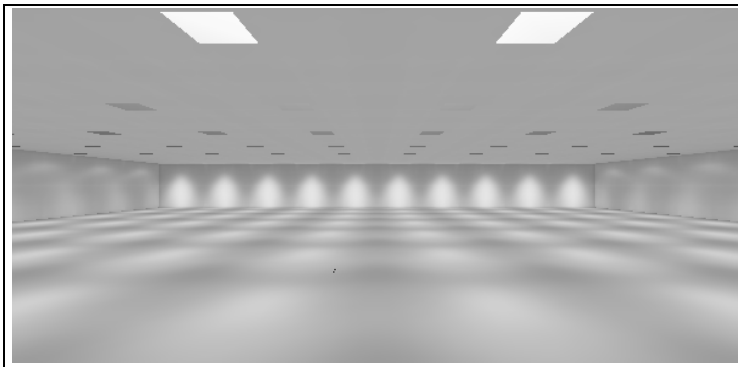

Figure 3: Visualization of Skylights in a Warehous

This very simple model only took a few minutes to create. Having seen the visualization capability resulting from IES formatted photometric files, several skylight manufacturers have indicated that they are interested in testing additional skylights.

It should be noted that the skylight photometric files have a significant amount of additional information contained in the file header. This file header information is included so that the skylight/light well combination is well defined. More importantly, this information makes it possible to automate the daylighting calculations that would be performed in conjunction with these files. Currently this information is in terms of user defined keywords as shown in Table 2. Hopefully in the next version of LM 63, standard keywords will be defining key skylight parameters.

Early versions of LM63 have the capability of containing multiple intensity distributions. This capability was infrequently used and is being eliminated from the revisions to LM63. However this type of file structure would have been ideal for skylights, which have multiple intensity distributions for the same product. With the constraint of one file per intensity distribution or one file per sun angle, we created a naming convention so that the sky condition and solar elevation could be recognized without having to open the file. The last two digits of the name indicate the solar elevation, an "o" before the number indicates an overcast sky and a "c" indicates a clear sky.

Table 2: Description of Skylight User Defined Header Information

Skylight descriptions [_SKYLIGHT] Yes/No [_MAJOR_AXIS] ###.# in degrees (default is zero, 0 = major axis N-S) measured clockwise looking down. [_GLAZING_VT] 0.## visible transmittance of glazing material at normal incidence [_GLAZING_HAZE] 0.## haze of glazing material [_GLAZING_CLARITY] 0.## clarity of glazing material [_UNITS_TYPE] Feet or Meters [_GLAZING_AREA] ##.# horizontal projection of glazing area
Light well description [_WELL] Yes/No [_WELL_HEIGHT] ##.# [_WELL_WIDTH] ##.# width at top of light well (dimension at bottom of light well defined under luminaire dimensions) [_WELL_LENGTH] ##.# length at top of light well (dimension at bottom of light well defined under luminaire dimensions) [_WELL_REFL] 0.## reflectance of walls of light well [_REFL_TYPE] Diffuse/Specular [_BOTTOM_DIFFUSER] Yes/No [_DIFFUSER_VT]] 0.## visible transmittance of diffuser material at normal incidence [_DIFFUSER_HAZE] 0.## haze of diffuser material [_DIFFUSER_CLARITY] 0.## clarity of diffuser material
sun/sky conditions [_SOLAR_ELEVATION] ##.# degrees [_SOLAR_AZIMUTH] ##.# degrees (+ west of south, - east of south) [_SKY_RATIO] 0.## ratio of diffuse to total horizontal [_SKY_CONDITION] clear, partly cloudy, overcast
test site/time conditions [TEST_LONG] ###.# longitude of the test location [TEST_LAT] ##.# latitude of test location [TEST_ELEV] ##### elevation of test location [TEST_DATE] mm/dd/yyyy month/ day/ year of test [TEST_TIME] standard local time of test [TEST_TZ] Time zone of test location (EST = 5, PST = 8)

Before all of the test data was converted into IES LM-63 formatted files, we sent a test photometric file to several software developers to determine if there were any incompatibilities with the files we had created and commonly available commercial software. Initially we had different intensities for each of the horizontal angles at the nadir (vertical angle = 0°). Theoretically, there should be a single value for all of the horizontal angles at the nadir as they define the same position. But given that the sun angle changes slightly as the photometric test progresses, there is some variation in the test data at the nadir for different horizontal angles and this was reflected in the photometric file. This variation at the nadir would cause some software to crash. Thus we averaged the intensities at the nadir for different horizontal angles and used this average value for all horizontal angles at the nadir.

Applying Skylight Photometrics to Lighting Software

If unlimited resources were available, one could characterize the photometrics of skylights by testing them under all combinations of sun angles relative to the skylight. As an economy measure, we have made the simplifying assumptions that skylight luminous intensity distributions under clear skies are primarily a function of solar altitude and azimuth. Implicit in this statement is that the relative solar azimuth to that of the skylight orientation is not important (e.g. if we rotate a skylight the distribution under the skylight does not change significantly). We know that this assumption is not true for some directional materials such as structured polycarbonate but that it is a reasonable approximation for clear skylights and dome skylights with relatively isotropic diffusing glazings.

Given the above assumptions, if one wanted to model a skylight with sunlight coming from a particular angle, one would need only to pick the skylight photometrics tested under a solar elevation close to the modeled solar elevation. So the solar azimuth in the model and photometric file align, one can rotate the photometrics azimuthally. This is accomplished by rotating the skylight in the lighting simulation software. Figure 4 illustrates how skylight photometrics measured in Scottsdale, Arizona can be applied to a skylighting design project in Redding, CA. One selects a photometric file for a skylight that has been tested at a solar elevation close to the solar elevation for the time and date that one is modeling for a skylighting project. Then the photometrics are rotated azimuthally (by rotating the skylight in the lighting software) so that the azimuthal direction of the "sun" lines up in both the project and the photometric file. In this example, one would rotate the skylights 50° in the counter-clockwise direction in plan view.

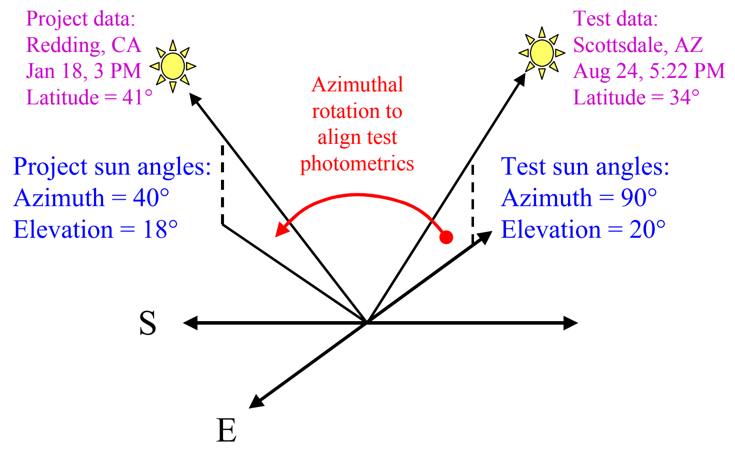

Figure 4: Sun angles of a project and its corresponding skylight photometric file

We tested the skylights during the summer season to have measurements over the greatest range of solar elevations. Separate photometric files were created for each 10-degree increment in solar elevation. All skylights have measurements to at least a 60 degree solar elevation. Only one overcast sky test was performed for each skylight/light well combination as the sky luminance distribution is assumed to be independent of solar position[16] and thus the intensity distribution under the skylight would also be constant.

Skylights were not tested under partly cloudy skies. Given that party cloudy skies can have such great variability in luminance patterns depending on cloud type and distribution, it is hard to define a representative partly cloudy sky. Partly cloudy skies can be modeled by superimposing overcast and clear sky weighted candela distributions. Similar weighting of sky luminance functions with respect to zenith angle and sky clearness have been previously performed by Perez et al.[17]

As described earlier, the luminous intensities in the skylight photometric files are normalized in terms of candelas per 1,000 lumens of ambient daylight falling on the skylight. To calculate the correct number of "lamp lumens" one need only multiply the horizontal projection of glazing area (contained in the photometric file header) by total horizontal illuminance. With only latitude, solar elevation and sky condition (clear, partly cloudy and overcast) one can easily calculate total horizontal illuminance from daylight availability equations in the IES Handbook[18].

For those designers who want to use the skylight photometric files now, weare providing along with the photometric files and reports a simple public domain spreadsheet, called SkyFit, which calculates the rotation angle and the daylight lumens entering the skylight for whatever latitude and time. The sign convention for rotation in the SkyFit spreadsheet is that rotation of the skylight in a clockwise direction is positive. A screen shot of SkyFit is shown in Figure 5.

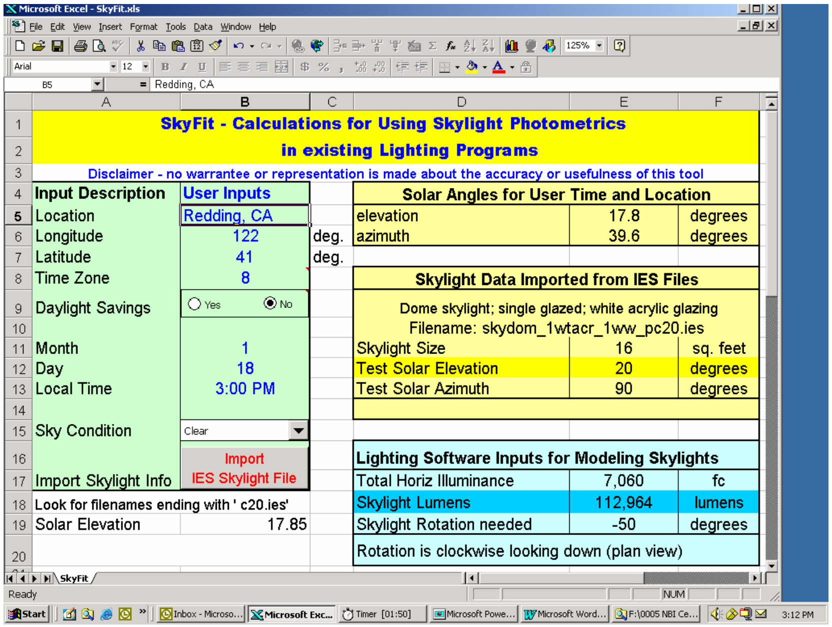

Figure 5: SkyFit Spreadsheet with Skylight Rotation and Lumens

Information provided by the user is entered on the right side of the SkyFit spreadsheet. This includes importing the appropriate skylight photometric file. The left side of the screen shows the program outputs with only the skylight lumens and skylight rotation entered by the user into a lighting program. Note skylight rotation does not include accounting for the rotation of the building - this is yet another rotation superimposed upon the rotation described above.

SkyFit is but a temporary stop gap measure. The few calculations performed here could be seamlessly performed within any lighting software that imports LM63 formatted photometric files. It is our hope that lighting designers demand this from their software vendors and that the lighting software industry responds.

Clear Skylights Invalidate Point Source Assumptions

The basis of calculation software using the photometric files is that the luminaire (skylight) is a point source and that illuminance varies as the square of the distance from the source. When the skylight does a relatively good job of diffusing, the skylight can be approximated as a luminous source. A low diffusion skylight however can be conceptualized as a "filter." It reduces the amount of light transmitted but does not change the basic spatial relationship that the "source" is 93 Million miles away. Moving twice as far away from the skylight does not reduce the illuminance to 1/4 of its prior value because the light is not spreading but is collimated. However, luminous energy (lumens) is conserved, when intensities (candela) are multiplied by their solid angles (steradians). The bottom line is that the photometric files generated from testing clear skylights are not intended for use within lighting software, which extrapolates these measurements to different distances.

This raises the question: what metric can we use to determine how diffusing does a skylight has to be before we can say that the skylight is a light "source" and not a "filter"? At this point we do not have a definitive answer, but it is likely a function of the measured haze of the skylight glazing material or the diffuser (if any) in the light well, and the light well depth and sun angle. These factors are reported in the photometric file header information as well as in the photometric reports.

Impact on Definition of the "Daylit Zone"

The material presented in this section is part of a much larger proposal to modify the California Title 24 Building Energy Efficiency Standards in regards to skylights.[19]

Currently, the California Energy Standards consider the daylit area under a skylight to be, "the footprint of the skylight plus, in each of the lateral and longitudinal dimensions of the skylight, the lesser of the floor-to-ceiling height …"[20] Lights in the daylit zone must be controlled separately from the remainder of the lights[21]. This definition of the daylit zone in essence defines an acceptable spacing criterion of at least 2.0 for skylights.

The method used to evaluate the appropriate spacing for skylights was the use of the calculated spacing criterion (SC). These spacing criterions were calculated from measurements of the luminous intensity distributions from white skylights under clear skies. The method used to calculate the spacing criterion is described in the IESNA Handbook and compares the illuminance between two luminaires (skylights) to that directly below a single luminaire (skylight). This method provides a simple method of evaluating the appropriate spacing of skylights for uniform illumination. This method provides a conservative (overly large) metric for spacing skylights because, "When other criteria are considered, such as overlap between luminaires, vertical illuminance, shadowing and illuminance distribution above the workplane, it generally is found that luminaires must be installed at some spacing-to-mounting-height ratio less than the value of the luminaire spacing criterion."[22]

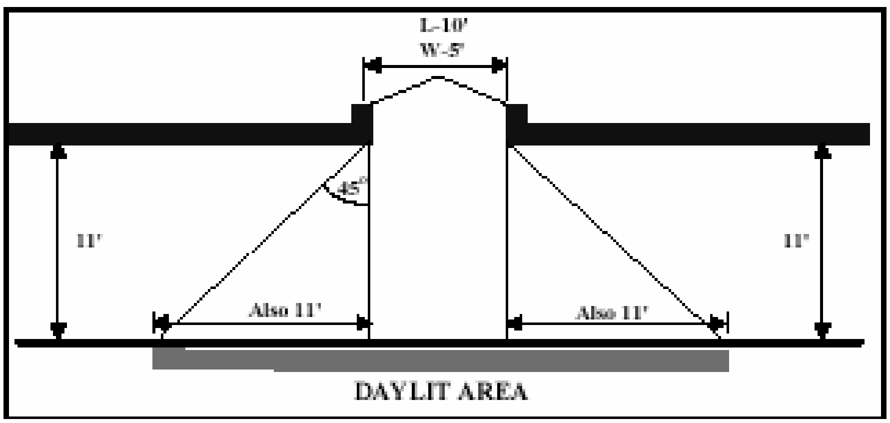

Figure 6: Existing Daylit Area Figure in the 2001 Title 24 Nonresidential Manual.

The current code language defines a horizontal (or plan) daylit zone as the "footprint" of the skylight plus the ceiling height in each direction from the side of the skylight. This expansion of the daylit zone under skylights is illustrated in the 2001 Title 24 Nonresidential Manual (see Figure 6) with a "spread angle" of 45 degrees. We desired a similar level of simplicity so a desired outcome would have a ratio of spacing width to ceiling height that would be a simple decimal (multiples of 5%) with a "spread angle" that is a multiple of 5 degrees.

The existing definition of the daylit area implicitly has a spacing criterion of 2.0. From comparing the spacing criterions of diffusing light fixtures which have spacing criterions around 1.5, it was our hypothesis that the spacing criterion for skylights would also be around 1.5 – substantially less the current value in the building efficiency standards.

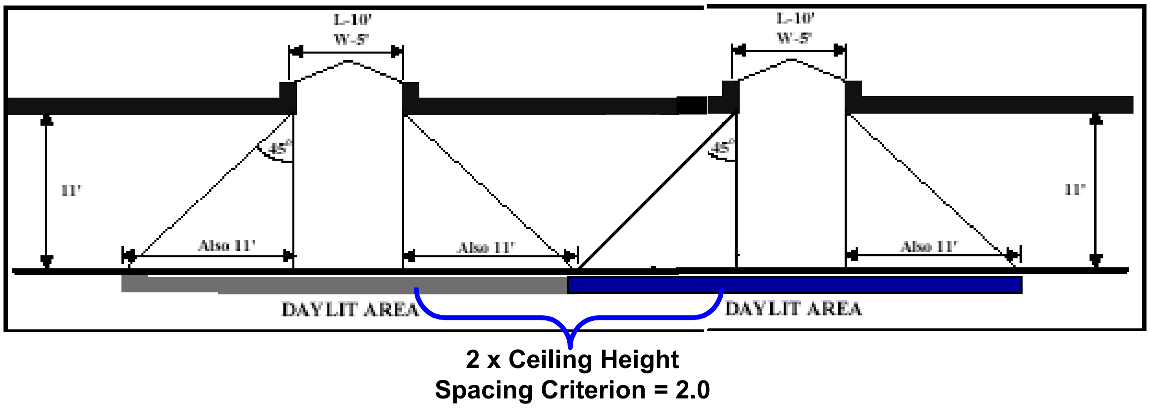

Figure 7: Relationship between the existing definition of daylit zone and its spacing criterion

The metric used to characterize the correct definition of the daylit zone under skylights is the spacing criterion. The spacing criterion is readily available for most area lighting luminaires with electric light sources. The spacing criterion is calculated from the luminous intensity distributions that are measured during photometric testing of luminaires. In the past this information has not been available for skylights. However, photometric testing of skylights was performed within the last year for the CEC sponsored Public Interest Energy Research (PIER) program. Since the distribution of light emitted from a skylight changes when the sun position changes, a separate photometric test was performed for each 10 degree increment in solar elevation (angle of sun above the horizon). Thus for each skylight tested, there would be photometric measurements made for when the sun was at 10 degrees, 20 degrees etc. to the maximum solar elevation on the day of the test (all measurements were in the summer or early fall). The data from these tests was compiled into IES LM 63-1995 photometric files and processed into photometric reports that include the spacing criterion. Unlike electric lighting fixtures, a skylight has more than one set of spacing criterions based upon the sun angle. Thus this evaluation of spacing criterion for skylights is based upon the spacing criterion for several skylights over a range of sun angles.

Figure 8: Compound parabolic skylight

The graphs in Figure 9 display the distribution of Spacing Criterion in the direction along the primary axis of the skylight (North-South) and across this axis (East-West) for four foot wide by four foot long white skylights above a minimal one-foot light well. The skylights tested were a single glazed white acrylic dome skylight, a double-glazed clear over white acrylic dome skylight, and a single glazed white PET compound parabolic skylight. The compound parabolic skylight was rotated so that the "ribs" of the skylight were parallel to the major axis in one set of tests and perpendicular in the other set of tests. An example of a compound parabolic skylight is shown in Figure 8

Each spacing criterion data point is for one of the four skylight conditions (single glazed white dome, double glazed white dome, and PET compound parabolic white dome in two orientations) and for each 10 degree increment in solar elevation over the course of a clear sky day from sunup to sundown.

The distribution of spacing criterions in Figure 9, clearly indicates that for these typical white diffusing skylights, the spacing criterion in both the along and across directions is 1.4 or less most of the time. The spacing criterion is a basic indication that for uniform light distribution the luminaires (in this case skylights) should be spaced no further apart than around 1.4 times the mounting height.

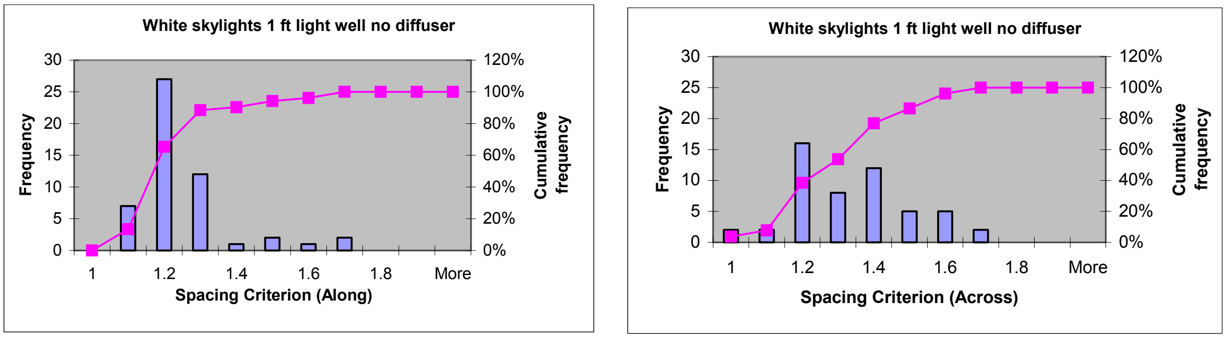

Figure 9: Frequency distribution of spacing criterions for white skylights

A second set of skylight photometric test results was also evaluated for its spacing criterions. This second set of skylights contained skylights having a prismatic diffuser at the bottom of a 3 foot or 6 foot light well. The skylight and well combinations were: a glass skylight with a 6 foot tall light well with white painted walls, a white acrylic dome with a 3 foot tall light well with a specular (metallic foil) surface and a white acrylic dome with a 6 foot tall light well with a specular (metallic foil) surface.

The graphs in Figure 10 plot the frequency distribution of spacing criterions in the across and along directions for skylight configurations that have a flat bottom diffuser. These results are similar to Figure 9, in that most of the time the spacing criterions for skylights with bottom diffusers are equal to or less than 1.4.

Thus the area that can be controlled together as a "daylit zone" under skylights should be based on this definition. If we modify the existing definition of daylit zone as the skylight "footprint" plus additional distance in each longitudinal and lateral dimension – that additional distance would be one half of the spacing criterion or 70% of the floor to ceiling height. The "spread angle" that describes how the skylit area increases with ceiling height is the arctangent of 0.7 or 35 degrees.

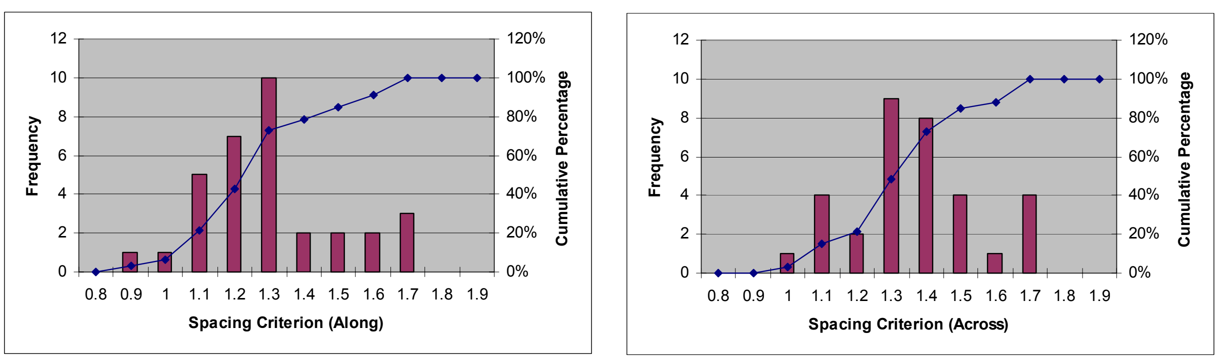

Figure 10: Frequency distribution of spacing criterions for skylights with diffuser at bottom of light well

Can Skylight Photometrics be Used to Size Skylights?

Proper sizing of skylights for energy savings considers the trade-offs between: 1) lights turned off or dimmed in response to daylight illumination, 2) solar heat gain through skylight glazing, 3) increases thermal transmittance of skylights as compared to an opaque roof. This calculation requires an annual simulation of the thermal and luminous performance of the skylighting system and is specific to the climate of the location considered and the relative costs of electricity and the heating fuel used.[23] In California's mild climate and high electricity costs relative to heating fuels, the optimally sized skylighting system during the middle of a summer day will provide twice the design light levels of the electric lighting system. These considerations call for a different method of sizing skylights as described in a paper by Heschong and McHugh.[24]

Thus, in general, the use of skylight photometrics in lighting software will not be the tool of choice for sizing skylights. Instead skylight photometry will be used to:

- Guide placement of skylights for uniform illumination or alternatively for highlighting
- Provide a method of comparison of different skylighting systems - does one want a narrow spread or wide spread of light?
- Guide the placement and selection of skylights for illuminating vertical surfaces such as walls.
- Guide the circuiting of lighting that can be turned off or dimmed with a photocontrol system
- Provide point by point calculations of a space for a given time and sky condition.
- Visualize either the separate or combined effect of the skylighting system and the electric lighting system in a rendering of a building design.

Conclusions

Skylighting low-rise nonresidential buildings can save a significant amount of energy. Given the pressing need to reduce lighting energy consumption, the lighting industry has much to gain from methods that apply skylights effectively with a complementary electric lighting system.

The skylight photometry research program has created a test methodology for collecting photometric information from skylights tested under outdoor conditions. This same test program has also created sample photometric files with header information that is useful for automating skylighting calculations. IESNA could provide a great service to the lighting industry by reviewing the test methodology and photometric file header information and incorporating this information into the appropriate IESNA light measurement (LM) standards.

This new information about skylights extends into the public arena as the definition of the "daylit zone" is revisited. If the market for skylights grows along with greater ease of specification and design of skylighting systems, the importance of appropriate treatment of skylights in the energy efficiency standards increases.

Lighting designers now have a new tool that can help them design effective skylighting systems as part of an overall lighting design. Existing lighting software can be used today with the skylight photometric files and the SkyFit spreadsheet. However, the lighting designer's job could be greatly simplified if the lighting software developers would automate calculations of solar angles and outdoor illumination. Some lighting programs calculate these parameters as part of their daylighting model but they are not currently configured to apply this model to the "lamp lumens" of the "skylight luminaire".

Lighting designers now have greater capabilities to evaluate skylighting systems (skylights, light wells, photocontrols and electric lighting) than they had even several months ago. We expect that this level of information will guide and record innovation in the skylighting and lighting industries.

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