August 31, 2010

Complex Product Visible Transmittance Research
Tubular Daylighting Devices
NFRC project number 05-105-DR4
-- DRAFT --

Background

Different methods and measurement facilities exist to measure the optical properties of complex daylighting products, such as tubular daylighting devices (TDDs). This project serves to inform NFRC's intention to develop a product rating for TDDs based on total visible transmission. Two TDD manufacturers have built goniophotometers to evaluate their devices. While these instruments provide angular specific data over a hemisphere, by integrating the multi-angle data, total VT can be calculated. These two instruments will be compared to a 6.5 foot (2 meter) integrating sphere method, by means of each of the three facilities measuring the same four TDD specimens.

Test Specimens

Four specimens were measured by three different facilities. The first, or reference, TDD (Figure 1) is not a commercial product. A very simple tubular skylight style construction was specified for this specimen to eliminate most of the incoming and outgoing lens complexity, for an initial comparison of the three measurement facilities. A flat clear acrylic sheet was used at the top of a 4 foot (1.2m) long single piece of typical polished aluminum sheet metal daylighting tube with a flat sheet of diffusing white acrylic at the bottom. Following the reference tube, three commercially available TDDs from three different manufacturers were measured, each was intended to be tested with a length to diameter ratio of 3.4:1, roughly 46” x 13.5” (1168mm x 343mm). Typically the tubes were mounted to a roughly 3 foot (1 m) square plywood base plate that simulated attachment to a ceiling penetration. A wooden strut was fastened between the outer lens end of the tube and the base at an angle to hold the length of the tube rigid at various angles when supported only with clamps at the base plate.

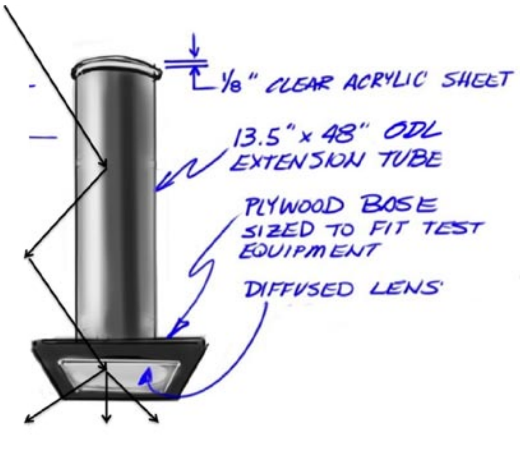


Figure 1 – Reference Tube

Test Conditions

All measurements were made at the solar angles depicted in Table 1. A clear sky condition was confirmed by measurement of a sky ratio (diffuse to direct) of <=0.3 (per IESNA handbook). The sky ratio measurement was made by comparing two exterior looking sensors, one unshaded and one shaded from direct solar radiation by at least a 2" (51mm) inch opaque disk held a distance of 24" (610mm) from the sensor.

Table 1. Measurement Angles

Sun Altitude (above horizontal)	Sun Azimuth (South is 180 deg.)	Incident Angle	
		Horiz. Entry Plane	Entry Plane at 22 deg. South Tilt
20	180	70	48
30	180, 210, 240	60	38,42,52
40	180	50	28
50	180	40	18
60	180, 210, 240	30	8,14,25

Test methods

LBNL

Measurements were made in direct sunlight using a large integrating sphere, labeled A in figure 2. The sphere dimensions are 76.5" (1943mm) inside diameter with a port diameter of 15" (381mm). The interior surface reflectance of the sphere is painted with a typical white latex paint. The measured interior surface reflectance of the sphere is 0.85 (using a Minolta XXX??? instrument).

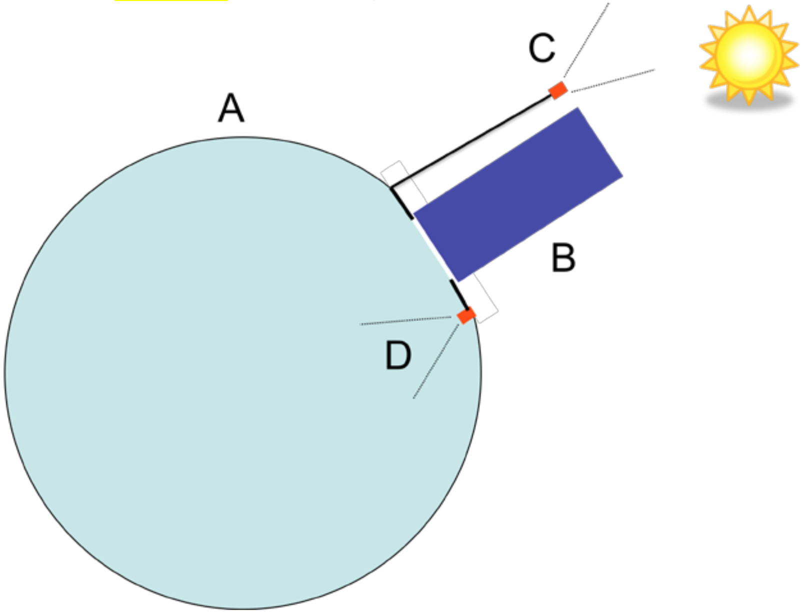


Figure 2 – Schematic of Integrating Sphere

Four Licor LI-210 photometric sensors are placed to look into the sphere, labeled D in figure 1. Three are located on a roughly 24” (610mm) diameter circle about the aperture (about 35 degrees off the line connecting the center of the sphere to the aperture). The last sensor is 90 degree off the center-aperture line. All four sensors are baffled such that they can not directly view the aperture. However, because the sphere is used to measure different incident angles relative to the aperture, it is not possible to baffle the view of the sensors from the variable position of the first reflection “hot spot” inside the sphere. Two additional sensors are arranged with an exterior view, labeled C in figure 1. These face perpendicular to the plane of the sphere aperture. One is unshielded to measure global illuminance and the other is shaded by a 2” (51mm) diameter opaque disc at a distance of 24” (610mm) to measure the diffuse component. The sky ratio that is reported is a ratio of the shaded exterior sensor to the unshaded exterior sensor.

Licor measurements are acquired and logged electronically by an Agilent 34970A data acquisition system. To generate a voltage signal to be measured by the data acquisition system, the current source signal from each Licor sensor is dropped over its own 1% precision resistor, roughly 8200 ohms for interior looking sensors and roughly 1300 ohms for exterior looking sensors. The resistors are chosen to give good measurement resolution within the expected range of light intensity without saturating the sensor’s ability to source current. The resistance is calculated to avoid exceeding 50mV at the highest light intensity expected. The datalogger has 6.5 digit resolution at the +/-100mV scale. The measurement integration time is 10 power line cycles to eliminate 60Hz hum and other electrical noise issues. Furthermore, each measurement scans each sensor four times, roughly 2 seconds apart. These four measurements are averaged together to further stabilize any noisy signal, however significant variation is seldom observed (standard deviation is typically 0.05% to 0.2% of the average value),

Figure 3 – TDD on integrating sphere

The sphere is rolled outside to make measurements (see figure 3). It has one motorized degree of freedom that allows tilting the aperture from looking at the horizon to the zenith and back down toward the opposite horizon. The azimuthal adjustment of the aperture is made by rotating the entire carrying structure of the sphere on its casters, by hand and then locking them in place.

Relative alignment to the sun can be made by use of an optical alignment scope. The scope is comprised of a tube with a small aperture at one end and a translucent screen at the other with concentric rings. Aligning the projection of the rays from the sun to the center of the concentric rings aligns the tube to the solar rays. The tube has two degrees of freedom, a protractor is used to pre-align the tube to the proper angle relative to the aperture and then the motorized altitude and hand adjusted azimuth angles are adjusted until the sun projects in alignment with the tube.

After alignment of the aperture to the sun at the desired angles, a reference measurement is collected and stored in the data logger with no specimen covering the aperture, referred to as an "open hole" measurement. The motorized sphere altitude is adjusted to bring the aperture to the horizon so that the specimen, labeled B in figure 2, can be mounted by means of clamping the 3 foot (1m) square base plate of the TDD assembly to the sphere face plate at the four corners of the TDD specimen plate. The sphere is raised by the motor back to the point where the solar alignment tube projects the sun rays to the center of the target and the second measurement taken with the TDD in place over the aperture. These two measurements are typically collected within 1-2 minutes. After the measurement with the specimen in place, the sphere is tilted down again, the specimen is removed and the sphere repositioned for another open hole reference at the same angle (again with 1-2 minutes), so that there is always a reference measurement taken before and after each tube specimen. Comparing the signals from the before and after open holes helps to reveal if there has been variation in sky conditions during the course of the sequential measurements. Next, the solar alignment jig is adjust to the next desired angle and another series of open hole, specimen, and open hole measurements are made.

Because each tube specimen may has a different/smaller tube aperture than the sphere aperture, when calculating the transmittance, Equation 1 is used to make a correction that multiplies the open hole illuminance by the area ratio of tube aperture divided by the sphere aperture (Equation 1).

Equation 1. Specimen Aperture vs. Port Aperture Area Correction

$$E_{Open,\ AreaCorr.} = E_{Open,\ Raw} \frac{A_{Spec.Aper.}}{A_{SphereAper.}}$$

Since it is not possible to measure the open hole reference at the same instant in time as the tube, an approximation is made that accounts for some (linear) change in sky conditions over the roughly 2-4 minutes elapsed between the before specimen open hole and the after specimen open hole. As shown in Equation 2, the transmittance is calculated by dividing the illuminance measured with the tube present, by the average of the area corrected illuminance of both open hole measurements (before and after the tube measurement).

Equation 2. Transmittance

$$T = \frac{2E_{Specimen}}{E_{OpenBefore,\ AreaCorr.} + E_{OpenAfter,\ AreaCorr.}}$$

These calculations are performed independently for each of the four inward looking sensors. The transmittance associated with each sensor is then averaged to diminish any bias an individual sensor may have as a result of its view of the interior of the sphere differing from the others. Because the center Licor sensor of the three surrounding the aperture was often higher than the other three, it was dropped from the average of all calculations. It is suspected that this sensor has the most direct view of the first bounce hot spot inside the sphere. For most measurements removing this sensor does not make a significant difference, but there were enough cases where it was systematically higher, that it seemed worth eliminating the outlying behavior. Thus, the transmittance was calculated from the average of three interior looking sensors, instead of the four present.

Because the specimen (when present) reflects more internal light back into the sphere compared to the open hole (which reflects none), a correction must be made to account for this boost to the signal when the specimen is present. The formula for this sphere correction factor is outlined in Equation 3. As can be seen by the correction factors tabulated in Table 2, for samples with less than 50% reflectance the uncorrected error is less than 2% of the transmittance value and 25%, less than 1%. TDD lens reflection data was not provided or measured for the specimens in this project, but because they can be assumed to have a low reflectance typical of high transmission daylighting materials, the adjustment should be no more than 1% without this correction. It may be useful to recognize that, if anything, this correction will uniformly lower the transmittance slightly compared to the values in this report from the integrating sphere.

Equation 3. Sphere Correction Factor

$$C = \left[1 - \frac{r_1 r_2 f_c}{1 - r_2(1 - f_c)}\right]$$

Where r_1 is the interior facing sample reflectance, r_2 is the interior sphere reflectance and f_c is the area ratio (port area over sphere surface area). Multiplying the sphere correction factor by the transmittance returns the corrected transmittance.

Table 2. Sphere correction factors as a function of sample reflectance (holding constant sphere port area ratio 100:1 and sphere reflectance 0.85)

sample reflectance, r_1	**Sphere correction factor, C**
0.05	1.00
0.10	0.99
0.15	0.99
0.20	0.99
0.25	0.99
0.30	0.98
0.35	0.98
0.40	0.98
0.45	0.98

0.50	0.97
0.55	0.97
0.60	0.97
0.65	0.97
0.70	0.96
0.75	0.96
0.80	0.96
0.85	0.96
0.90	0.95
0.95	0.95
1.00	0.95

The four test samples were assembled by each lab, with the exception of the Solatube product which shipped assembled. As a result, it is important to report the as built dimensions of the tubes for each test location, as this may effect both the optical performance and the incoming aperture value that is used when computing VT.

Table 3. As built dimensions of the four TDD specimens measured at LBNL.

Specimen	**Diameter**	**Length**	**L/D ratio**
Reference	13.5” (343mm)	48” (1219mm)	3.55
Tube A	13.5” (344mm)	46.7” (1186mm)	3.45
Tube B	13.5” (343mm)	45.5” (1156mm)	3.37
Tube C	13.4” (342mm)	46” (1168mm)	3.42

SOLATUBE

Solatube has developed a goniophotometer specifically for testing tubular daylighting products. It is located inside a moveable “lighthouse” that can be positioned to within +/- 15 degrees of any existing solar altitude and within +/- 90 degrees of any solar azimuth. This allows rapid testing of many solar angles without waiting for the sun to be in the exact position. The test equipment consists of a quarter arc rotating arm at a constant radius from the center of the diffuser in the ceiling. This radius is greater than 5x the aperture of the diffuser (an IESNA requirement) but, we have also developed an algorithm in the evaluation software that accounts for larger apertures. The rotating arc has a LICOR sensor located every 5 degrees from a point directly under the diffuser (@ 0 degrees) to a point closest to the ceiling (@ 88.5 degrees) or a total of 19. The arc is rotated in increments of 20 degrees between each measurement for a total of 361 light measurements in the hemisphere below the diffuser. All of these measurements can be accomplished in less than three minutes. There are also two LICOR sensors on the roof (outward looking sensors) of the lighthouse that are in the same plane as the tube opening and monitor the total available light and the diffuse content.

The data post processing is done in a spreadsheet. An example is in Appendix I. The front page provides the results of the test. This example was the reference tube at a solar altitude of 20 degrees. The total luminous flux pertains to the total lumens measured in the interior of the lighthouse. The total available light is the total measured in the plane of the tube multiplied by the tube aperture. The ratio of these two numbers is the Vt. (21.6%) The sky condition is also shown. The lumens per zone information is used for our photometric files with lighting designers/engineers.

The second page (illuminance) provides the actual recorded measurements of all of the sensors inside and outside the lighthouse and the associated time. These values are in lux. The average of the roof measurements is used for determining the available light. Skip the luminous intensity and go to the luminous flux (lumens). These values are determined from the above sensor measurements, which are multiplied by the associated area related to these measurements. The areas are categorized as the midpoint between each of the vertical and horizontal measurement points. The accumulative totals for each area are added and become the total interior light collected. (The total luminous flux)

The positioning of the lighthouse in relation to the actual suns angle is accomplished with a pinhole sun image onto a round target for determining positioning error. The positioning tolerance during measurements is less than 1 degree.

All of the above format, equipment and procedure exceeds the requirements established for light measurements by IESNA.

Sky conditions for testing have been defined as less than or equal to a ratio of 0.3 to 1 diffuse to direct sunlight. We have tested numerous tubes at the same solar altitude, but within the 0.3 limit and their Vt has remained within +/- 2% points of each other. This variance increased in higher diffuse conditions, so the 0.3 limit appears to be a valid number.

The most important part of this test is the assembly and dimensions of the product. The length, upper aperture and assembly of the tube must be the same for all tests or there can be a major variance. Also, the longer the tube, the more accurate the measurement, because of the multiple bounces.

VELUX

See appendix II for a detailed description of the Velux test and calculation method.

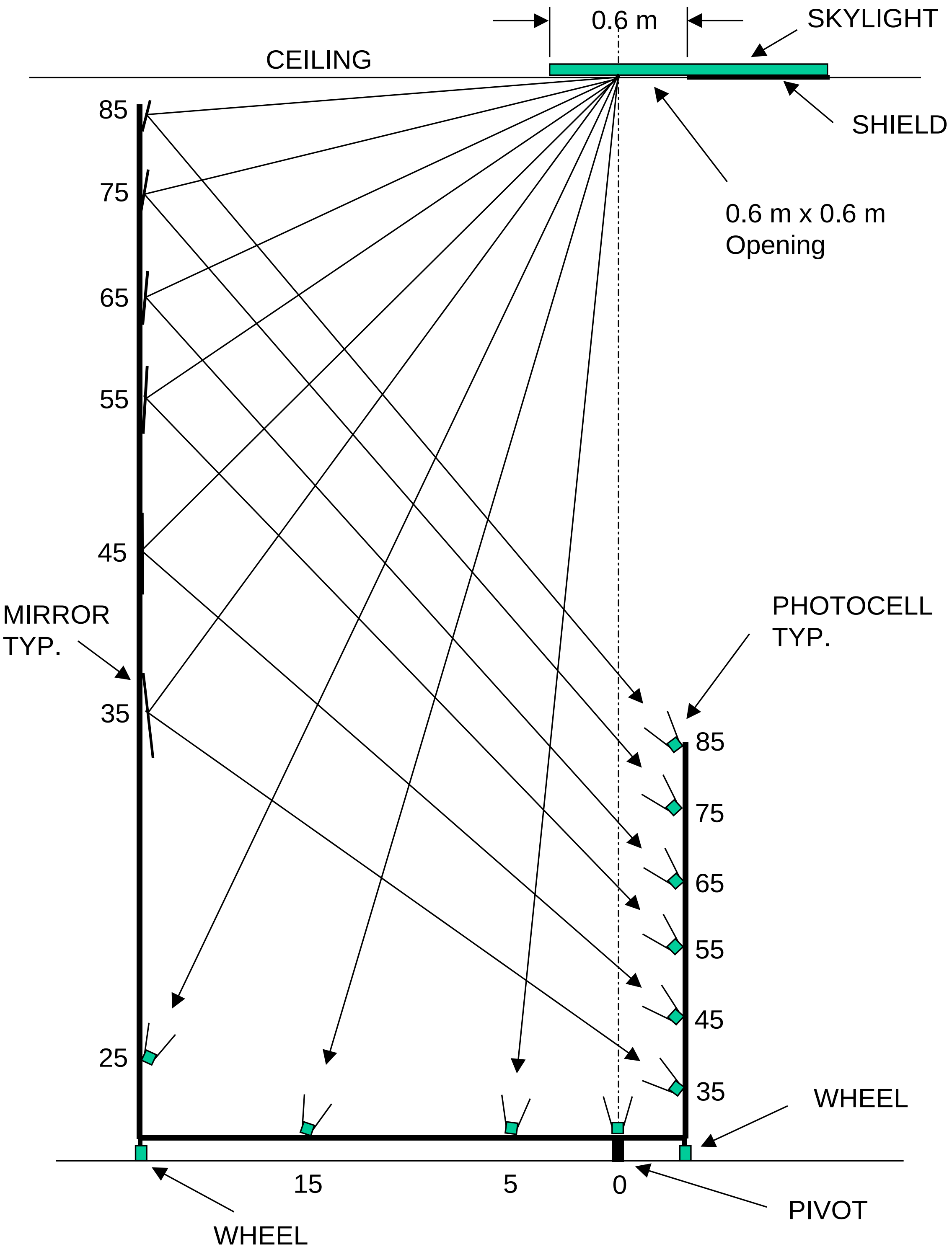


Figure 4 – Schematic of Velux test setup

Data

Reference tube, Total Visible Transmission

SALT	LBNL 1	sky ratio
30	34.0%	0.29
40	37.5%	0.24
50	41.6%	0.23
60	45.7%	0.23
70	48.3%	0.24
90	57.1%	0.24

SALT	LBNL 2	sky ratio
20	21.7%	0.17
30	31.4%	0.13
40	37.0%	0.12
50	41.7%	0.11
60	44.4%	0.10
90	55.8%	0.11

SALT	Lab X	sky ratio
25.7	30.2%	0.38
28.1	32.2%	0.36
29.6	33.0%	0.39
30.6	33.5%	0.36
33.5	34.4%	0.31
38.3	37.3%	0.32
40.3	38.1%	0.31
41.1	38.6%	0.29
43.2	39.3%	0.27
46.7	40.7%	0.28
47.7	41.1%	0.28
57.7	44.4%	0.27
60	45.0%	0.25

SALT	Lab Y	sky ratio
20	21.6%	0.21
30	29.4%	0.28
40	34.7%	0.23
50	38.7%	0.18
60	40.9%	0.11

Specimen A, Total Visible Transmission

azimuth	SALT	LBNL	sky ratio
180	20	27.5%	0.24
180	30	32.8%	0.19
180	40	43.6%	0.17
180	50	53.5%	0.17
180	60	62.6%	0.18
210	30		
210	60	53.3%	0.17
240	30		
240	60		

azimuth	SALT	Lab X	sky ratio
180	20	34.1%	0.47
180	21	32.5%	0.26
180	26	34.3%	0.26
180	28	34.8%	0.25
180	32	36.1%	0.22
180	32.2	40.4%	0.33
180	35.9	42.4%	0.32
180	39	40.5%	0.2
180	41.7	49.4%	0.3
180	44.9	50.3%	0.27
180	50.5	51.3%	0.28
180	51	48.3%	0.2
180	53.8	49.7%	0.16
180	56	54.4%	0.25
180	58	54.6%	0.16
180	61	59.0%	0.25
180	61	56.7%	0.25

azimuth	SALT	Lab Y	sky ratio
180	20	22.9%	0.23
180	30	27.0%	0.17
180	40	35.1%	0.13
180	50	44.5%	0.11
180	60	52.2%	0.15
210	30	26.6%	0.16
210	60	52.1%	0.14
240	30	25.7%	0.13
240	60	54.1%	0.11

Specimen B, Total Visible Transmission

azimuth	SALT	LBNL	sky ratio
180	20	57.5%	0.24
180	30	51.0%	0.18
180	40	45.0%	0.14
180	50	44.7%	0.12
180	60	39.8%	0.11
210	30	52.5%	0.23
210	60		
240	30		
240	60		

azimuth	SALT	Lab X	sky ratio
180	20	51.5%	0.56
180	23	49.9%	0.54
180	30.6	49.6%	0.43
180	39.6	50.1%	0.38
180	45.7	47.1%	0.34
180	49.7	46.4%	0.32
180	50.5	44.6%	0.32
210	31.4	50.8%	0.43
210	51	45.2%	0.32
210	60.5	43.5%	0.32
240	32	51.3%	0.43
240	61	43.0%	0.32

azimuth	SALT	Lab Y	sky ratio
180	20	53.1%	0.27
180	30	45.3%	0.23
180	40	41.2%	0.19
180	50	40.6%	0.18
180	60	38.1%	0.20
210	30	45.7%	0.26
210	60	39.3%	0.22
240	30	45.0%	0.17
240	60	36.9%	0.19

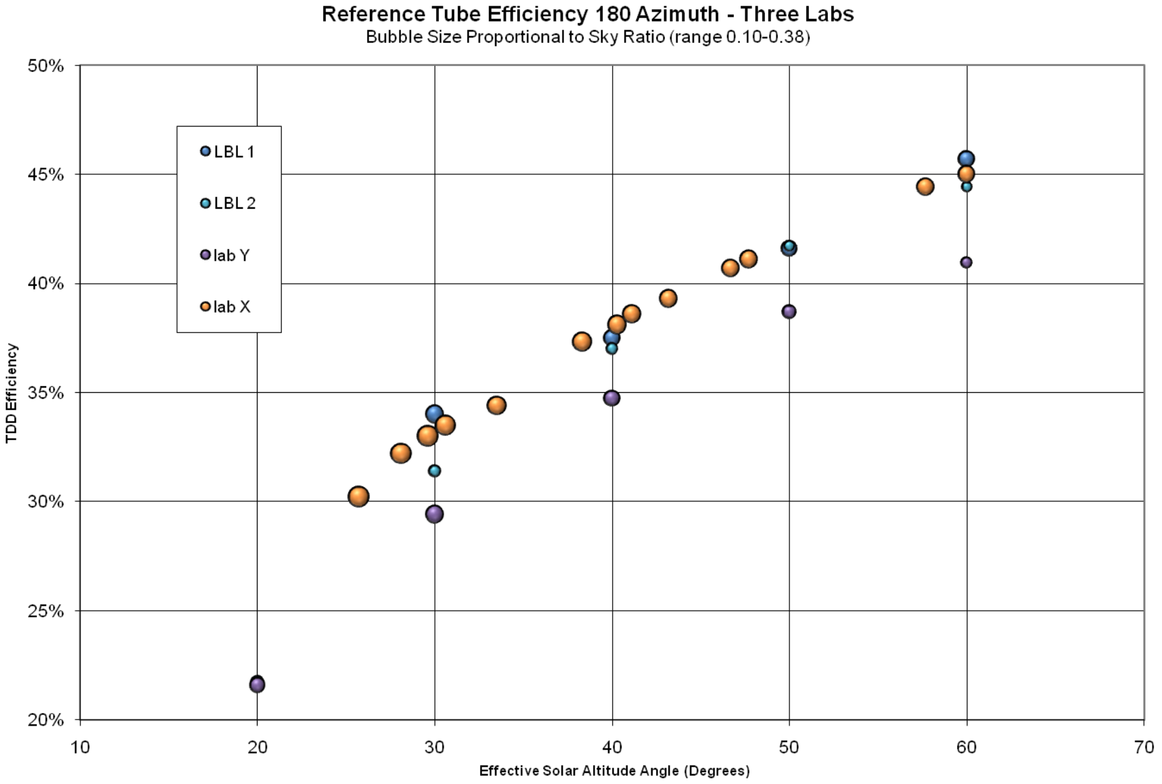
Specimen C, Total Visible Transmission

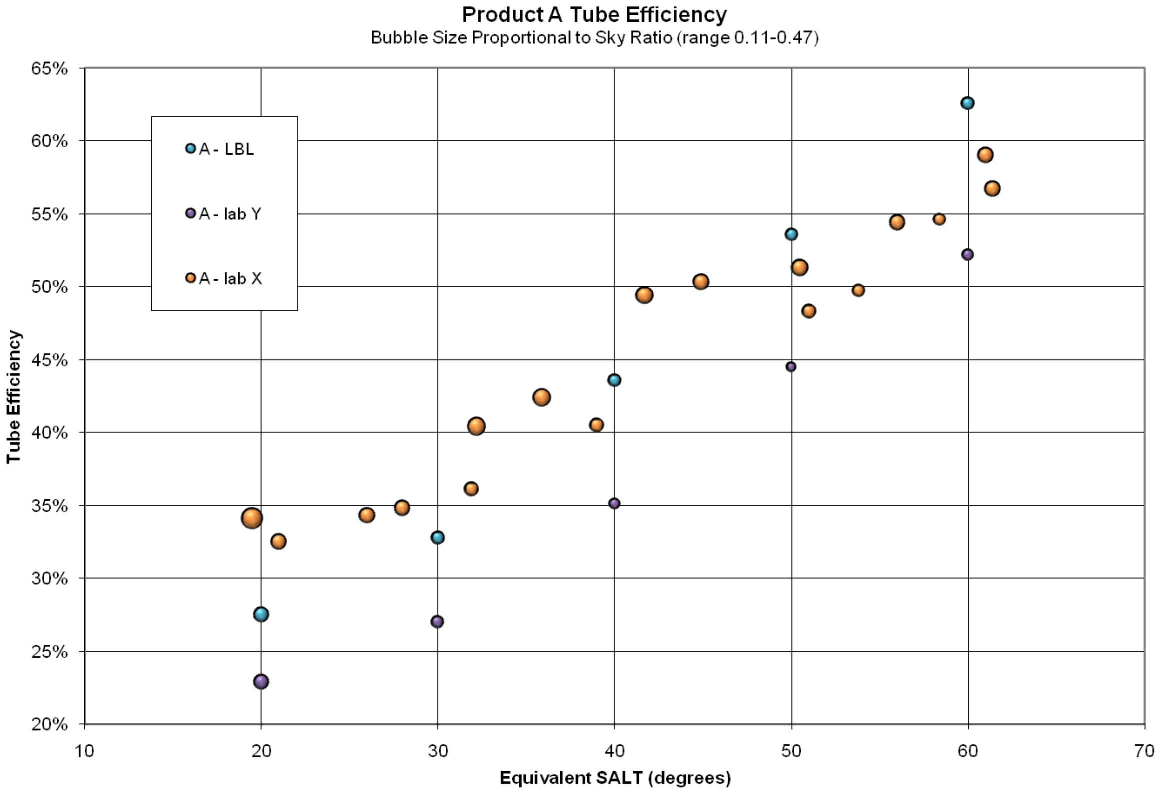
azimuth	SALT	LBNL	sky ratio
180	20	28.3%	0.18
180	30	31.6%	0.13
180	40	37.6%	0.11
180	50	42.7%	0.09
180	60	48.1%	0.09
210	30	31.0%	0.23
210	60	42.4%	0.23
240	30	28.9%	0.27
240	60	30.4%	0.38

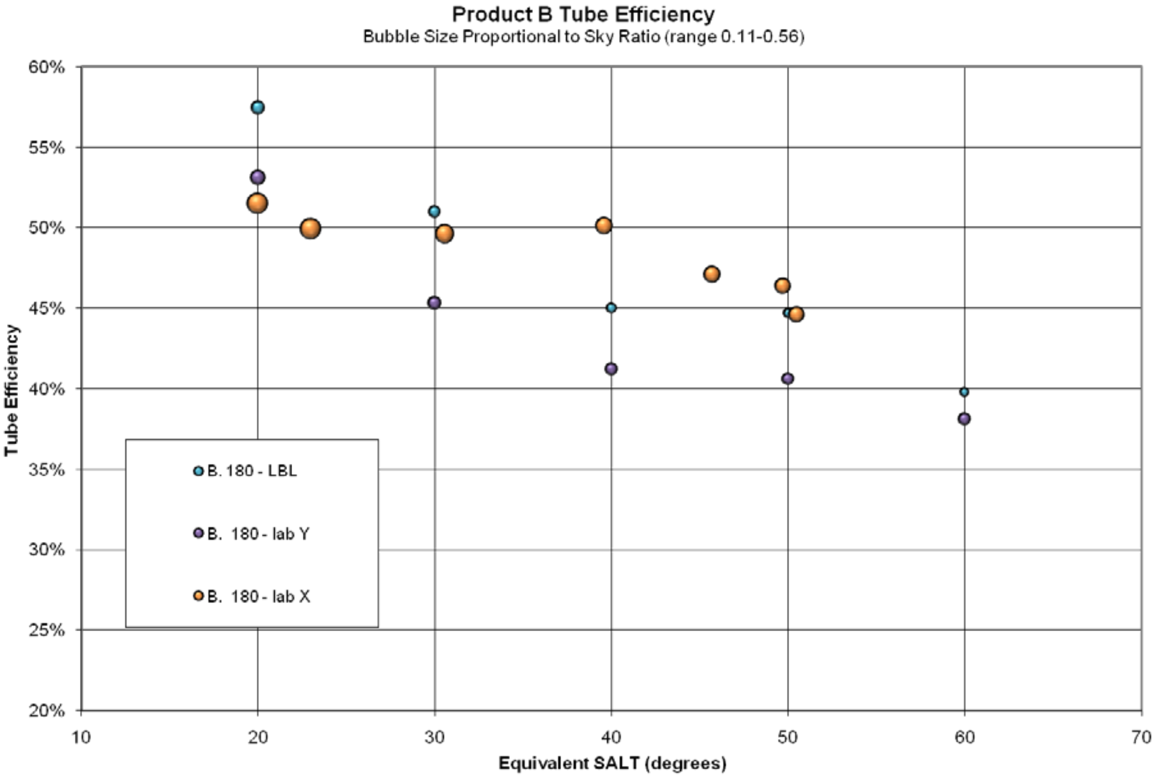
azimuth	SALT	Lab X	sky ratio
180	20	21.9%	0.50
180	24.3	22.2%	0.54
180	30	24.8%	0.36
180	33	24.9%	0.38
180	36	27.4%	0.32
180	39	27.7%	0.38
180	40	28.2%	0.30
180	45.7	30.7%	0.27
180	48.7	32.6%	0.32
180	49.7	34.6	0.28

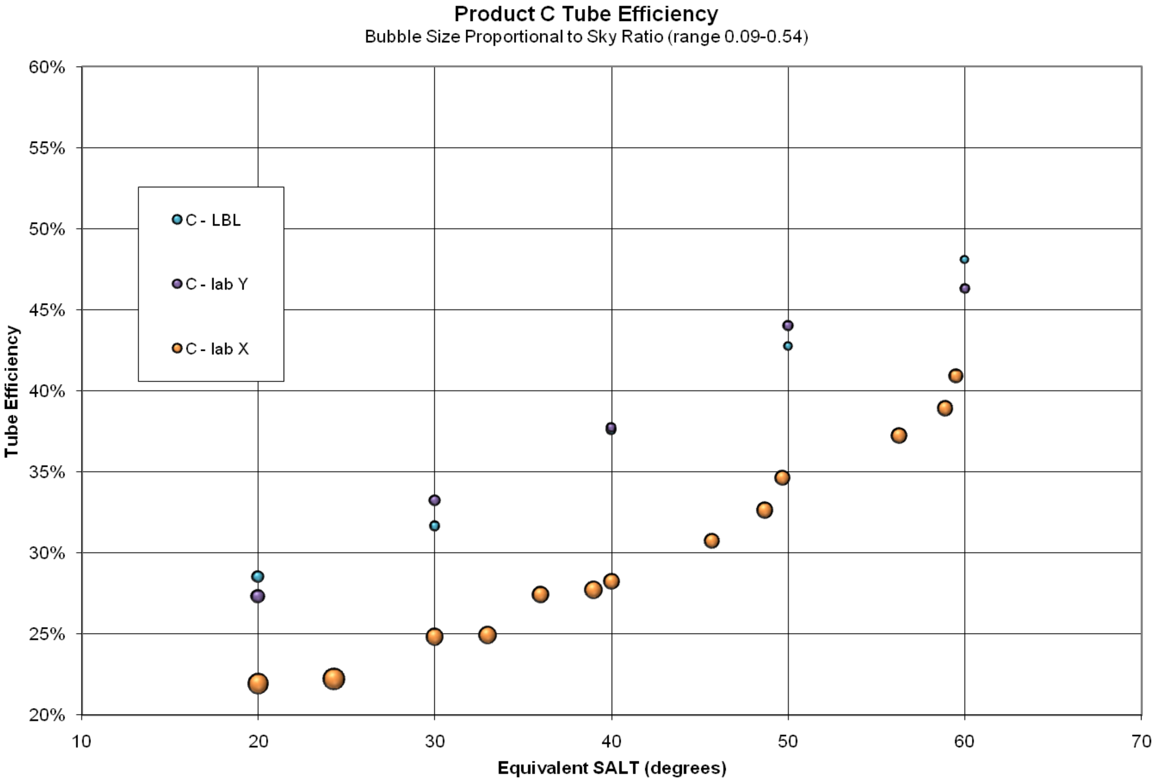
azimuth	SALT	Lab Y	sky ratio
180	20	27.3%	0.23
180	30	33.2%	0.15
180	40	37.7%	0.13
180	50	44.0%	0.13
180	60	46.3%	0.12
210	30	28.8%	0.14
210	60	45.4%	0.13
240	30	26.0%	0.15
240	60	43.0%	0.12

		%	
180	**56.3**	**37.2%**	**0.29**
180	**58.9**	**38.9%**	**0.29**
180	**59.5**	**40.9%**	**0.25**
210	**30.6**		**0.36**
210	**60**	**43.1%**	**0.25**
240	**31.4**		**0.36**
240	**60.5**	**43.6%**	**0.25**


Reference Tube Efficiency 180 Azimuth - Three Labs
Bubble Size Proportional to Sky Ratio (range 0.10-0.38)
LBL 1
LBL 2
lab Y
lab X
TDD Efficiency
50%
45%
40%
35%
30%
25%
20%
10
20
30
40
50
60
70
Effective Solar Altitude Angle (Degrees)

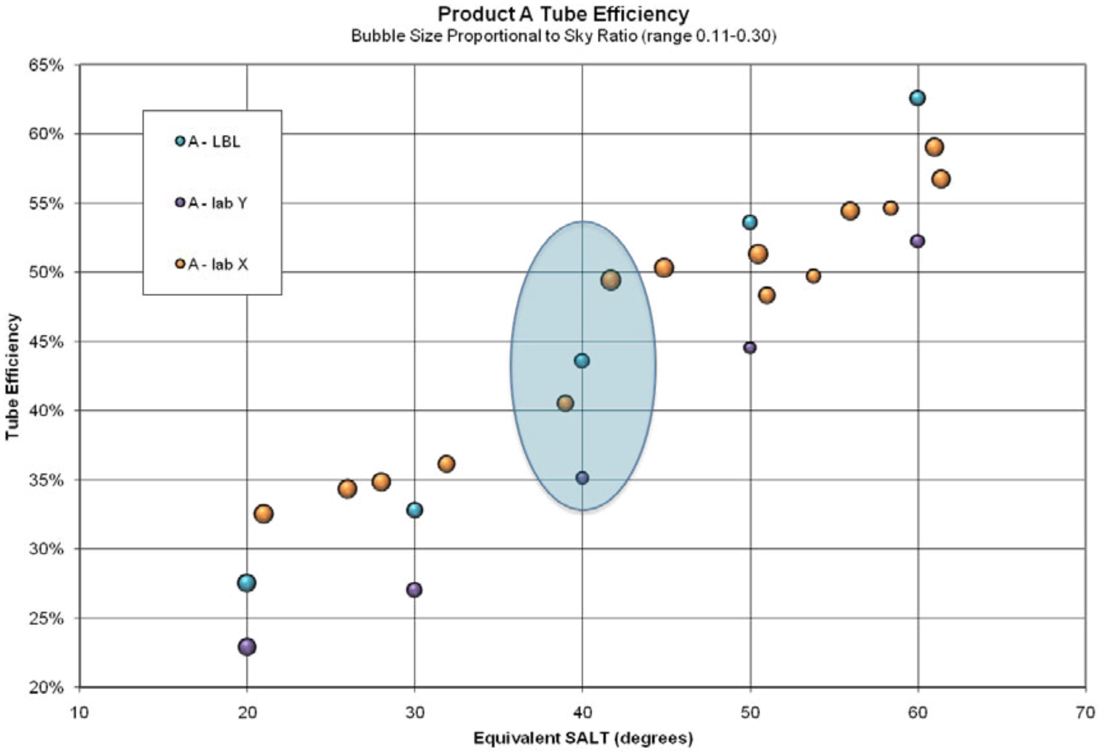

Product A Tube Efficiency
Bubble Size Proportional to Sky Ratio (range 0.11-0.47)
A - LBL
A - lab Y
A - lab X
Tube Efficiency
65%
60%
55%
50%
45%
40%
35%
30%
25%
20%
10
20
30
40
50
60
70
Equivalent SALT (degrees)


Product B Tube Efficiency
Bubble Size Proportional to Sky Ratio (range 0.11-0.56)
60%
55%
50%
45%
40%
35%
30%
25%
20%
Tube Efficiency
10
20
30
40
50
60
70
Equivalent SALT (degrees)
B. 180 - LBL
B. 180 - lab Y
B. 180 - lab X


Product C Tube Efficiency
Bubble Size Proportional to Sky Ratio (range 0.09-0.54)
60%
55%
50%
45%
40%
35%
30%
25%
20%
Tube Efficiency
10
20
30
40
50
60
70
Equivalent SALT (degrees)
C - LBL
C - lab Y
C - lab X

Discussion of Results

The trends of VT versus angle of incidence were consistent over the three laboratory measurements for all four samples. However, the absolute value at several points showed considerable variation. For other NFRC rated properties such as U-factor, the requirement for inter-laboratory comparisons is that results do not vary by more than +/-10%. Is this right? In this exercise, twelve out of the forty five measurements taken at 180 degrees azimuth for product tubes A, B and C exceeded +/-10% from the average of the three labs. By comparison, for simpler reference tube, all labs reported values within +9%, -6.7% of the average. These percentages are not absolute differences, but rather relative to the VT value, hence the same delta % at a higher VT is a lower % difference. Some observations that may contribute to understanding these variations are discussed below.



Lab X: 8.9% absolute difference over 2.7 degrees

Lab X vs Lab Y 14.3% absolute difference

The three devices used to test the TDD's were of two major types: two goniophotometers and one large integrating sphere. As shown in the equipment descriptions above, these two types of devices use a fundamentally different approach to produce a VT. The goniophotometers require more calculations to create a single VT number from the detailed angular data. The goniophotometers use a ratio signal of exterior sensors to interior sensors, which requires a highly accurate and stable calibration of all sensors. The integrating sphere uses a ratio of the same inward looking sensors with and without the sample being present, which makes it less dependent on the calibration of the sensors, but makes it more susceptible to short time scale changes in sky conditions between the two measurements.

The light coming from the complex optics typically found in a TDD will usually not be homogeneous. Because the goniophotometers sample at discrete points, there is a risk that these points do not accurately measure intensity variations that are smaller than the spacing between measurement points. Use of the integrating sphere needs to consider sensor bias toward the higher intensity spot that occurs at the first reflection inside of the sphere. The sensors in the integrating sphere are shielded by baffles from ‘seeing’ the sample aperture directly. Ideally baffles would also be placed to prevent the sensors from seeing the hot spots caused by the first reflection. Because the sphere is used to make measurements at multiple angles of incidence, it is not possible to baffle the sensors from these hot spots. This effect is minimized by the fact that each sensor sees a large area of the interior sphere surface. Multiple sensors in the sphere placed at different locations are used in the calculations. Variation between the three reported sensors is typically less than 0.2%, with no individual measurements exceeding -1.9%, +3.7% from the average. The multiple sensors are averaged to minimize any error related to hot spots. Note, that one of the four sensors in the integrating sphere was dropped from the average as an outlier because of suspected excessive bias toward the first reflection hot spot.

Conclusions

References/Bibliography

Kessel, J. Transmittance Measurements in the Integrating Sphere. Applied Optics, Vol.25, page 2752. 1986

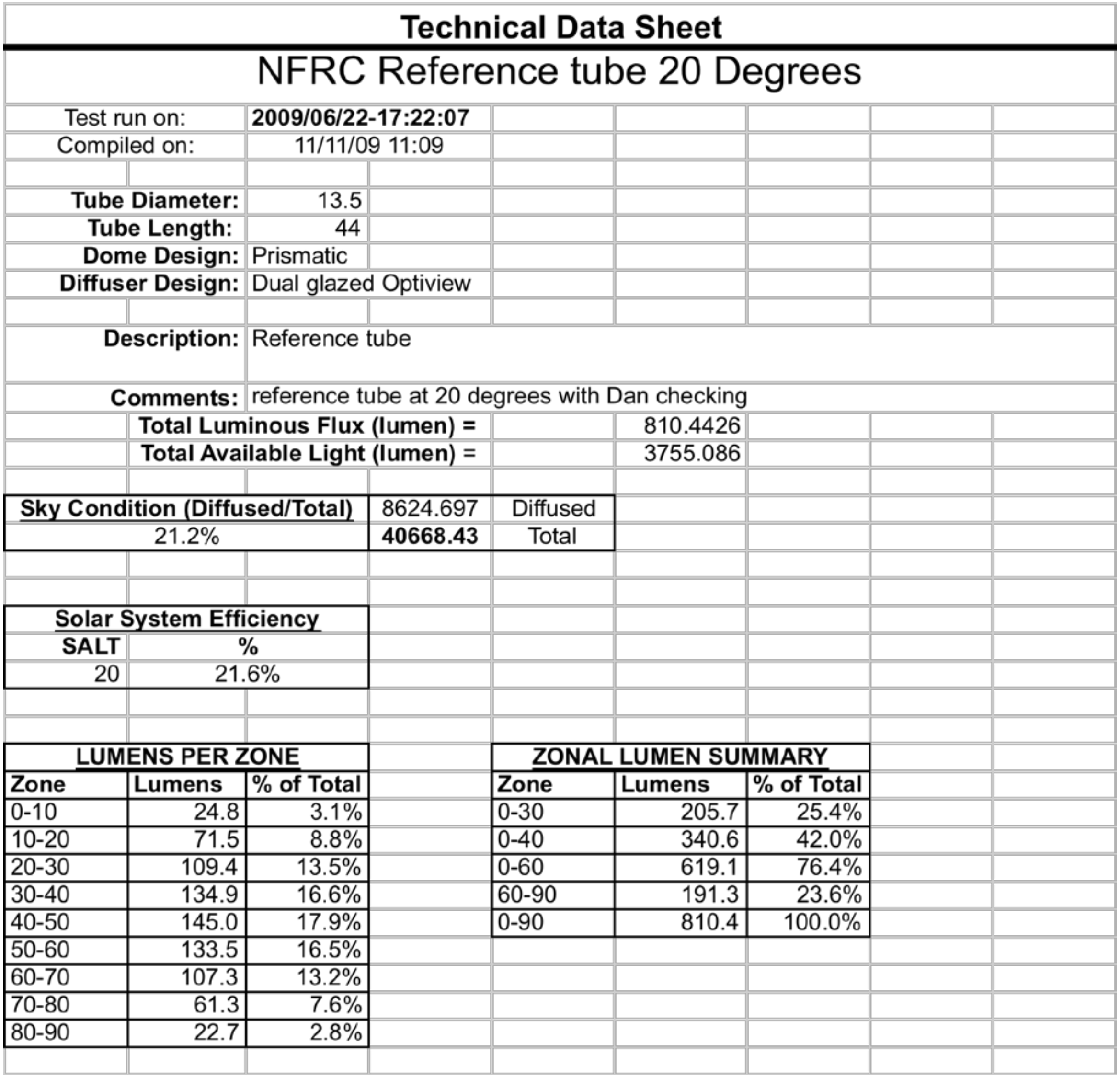
Kessel, J., Selkowitz, S. Integrating Sphere Measurements of Directional-Hemispherical Transmittance of Window Systems. Illuminating Engineering Society Annual Technical Conference. 1984

G.A. Zerlaut and T.E. Anderson, A large multipurpose solar-illuminated 8-ft. integrating sphere, Proc. SPIE, vol. 502 (1989) pp. 152-160.

ASTM E 1175-87 Standard Test Method for Determining Solar or Photopic Reflectance, Transmittance, and Absorptance of Materials Using a Large Diameter Integrating Sphere. 1987, reapproved 1996

Appendix I – Solatube Technical Data Sheet for calculations

(Front Page of spreadsheet)



Technical Data Sheet

NFRC Reference tube 20 Degrees

Test run on:	**2009/06/22-17:22:07**
Compiled on:	11/11/09 11:09
Tube Diameter:	13.5
Tube Length:	44
Dome Design:	Prismatic
Diffuser Design:	Dual glazed Optiview
Description:	Reference tube
Comments:	reference tube at 20 degrees with Dan checking
Total Luminous Flux (lumen) =	810.4426
Total Available Light (lumen) =	3755.086

Sky Condition (Diffused/Total)	8624.697	Diffused
21.2%	**40668.43**	Total

Solar System Efficiency	
SALT	**%**
20	21.6%

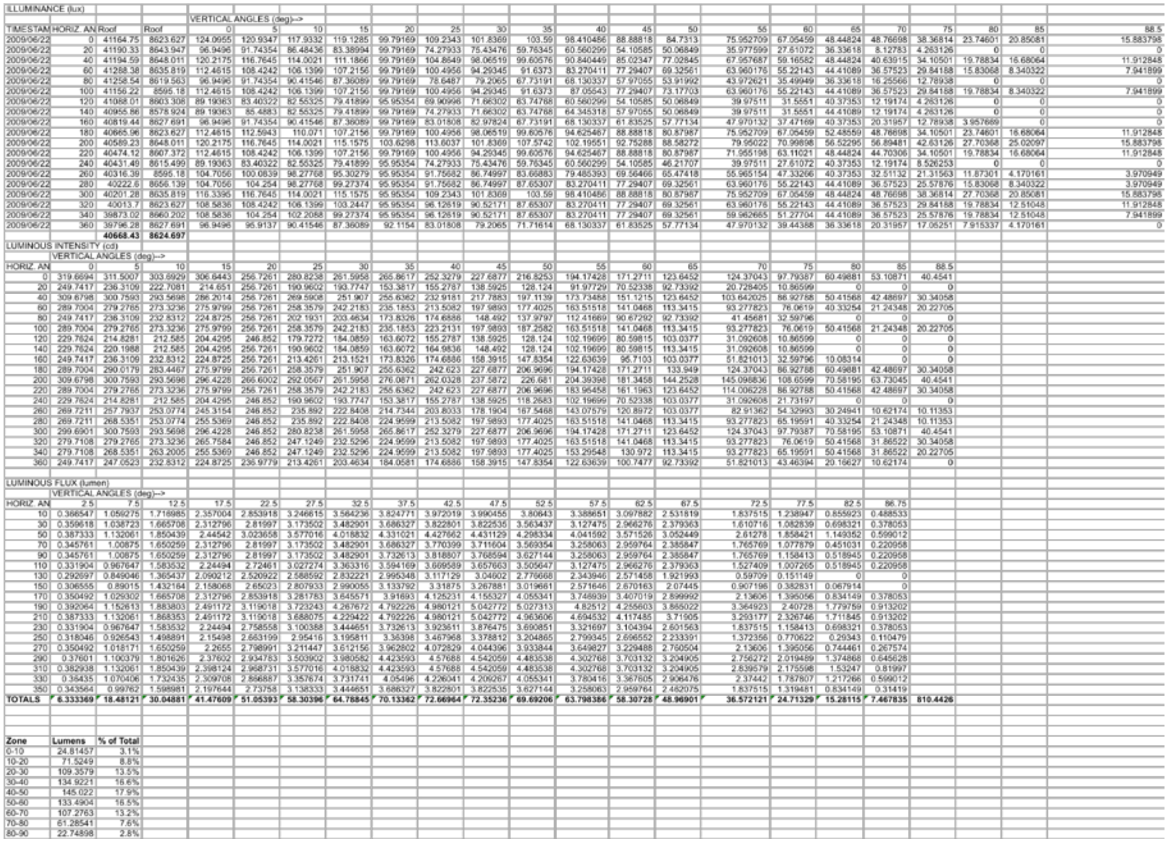
LUMENS PER ZONE

Zone	Lumens	% of Total
0-10	24.8	3.1%
10-20	71.5	8.8%
20-30	109.4	13.5%
30-40	134.9	16.6%
40-50	145.0	17.9%
50-60	133.5	16.5%
60-70	107.3	13.2%
70-80	61.3	7.6%
80-90	22.7	2.8%

ZONAL LUMEN SUMMARY

Zone	Lumens	% of Total
0-30	205.7	25.4%
0-40	340.6	42.0%
0-60	619.1	76.4%
60-90	191.3	23.6%
0-90	810.4	100.0%

Second page of spreadsheet (illumination data)



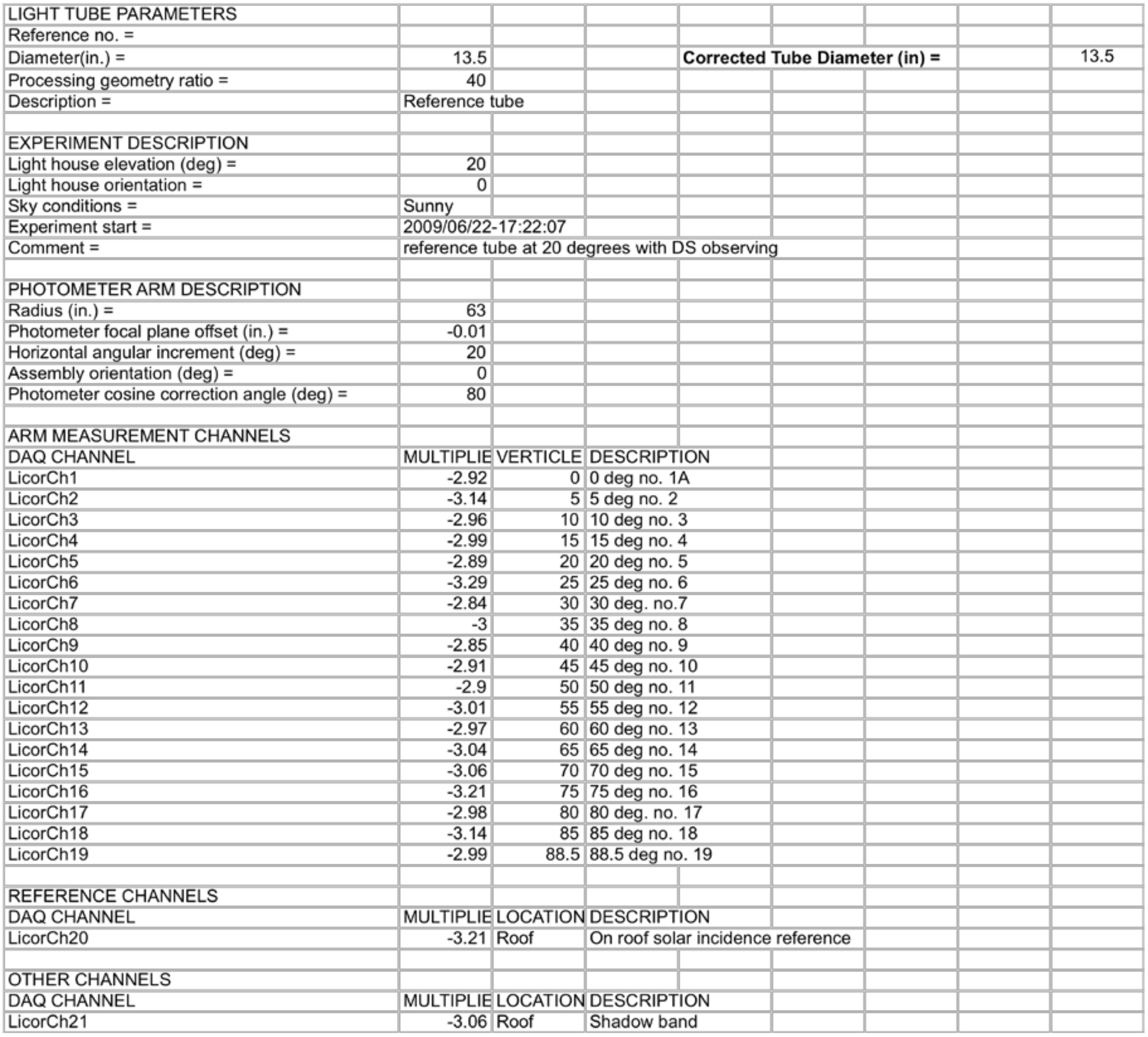
ILLUMINANCE (lux)																						
				VERTICAL ANGLES (deg)-->																		
TIMESTAM	HORIZ. AN	Roof	Roof	0	5	10	15	20	25	30	35	40	45	50	55	60	65	70	75	80	85	88.5
2009/06/22	0	41164.75	8623.627	124.0955	120.9347	117.9332	119.1285	99.79169	109.2343	101.8369	103.59	98.410486	88.88818	84.7313	75.952709	67.05459	48.44824	48.76698	38.36814	23.74601	20.85081	15.883798
2009/06/22	20	41190.33	8643.947	96.9496	91.74354	86.48436	83.38994	99.79169	74.27933	75.43476	59.76345	60.560299	54.10585	50.06849	35.977599	27.61072	36.33618	8.12783	4.263126	0	0	0
2009/06/22	40	41194.59	8648.011	120.2175	116.7645	114.0021	111.1866	99.79169	104.8649	98.06519	99.60676	90.840449	85.02347	77.02845	67.957687	59.16582	48.44824	40.63915	34.10501	19.78834	16.68064	11.912848
2009/06/22	60	41288.38	8635.819	112.4615	108.4242	106.1399	107.2156	99.79169	100.4956	94.29345	91.6373	83.270411	77.29407	69.32561	63.960176	55.22143	44.41089	36.57523	29.84188	15.83068	8.340322	7.941899
2009/06/22	80	41258.54	8619.563	96.9496	91.74354	90.41546	87.36089	99.79169	78.6487	79.2065	67.73191	68.130337	57.97055	53.91992	43.972621	35.49949	36.33618	16.25566	12.78938	0	0	0
2009/06/22	100	41156.22	8595.18	112.4615	108.4242	106.1399	107.2156	99.79169	100.4956	94.29345	91.6373	87.05543	77.29407	73.17703	63.960176	55.22143	44.41089	36.57523	29.84188	19.78834	8.340322	7.941899
2009/06/22	120	41088.01	8603.308	89.19363	83.40322	82.55325	79.41899	95.95354	69.90998	71.66302	63.74768	60.560299	54.10585	50.06849	39.97511	31.5551	40.37353	12.19174	4.263126	0	0	0
2009/06/22	140	40955.86	8578.924	89.19363	85.4883	82.55325	79.41899	99.79169	74.27933	71.66302	63.74768	64.345318	57.97055	50.06849	39.97511	31.5551	44.41089	12.19174	4.263126	0	0	0
2009/06/22	160	40819.44	8627.691	96.9496	91.74354	90.41546	87.36089	99.79169	83.01808	82.97824	67.73191	68.130337	61.83525	57.77134	47.970132	37.47169	40.37353	20.31957	12.78938	3.957669	0	0
2009/06/22	180	40665.96	8623.627	112.4615	112.5943	110.071	107.2156	99.79169	100.4956	98.06519	99.60676	94.625467	88.88818	80.87987	75.952709	67.05459	52.48559	48.76698	34.10501	23.74601	16.68064	11.912848
2009/06/22	200	40589.23	8648.011	120.2175	116.7645	114.0021	115.1575	103.6298	113.6037	101.8369	107.5742	102.19551	92.75288	88.58272	79.95022	70.99898	56.52295	56.89481	42.63126	27.70368	25.02097	15.883798
2009/06/22	220	40474.12	8607.372	112.4615	108.4242	106.1399	107.2156	99.79169	100.4956	94.29345	99.60676	94.625467	88.88818	80.87987	71.955198	63.11021	48.44824	44.70306	34.10501	19.78834	16.68064	11.912848
2009/06/22	240	40431.49	8615.499	89.19363	83.40322	82.55325	79.41899	95.95354	74.27933	75.43476	59.76345	60.560299	54.10585	46.21707	39.97511	27.61072	40.37353	12.19174	8.526253	0	0	0
2009/06/22	260	40316.39	8595.18	104.7056	100.0839	98.27768	95.30279	95.95354	91.75682	86.74997	83.66883	79.485393	69.56466	65.47418	55.965154	47.33266	40.37353	32.51132	21.31563	11.87301	4.170161	3.970949
2009/06/22	280	40222.6	8656.139	104.7056	104.254	98.27768	99.27374	95.95354	91.75682	86.74997	87.65307	83.270411	77.29407	69.32561	63.960176	55.22143	44.41089	36.57523	25.57876	15.83068	8.340322	3.970949
2009/06/22	300	40201.28	8635.819	116.3396	116.7645	114.0021	115.1575	95.95354	109.2343	101.8369	103.59	98.410486	88.88818	80.87987	75.952709	67.05459	48.44824	48.76698	38.36814	27.70368	20.85081	15.883798
2009/06/22	320	40013.7	8623.627	108.5836	108.4242	106.1399	103.2447	95.95354	96.12619	90.52171	87.65307	83.270411	77.29407	69.32561	63.960176	55.22143	44.41089	36.57523	29.84188	19.78834	12.51048	11.912848
2009/06/22	340	39873.02	8660.202	108.5836	104.254	102.2088	99.27374	95.95354	96.12619	90.52171	87.65307	83.270411	77.29407	69.32561	59.962665	51.27704	44.41089	36.57523	25.57876	19.78834	12.51048	7.941899
2009/06/22	360	39796.28	8627.691	96.9496	95.9137	90.41546	87.36089	92.1154	83.01808	79.2065	71.71614	68.130337	61.83525	57.77134	47.970132	39.44388	36.33618	20.31957	17.05251	7.915337	4.170161	0
		40668.43	**8624.697**																			

LUMINOUS INTENSITY (cd)																			
	VERTICAL ANGLES (deg)-->																		
HORIZ. AN	0	5	10	15	20	25	30	35	40	45	50	55	60	65	70	75	80	85	88.5
0	319.6694	311.5007	303.6929	306.6443	256.7261	280.8238	261.5958	265.8617	252.3279	227.6877	216.8253	194.17428	171.2711	123.6452	124.37043	97.79387	60.49881	53.10871	40.4541
20	249.7417	236.3109	222.7081	214.651	256.7261	190.9602	193.7747	153.3817	155.2787	138.5925	128.124	91.97729	70.52338	92.73392	20.728405	10.86599	0	0	0
40	309.6798	300.7593	293.5698	286.2014	256.7261	269.5908	251.907	255.6362	232.9181	217.7883	197.1139	173.73488	151.1215	123.6452	103.642025	86.92788	50.41568	42.48697	30.34058
60	289.7004	279.2765	273.3236	275.9799	256.7261	258.3579	242.2183	235.1853	213.5082	197.9893	177.4025	163.51518	141.0468	113.3415	93.277823	76.0619	40.33254	21.24348	20.22705
80	249.7417	236.3109	232.8312	224.8725	256.7261	202.1931	203.4634	173.8326	174.6886	148.492	137.9797	112.41669	90.67292	92.73392	41.45681	32.59796	0	0	0
100	289.7004	279.2765	273.3236	275.9799	256.7261	258.3579	242.2183	235.1853	223.2131	197.9893	187.2582	163.51518	141.0468	113.3415	93.277823	76.0619	50.41568	21.24348	20.22705
120	229.7624	214.8281	212.585	204.4295	246.852	179.7272	184.0859	163.6072	155.2787	138.5925	128.124	102.19699	80.59815	103.0377	31.092608	10.86599	0	0	0
140	229.7624	220.1988	212.585	204.4295	256.7261	190.9602	184.0859	163.6072	164.9836	148.492	128.124	102.19699	80.59815	113.3415	31.092608	10.86599	0	0	0
160	249.7417	236.3109	232.8312	224.8725	256.7261	213.4261	213.1521	173.8326	174.6886	158.3915	147.8354	122.63639	95.7103	103.0377	51.821013	32.59796	10.08314	0	0
180	289.7004	290.0179	283.4467	275.9799	256.7261	258.3579	251.907	255.6362	242.623	227.6877	206.9696	194.17428	171.2711	133.949	124.37043	86.92788	60.49881	42.48697	30.34058
200	309.6798	300.7593	293.5698	296.4228	266.6002	292.0567	261.5958	276.0871	262.0328	237.5872	226.681	204.39398	181.3458	144.2528	145.098836	108.6599	70.58195	63.73045	40.4541
220	289.7004	279.2765	273.3236	275.9799	256.7261	258.3579	242.2183	255.6362	242.623	227.6877	206.9696	183.95458	161.1963	123.6452	114.006228	86.92788	50.41568	42.48697	30.34058
240	229.7624	214.8281	212.585	204.4295	246.852	190.9602	193.7747	153.3817	155.2787	138.5925	118.2683	102.19699	70.52338	103.0377	31.092608	21.73197	0	0	0
260	269.7211	257.7937	253.0774	245.3154	246.852	235.892	222.8408	214.7344	203.8033	178.1904	167.5468	143.07579	120.8972	103.0377	82.91362	54.32993	30.24941	10.62174	10.11353
280	269.7211	268.5351	253.0774	255.5369	246.852	235.892	222.8408	224.9599	213.5082	197.9893	177.4025	163.51518	141.0468	113.3415	93.277823	65.19591	40.33254	21.24348	10.11353
300	299.6901	300.7593	293.5698	296.4228	246.852	280.8238	261.5958	265.8617	252.3279	227.6877	206.9696	194.17428	171.2711	123.6452	124.37043	97.79387	70.58195	53.10871	40.4541
320	279.7108	279.2765	273.3236	265.7584	246.852	247.1249	232.5296	224.9599	213.5082	197.9893	177.4025	163.51518	141.0468	113.3415	93.277823	76.0619	50.41568	31.86522	30.34058
340	279.7108	268.5351	263.2005	255.5369	246.852	247.1249	232.5296	224.9599	213.5082	197.9893	177.4025	153.29548	130.972	113.3415	93.277823	65.19591	50.41568	31.86522	20.22705
360	249.7417	247.0523	232.8312	224.8725	236.9779	213.4261	203.4634	184.0581	174.6886	158.3915	147.8354	122.63639	100.7477	92.73392	51.821013	43.46394	20.16627	10.62174	0

LUMINOUS FLUX (lumen)																			
	VERTICAL ANGLES (deg)-->																		
HORIZ. AN	2.5	7.5	12.5	17.5	22.5	27.5	32.5	37.5	42.5	47.5	52.5	57.5	62.5	67.5	72.5	77.5	82.5	86.75	
10	0.366547	1.059275	1.716985	2.357004	2.853918	3.246615	3.564236	3.824771	3.972019	3.990455	3.80643	3.388651	3.097882	2.531819	1.837515	1.238947	0.855923	0.488533	
30	0.359618	1.038723	1.665708	2.312796	2.81997	3.173502	3.482901	3.686327	3.822801	3.822535	3.563437	3.127475	2.966276	2.379363	1.610716	1.082839	0.698321	0.378053	
50	0.387333	1.132061	1.850439	2.44542	3.023658	3.577016	4.018832	4.331021	4.427662	4.431129	4.298334	4.041592	3.571526	3.052449	2.61278	1.858421	1.149352	0.599012	
70	0.345761	1.00875	1.650259	2.312796	2.81997	3.173502	3.482901	3.686327	3.770399	3.711604	3.569354	3.258063	2.959764	2.385847	1.765769	1.077879	0.451031	0.220958	
90	0.345761	1.00875	1.650259	2.312796	2.81997	3.173502	3.482901	3.732613	3.818807	3.768594	3.627144	3.258063	2.959764	2.385847	1.765769	1.158413	0.518945	0.220958	
110	0.331904	0.967647	1.583532	2.24494	2.72461	3.027274	3.363316	3.594169	3.669589	3.657663	3.505647	3.127475	2.966276	2.379363	1.527409	1.007265	0.518945	0.220958	
130	0.292697	0.849046	1.365437	2.090212	2.520922	2.588592	2.832221	2.995348	3.117129	3.04602	2.776668	2.343946	2.571458	1.921993	0.59709	0.151149	0	0	
150	0.306555	0.89015	1.432164	2.158068	2.65023	2.807933	2.990055	3.133792	3.31875	3.267881	3.019661	2.571646	2.670163	2.07445	0.907196	0.382831	0.067914	0	
170	0.350492	1.029302	1.665708	2.312796	2.853918	3.281783	3.645571	3.91693	4.125231	4.155327	4.055341	3.748939	3.407019	2.899992	2.13606	1.396056	0.834149	0.378053	
190	0.392064	1.152613	1.883803	2.491172	3.119018	3.723243	4.267672	4.792226	4.980121	5.042772	5.027313	4.82512	4.255603	3.865022	3.364923	2.40728	1.779759	0.913202	
210	0.387333	1.132061	1.868353	2.491172	3.119018	3.688075	4.229422	4.792226	4.980121	5.042772	4.963606	4.694532	4.117485	3.71905	3.293177	2.326746	1.711845	0.913202	
230	0.331904	0.967647	1.583532	2.24494	2.758558	3.100388	3.444651	3.732613	3.923611	3.876475	3.690851	3.321697	3.104394	2.601563	1.837515	1.158413	0.698321	0.378053	
250	0.318046	0.926543	1.498891	2.15498	2.663199	2.95416	3.195811	3.36398	3.467968	3.378812	3.204865	2.799345	2.696552	2.233391	1.372356	0.770622	0.29343	0.110479	
270	0.350492	1.018171	1.650259	2.2655	2.798991	3.211447	3.612156	3.962802	4.072829	4.044396	3.933844	3.649827	3.229488	2.760504	2.13606	1.396056	0.744461	0.267574	
290	0.37601	1.100379	1.801626	2.37602	2.934783	3.503902	3.980582	4.423593	4.57688	4.542059	4.483538	4.302768	3.703132	3.204905	2.756272	2.019489	1.374868	0.645628	
310	0.382938	1.132061	1.850439	2.398124	2.968731	3.577016	4.018832	4.423593	4.57688	4.542059	4.483538	4.302768	3.703132	3.204905	2.839579	2.175598	1.53247	0.81997	
330	0.38435	1.070406	1.732435	2.309708	2.866887	3.357674	3.731741	4.05496	4.226041	4.209267	4.055341	3.780416	3.367605	2.906476	2.37442	1.787807	1.217266	0.599012	
350	0.343564	0.99762	1.598981	2.197644	2.73758	3.138333	3.444651	3.686327	3.822801	3.822535	3.627144	3.258063	2.959764	2.462075	1.837515	1.319481	0.834149	0.31419	
TOTALS	**6.333369**	**18.48121**	**30.04881**	**41.47609**	**51.05393**	**58.30396**	**64.78845**	**70.13362**	**72.66964**	**72.35236**	**69.69206**	**63.798386**	**58.30728**	**48.96901**	**36.572121**	**24.71329**	**15.28115**	**7.467835**	**810.4426**

Zone	**Lumens**	**% of Total**
0-10	24.81457	3.1%
10-20	71.5249	8.8%
20-30	109.3579	13.5%
30-40	134.9221	16.6%
40-50	145.022	17.9%
50-60	133.4904	16.5%
60-70	107.2763	13.2%
70-80	61.28541	7.6%
80-90	22.74898	2.8%

Third Page of Spreadsheet – Description



LIGHT TUBE PARAMETERS								
Reference no. =								
Diameter(in.) =	13.5			**Corrected Tube Diameter (in) =**				13.5
Processing geometry ratio =	40							
Description =	Reference tube							
EXPERIMENT DESCRIPTION								
Light house elevation (deg) =	20							
Light house orientation =	0							
Sky conditions =	Sunny							
Experiment start =	2009/06/22-17:22:07							
Comment =	reference tube at 20 degrees with DS observing							
PHOTOMETER ARM DESCRIPTION								
Radius (in.) =	63							
Photometer focal plane offset (in.) =	-0.01							
Horizontal angular increment (deg) =	20							
Assembly orientation (deg) =	0							
Photometer cosine correction angle (deg) =	80							
ARM MEASUREMENT CHANNELS								
DAQ CHANNEL	MULTIPLIE	VERTICLE	DESCRIPTION					
LicorCh1	-2.92	0	0 deg no. 1A					
LicorCh2	-3.14	5	5 deg no. 2					
LicorCh3	-2.96	10	10 deg no. 3					
LicorCh4	-2.99	15	15 deg no. 4					
LicorCh5	-2.89	20	20 deg no. 5					
LicorCh6	-3.29	25	25 deg no. 6					
LicorCh7	-2.84	30	30 deg. no.7					
LicorCh8	-3	35	35 deg no. 8					
LicorCh9	-2.85	40	40 deg no. 9					
LicorCh10	-2.91	45	45 deg no. 10					
LicorCh11	-2.9	50	50 deg no. 11					
LicorCh12	-3.01	55	55 deg no. 12					
LicorCh13	-2.97	60	60 deg no. 13					
LicorCh14	-3.04	65	65 deg no. 14					
LicorCh15	-3.06	70	70 deg no. 15					
LicorCh16	-3.21	75	75 deg no. 16					
LicorCh17	-2.98	80	80 deg. no. 17					
LicorCh18	-3.14	85	85 deg no. 18					
LicorCh19	-2.99	88.5	88.5 deg no. 19					
REFERENCE CHANNELS								
DAQ CHANNEL	MULTIPLIE	LOCATION	DESCRIPTION					
LicorCh20	-3.21	Roof	On roof solar incidence reference					
OTHER CHANNELS								
DAQ CHANNEL	MULTIPLIE	LOCATION	DESCRIPTION					
LicorCh21	-3.06	Roof	Shadow band					

Appendix II – VELUX – Documentation of measurements and calculations

1.0 Scope and Purpose

This guide provides uniform methods for determining and reporting the photometric characteristics of skylights and tubular daylighting devices that incorporate a means to diffuse the natural hemispherical daylight as the daylight passes through the daylighting system. It describes the procedures to be followed and the precautions to be observed in obtaining uniform and reproducible measurements of skylights with diffuse glass or plastic glazing and tubular daylighting devices. This guide identifies the components and the structure type needed to adequately measure daylighting devices. The procedures, calibration of the equipment, and determination of sun angles and sky conditions are also discussed.

Unlike electric luminaries, that require only one photometric test, skylights require a separate test to characterize their performance at different sun angles as well as a separate measurement to determine the sky conditions. Skylights are very often large, and exceed the size capabilities of typical intensity distribution photometers. Therefore, a method was created and proven to accurately measure data and have the results put in standardized photometric file format such as IES LM63-1995[1]. The collection of results can then be used by lighting design software programs to simulate how skylights under the desired test conditions will fill a space with daylight. This equipment is also accurate with regard to the effects of test distance.[6]

This is only one method of achieving candle power distribution curves and efficiency data for skylights and tubular daylighting devices with diffusing properties. In addition, this method mirrors the proven method used to measure electric lights but includes many adjustments because of the very intense movable light source, the sun. Since 2002 this method has been proven to produce consistent repeatable results for measuring skylights and tubular daylighting devices under actual sky conditions. Secondly, in 2009 we now have two skylight photometers and one integrating sphere that are being used to produce consistent repeatable results with only a 4% maximum difference between all three laboratories which are located in different geographic parts of the United States.

This is very knowledgeable information that needs to be shared so it can be put into action to benefit the public and lighting design industry. However, keep in mind that daylight photometry is in the infancy stages of research, therefore, further development of these methods will continue and new methods are being researched and may even be developed. For example, simulations could someday produce fast reliable results but the simulated sky models need to be produced and validated from measured results. Therefore, further research will be conducted to improve these methods and to investigate other possible methods of achieving accurate skylight candle power distribution curves and efficiency data.

2.1 General Lighting Characteristic

For additional information on subjects covered in this guide consult the following publications:

IESNA General Guide to Photometry
IESNA Practical Guide to Photometry
IESNA Lighting Handbook
IESNA Guide for Reporting General Lighting Equipment Engineering Data for Indoor Luminaires
IESNA Standard File Format for Electronic Transfer of Photometric Data

3.0 Principles of the Test System

3.1 Luminaire Luminance Characteristics

Luminaire Luminance characteristics are reported to facilitate evaluation of certain quality aspects of light design. Maximum luminance is measured directly from the daylight luminaire while average luminance is a quantity calculated from photometric data. The angle of the sun in relation to the daylighting luminaire will vary over time and this will produce a wide range of results, daylight lumenaires are not considered symmetrical. A complete set of vertical planer angles are required to measure and accurately report the light distribution from daylight luminaires. In addition, the results from one sun angle are not valid for other sun angles.

3.2 Selection and Preparation of Daylight Luminaire

3.2.1 Luminaires selected for test should be clean and representative of the manufacturer's regular product. Daylighting devices should be mounted and/or assembled according to the installation instructions.

4.0 **Test Distance**

The photometer and building housing the photometer should be set up to measure the largest desirable daylighting device. The distance between the daylight luminare and the photo detector should be sufficiently large so that the inverse square law (ISL) can be applied at the distance needed for the largest daylight luminaire to be tested by a photometer. Smaller daylight luminaires can also be tested. The minimum distance from the daylight luminaire to the photo detector must be at least five times the largest luminous opening dimension of the daylighting luminaire. Directional light output should be measured with many detectors at an appropriate distance from the lamp.

For example, if you are trying to measure the luminous intensity of a 24" x 24" skylight. The longest distance would be the 34" diagonal. Therefore, the minimum test distance needs to be 5 times the 34", which is 170 inches or 14.17feet. For a tubular daylighting device with a circular daylight opening of 21”, the minimum test distance would be 105” or 8.75 feet.

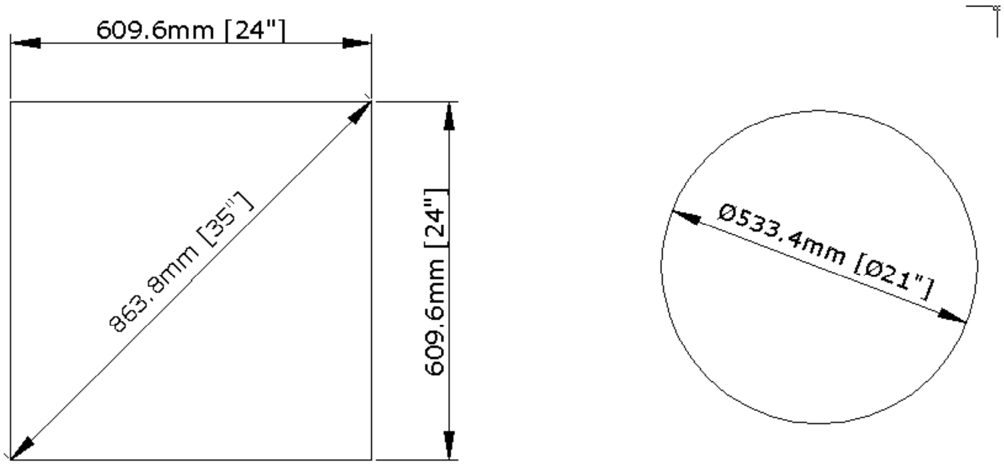


Figure 1

When performing photometry of luminaires, a rotating mirror goniophotometer is commonly used. This turns the light path to near-horizontal and substantially reduces space. However, a rotating mirror system cannot be used with a skylight because of mechanical interference problems, but a system using individual mirrors can be used. If a mirror is positioned at a vertical angle of interest, the light path can be redirected to a conveniently placed photo detector, reducing the required chamber size.

5.0 Photometer Basic construction

5.1 Tubular Daylight Photometer

An example of a photometer used to measure tubular daylighting devices 1.7’ (21”) or smaller is illustrated in Figure 2. The frame should be developed so all the photo detectors are positioned to exceed the test distance described in section 4. In addition, by positioning photo detectors in a 180 degree arc around the daylighting device means that the photometer will have to rotate less that 180 degrees. If the photo detectors are positioned from 0 to 85 degrees in one direction the photometer would have to rotate just less than 360 degrees. This would also increase the testing time. If possible the photometer should be developed to minimize the testing time.

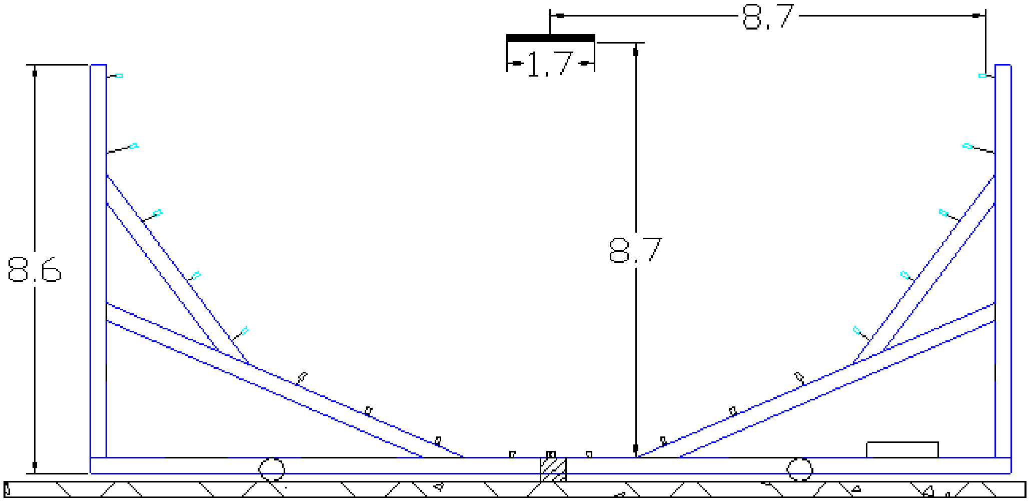
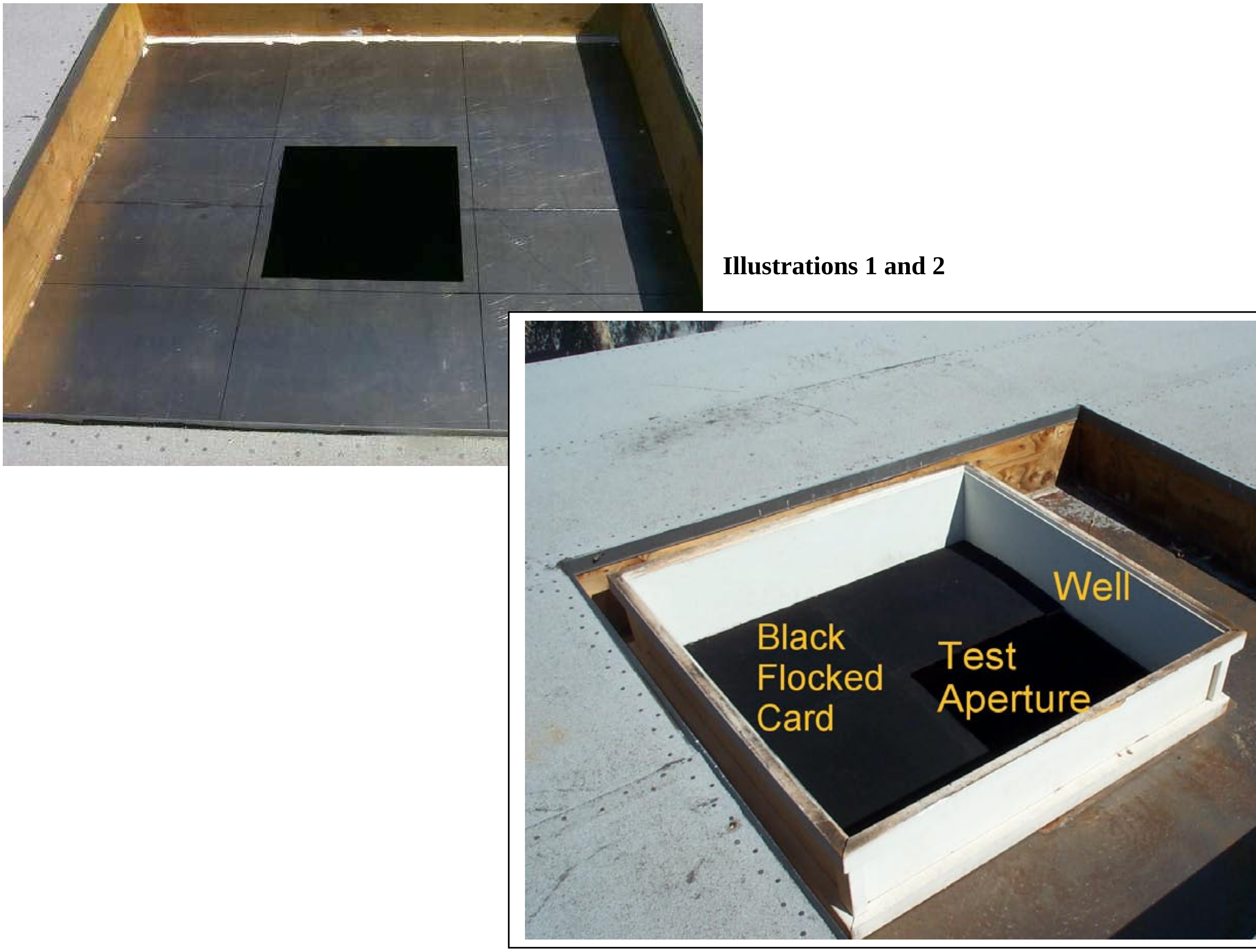


Figure 2 Cross Section of Simple Photometer.

5.2 Skylight Photometer

However, many standard and popular skylights are 1.2 x 1.2 m (4 x 4 ft.). In order to meet the test distance the equipment would have to be set up so that the distance between the skylight and the photo detectors are at least 5 times the diagonal to meet IES standards. The diagonal of such a skylight is 1.7m (5.7 ft.) and thus a test distance of 8.5m (27.9 ft.) is needed. Therefore, the minimum room size that will allow data collection over a complete downward hemisphere is over 17.0 m x 17.0 m (56 x 56 ft.) with a ceiling height of over 8.5m (27.9 ft.). Such a size of chamber is not practical from the standpoint of cost and availability. Therefore, larger skylights can be measured in 4 equal quadrants and then the results can be summed. For example the nominal bottom opening of each 4 ft x 4 ft skylight is 1.5 sq.m (16 sq. ft.), however, only one quarter of this or 2 ft x 2 ft (4sq. ft) can be exposed to the photometer at any one time. The remaining area is blocked by the ceiling. The blocked light must not be allowed to reflect from the roof back into the skylight well to any significant degree, because it may reflect again and be added to the light being measured. To avoid these reflections a non-reflective black cloth is laid over the three unexposed quadrants of the skylight's well bottom, on top of the roof, inside and at the bottom of the skylight well. This reduces inter-reflected light to a negligible level, as has been verified by measurements and calculations provided in appendix A and an example of a space saving rotating photometer with the anti-reflective shields can be viewed in figure 3 and illustrations 1 and 2 show and example of the aperture in the ceiling of the photometer building.



Illustrations 1 and 2

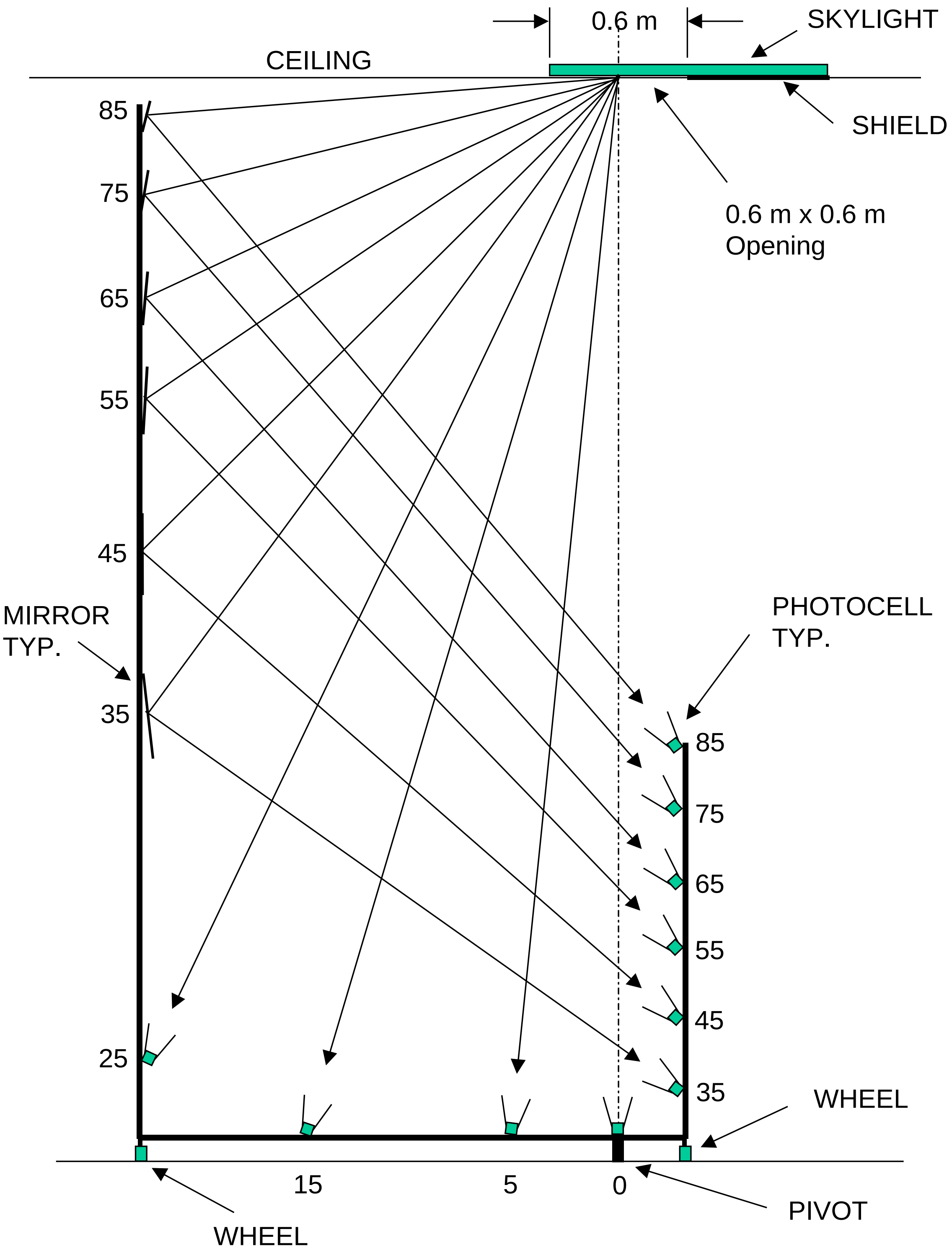

0.6 m
SKYLIGHT
CEILING
SHIELD
0.6 m x 0.6 m
Opening
85
75
65
55
45
MIRROR
TYP.
35
25
PHOTOCELL
TYP.
85
75
65
55
45
35
WHEEL
15
5
0
PIVOT
WHEEL

Figure 3

5.3 Electrical/Electronic System

Each photo detectors is a silicon cell, spectrally corrected to the CIE V(λ) curve, with f_1' < 2%.[7] This photo detector should be used because it exhibits low noise, appropriate sensitivity, excellent stability and linearity, fast response, and low temperature sensitivity. The use of photo detectors and suitable measuring circuits are described in references 10, 12, and 13.(LM-46-04).

Enough photo detectors should be positioned starting at the nadir point directly below the daylight luminaire and continue angular toward the ceiling plane. Ten Photo detectors were used in the photometer shown in figure 3. More can be used if desired but less is not recommended. These photo detectors need to be supported by a rigid structure that can be rotate around the daylighting device to allow for the measurements of each angular plane or half plane depending of the size of the daylighting device. Black painted 100 mm (4 inch) square steel tubing provides an ideal choice of framing material for a photometer needed to measure a 4’ x 4’ skylight when mirrors where used to reduce the size of the structure. Additional bracing and adequate frame size should be used to ensure the structure is stabilized quickly after each movement to the next vertical plane.

5.4 Amplifier Box

An amplifier box should be positioned adjacent to each photo detector. The amplifier needs to be equipped with a switchable feed back resistor to provide high or low gain readings. The feedback resistors need to be chosen to allow measurements to be recorded up to 350,000 candelas. The measurement range created is sufficient to cover the range from direct sunlight to the low levels found with highly diffusing skylights. Thus there are not limitations on the type of skylight than can be measured, apart from size. Each amplifier output runs to a main electronics interface box that is located on the horizontal rotating arm.

5.5 Electronic Interface Box

Because of the short-term variability of daylight, it is necessary to capture the results as fast as possible by using sensors that are connected to a data logger with recording capability (ISNA 8-21). The amplified analog signal needs to be converted to digital and sent to computer interface equipment. The entire system should be multi-channel such that the computer monitors all photocells simultaneously.

5.6 Computer Interface Board

Output from the electronics box runs to a computer equipped with a multiple channel interface. This allows the software to read the signal generated by each amplifier.

The computer interface board is equipped with output channels. The software is able to cause pulses to be sent to a stepper motor, thus causing rotation of the photometer about its vertical axis to any desired horizontal angle.

If any photo detector, when operating in a high gain condition, indicates an over-range condition, this is identified by the software. The computer then sends an output pulse to the amplifier boxes adjacent to the photo detectors, switching a relay that selects a different feedback resistor, thereby setting the gain stage to low.

The entire process may be automated, such that a complete test at any array of horizontal angles can be collected under computer control using high and/or low gain stages. The software automatically rejects out-of-range readings taken using the high gain stage, and for those angles, substitutes the low gain stage readings.

5.7 Vertical Angular planes (step motor)

When measuring daylight devices the quickness of the test is very important. The number of measured planes needs to be enough to accurately capture the luminous intensity while providing a quick testing time. When measuring daylighting devices, at least sixteen planes of measurements taken every 22.5 degree are recommend to achieve this luminous intensity curve if the photometer can only measure half planes (Figure 3) When measuring smaller daylighting devices and using a photometer that can measure horizontal angles in both directions as in figure 2, eight full planes of measurements every 22.5 degrees are the required minimum number of vertical planes..

Vertical angular plane measurements should be every 22.5 degrees, with a tolerance of +/-1 degree for both location and repeatability. For example a high powered digital stepper motor could be used in conjunction with the appropriate sized solid rubber tire to position the photometer at each vertical plane position. For the skylight photometer viewed in figure 3 the circumference of the wheel is 63cm (2.0 ft.) and thus it travels this distance in one revolution. The digital pulses per revolution are 50,800 and therefore each pulse corresponds to a linear movement of the wheel of 63/50,800, or 0.012mm (0.0005 ins.) The distance of the wheel from the central pivot point at the photometer center is 2.1 meters, (7.0 feet). A single pulse relayed to the stepper motor therefore causes it to rotate 0.012/2100 radians, or 0.0003°, which is therefore the horizontal angular resolution of the photometer.

Aligning the photometer back to 0 degree or the due North position can be achieved by placing a reflector on the wall of the building at the 0 degrees due North position and place a laser on the leading edge of the photometer so that when the photometer is returning to the original position the laser will senses the reflector and cause the photometer to stop at the 0 degree original home position.

5.8 Data Collection Speed

It is important that data collection occurs at high speed, as the results should not be significantly affected by movement of the sun during the test. Therefore, a multiple cell photometer should be used to capture the whole vertical plane reading near-instantaneously.

One set of vertical plane measurements are needed for tubular daylight devices and skylights that are smaller than the photometer buildings daylight open. For example a photometer building with a 2’ x 2’ opening at the ceiling level can measure a tunnel diameter up to 24” or a 2’ x 2’ skylight with one set of vertical plane measurements. An ideal set of vertical planer measurements could be captured by measuring the light output at every 22.5 degrees around a 360 degree circle. However, if a 4’x 4’ skylight is being measured, four sets of measurements will be needed before all the results can be added together to arrive at the absolute results. Each set of measurements should be achieved within 2 minutes. The photometer then rotates in the opposite direction, back to its zero degrees reference plane. During this time, the skylight is repositioned for the second quadrant. This procedure is repeated until all four quadrants have been measured. Further detail about testing times in relation to solar angles can be found in section 9.5.

Four sets of measurements will be needed as described above if measuring tubular daylight devices while changing the orientation to face North, East, South, and West. Under these circumstances testing will have to start about 6 – 8 minutes prior to the time of the desired sun angle.

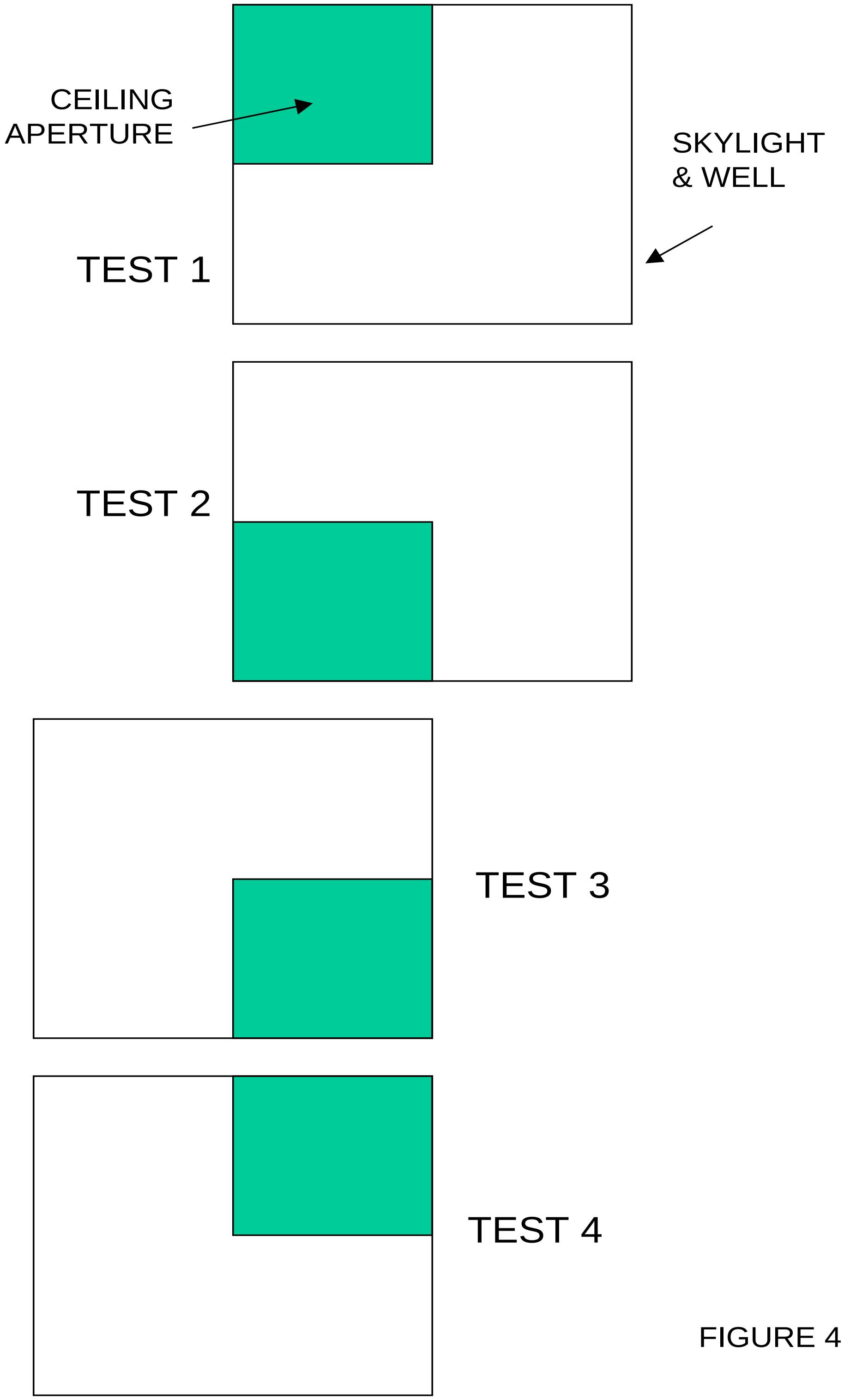


FIGURE 4

5.9 Automated Photometer

A photometric test system may be partially or fully automated through a computer. The linearity of the complete system should be maintained with frequent checks throughout its range.

6.0 Photometer Structure

6.1 A structure to house the photometer needs to be large enough for the photometer, the data logging equipment, and the computer. In addition, all extraneous light other that what is coming through daylighting device needs to be blocked during the test. Refer to Figure 5 and 6 for photometer housing used to measure 4' x 4' skylights and smaller devices.

Rotating and tilting a building with the photometer inside would allow the rapid simulation of solar elevations and azimuths. (one would not have to wait for the sun to move and would not be limited to time of year to test) Either photometer (figures 2 and 3) could be utilized with this structure design. The incident angle to the tube opening would determine the suns angle and the tube/floor/sensors geometry would remain constant.

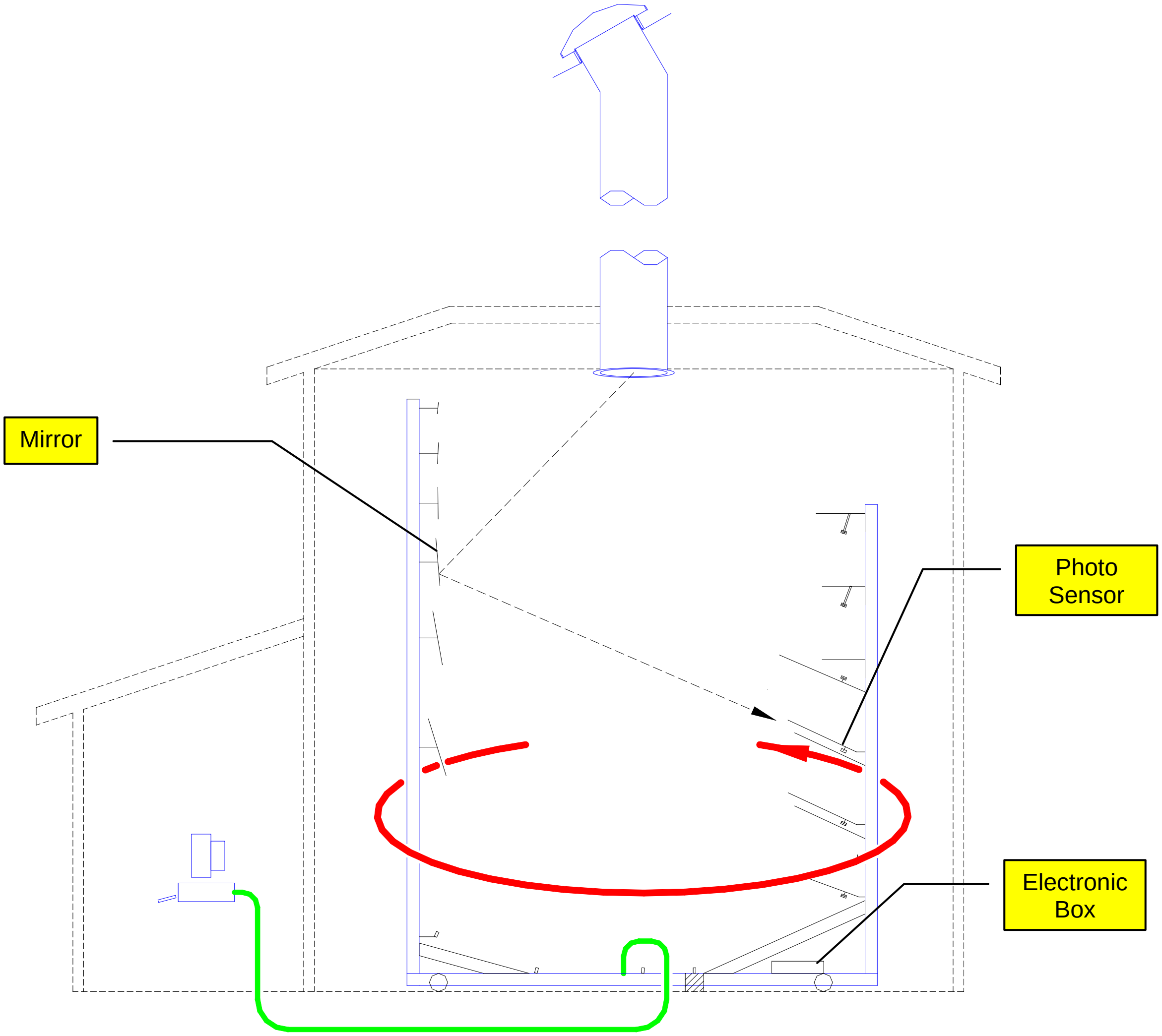


Figure 5

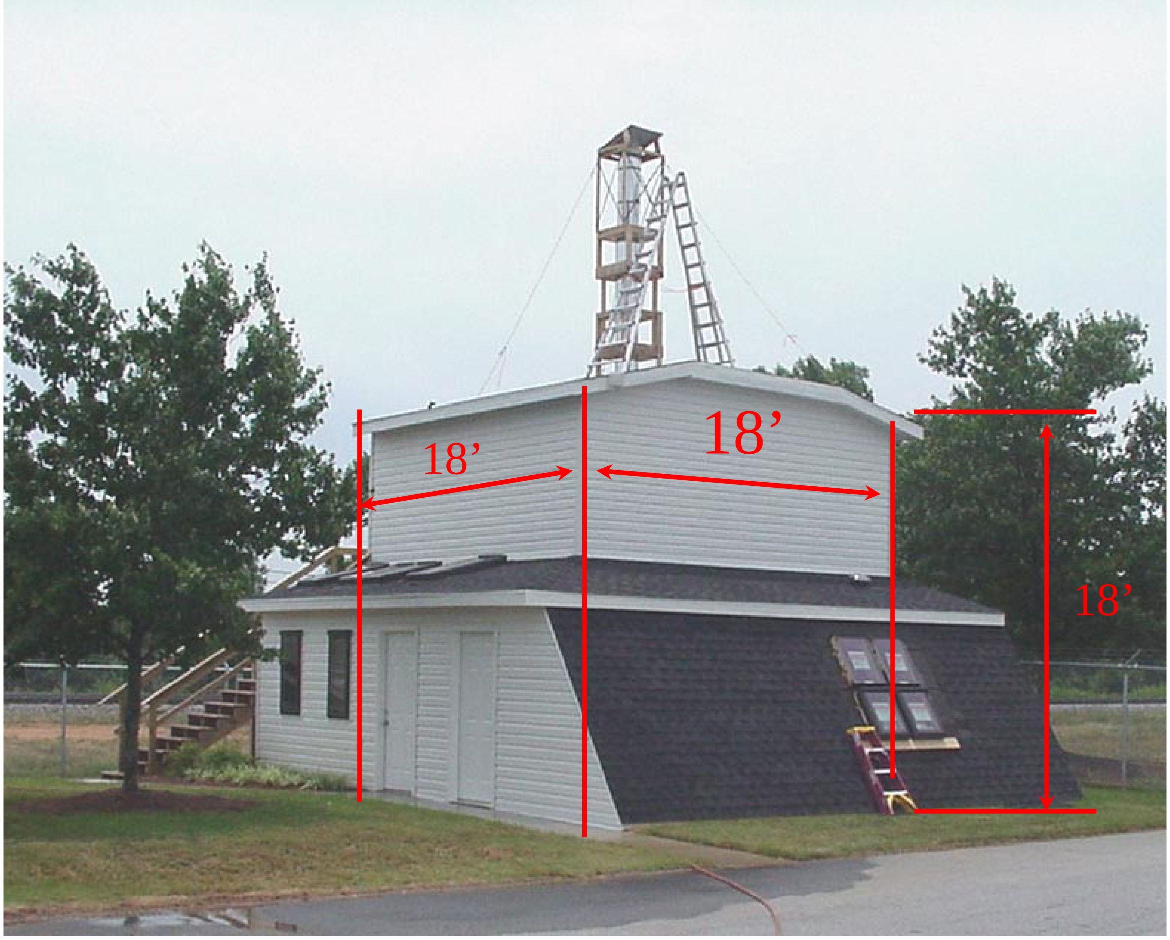


Figure 6

The chamber floor area is 18’ x 18’ and its actual height is 18 ft. The roof of the building should receive direct sunlight without blockage from other structures or trees.

Prior to the daylighting device being positioned over the ceiling aperture the photometer needs to be calibrated.

7.1 Periodic Calibration and Accuracy

Because the accuracy of the data depends on the initial set up, particular attention should be given to providing proper calibration and verifying accuracy. An absolute calibration is necessary and can be achieved by using the calibration fixture in figure 7.

The aiming of the photo detectors and the positioning of the mirrors need to be verified and adjusted with a laser with a specially designed holder that can be clamped into the photo detector holders. The laser should maintain contact with the center of the skylight diffuser or light shaft opening while the photometer is rotated. All photo detectors and mirror positions need to be verified using the laser, to ensure that the entire angular coordinates of the measurement system are precise.

To achieve calibration, a series of calibrating factors must be developed, one factor for each photo detector, in the form of candelas per millivolt. These can then be stored in a data file and used to automatically convert the amplifier output voltage to absolute candelas.

A further factor to apply the gain stage change between high and low settings was fixed at x100 for each photo detector. This factor is dependent upon the feedback resistors used, which are precision rated to ± 1%.

The multiple cell photometer should be calibrated with a special form of a standard lamp. An illustration of this calibration fixture can be shown in figure 7. This special calibration fixture should provide a wide spread of light that is reasonably uniform with respect to changing vertical angles. This source is calibrated over a range of vertical angles on a mirror photometer with the lamp operating at a specific current, which is itself calibrated traceable to NIST. Intensity values were collected at each vertical angle of interest in the vertical plane perpendicular to the lamp's axis.

Figure 7

Ideally, a calibration source should be of about the same intensity as the light to be tested. This is a little difficult when the source to be tested is the sun. Therefore, care needs to be taken in ensuring that the calibrations between the scales on the system are very accurate. If one scale is 10x, it should be 10.00, not 10.01. This can be achieved using precision resistors in the amplifier circuit. Otherwise, if the calibration and testing are done, say 3 scales apart, the error can be multiplied and become significant.

There is an easy check on all of this. Run a photometric test, and also use a properly calibrated illuminance meter and place it next to a photocell. Verify that it gives the same reading as the photometric test report shows. Then the user knows that any scaling errors in the calibration are not a problem. Typically there should be a plus or minus 2% difference, or less.

Since the photometer is measuring light coming through a skylight. The actual levels measured may only be 10, 20, 50 fc., not the 10,000 fc that direct sunlight produces. The theory that states the calibration source needs to be equivalent to the source being measured is not nearly as great a problem as some might think.

The calibration source is placed at the center of the daylight opening at ceiling level. The surrounding surfaces are black. Knowing the absolute intensity at each angle from the mirror photometer data, the candelas per millivolt calibration factor was determined for each photodetector. Note that effects due to differing test distances and possible differences in the reflectances of the various mirrors will cancel when these factors are applied to test readings.

7.2 Data Reduction

Data reduction consisted of developing standard IES files for each skylight, and for each 10 degree elevation of the sun[8]. Test reports also were produced in a format similar to that used for indoor luminaires.

Modifications to existing software were required to handle a unique characteristic of skylights: They possess no axis of symmetry. Data presentation therefore was developed for all measured planes from 0 degrees (designated as north) to 337.5° in 22.5° steps.

As part of the data reduction, all data can be prorated to 1000 lumens incident upon the upper plane of the skylight to form a constant reference basis or an absolute value can be outputted to the file.

7.3 Stray Light

Precautions should be taken to eliminate stray light from the test environment by the use of adequate shielding and baffling. For moving photo detector photometers, the light incident on the photo detector must only be that which is directly transmitted from the daylighting device or mirror corresponding to a given photo detector.(LM-35-02)
The presence of stray light can be detected by blocking off the direct light from the source.

Black shields should be installed between each of the photo detectors to prevent stray light from being picked up by another sensor other than the intended photo detector

To minimize the effects of stray light it is recommended that walls, ceilings, floor of the photometric test room, and the equipment be painted flat black or covered with matte cloth such as black velvet to eliminate reflected light.

Any remaining stray light can be measured by running a complete test with the direct light from the luminaries completely shielded from the photo detector. This light can then be subtracted from the data, taking into account the variations of stray light for each vertical angle in each plane or half plane measurement.

8.1 Sky Conditions

Verify and record the sky conditions visually and use the IESNA standards to calculate the sky conditions. Skies are divided into three categories: clear, partly cloudy, and overcast. Calculation of daylight availability at a site begins with a determination of the solar position, which is a function of latitude and longitude of the site, day of year, and local time.

Either the sky-ratio method or the sky-cover method is used to classify a sky. The sky ratio is determined by dividing the horizontal sky irradiance by the global horizontal irradiance. Since the sky ratio approaches 1.0 when the solar altitude approaches zero (regardless of the sky condition), this method is not accurate for low solar altitudes. The sky conditions are defined as follows:

Clear:	sky ratio <= 0.3
Partly cloudy:	0.3 < sky ratio < 0.8
Overcast:	0.8 <= sky ratio

This should be accomplished by positioning a high quality illuminance meter near the top of the skylight in an unobstructed location and in a location that doesn’t interfere with the light penetrating the skylight. If the skylight is being measured as it would be install, the sky condition measurements (ratio) should be taken while the meter is facing parallel to the ground or straight upward. However, if a tilting photometer is used the meter should tilt with the skylight or TDD. Two readings are taken to check climatic conditions: one for total horizontal illuminance, and a second where the direct sunlight is screened from the photocell using a paddle. A ratio is calculated for the diffuse/total illuminance. If this ratio is less than 0.3, conditions are defined as clear. If the ratio exceeds 0.8, conditions are considered to be overcast. Refer to the daylighting section of the IESNA handbook.

Screening the direct sunlight from the photocell was accomplished by holding a 3 inch diameter shield 18” to 24” from the photometer sensing element. The shield should be attached to a rigid thin handle that allows for consistent measurements and doesn’t interfere with the direct or indirect sun light. The sky condition monitoring station should be positioned in a location near top of the skylight being measured but should not interfere with the direct or indirect light making contact with the skylight to be measured.

The ratio of horizontal diffuse to total horizontal illuminance needs to be listed in the printed reports and in the IES files as "sky ratio."

Total horizontal illuminance readings need to be recorded at the same time as each plane of photometric data is collected. This records any changes in the daylight condition, and these readings can be used to normalize the photometric data, see later.

9.0 Testing Procedures

9.1 General Test Conditions

Skylights and tubular daylighting devices should be clean and mounted according to the manufactures installation instructions prior to testing.

All glass, reflectors, and optical parts should be thoroughly cleaned before any measurements are made unless the purpose of the test is to determine the effect of dirt on the Daylighting device. When cleaning a daylighting device, it is desirable to return the daylighting device to as near "like new" conditions as possible, avoiding usage of corrosive or abrasive materials which might alter the finish of the lamp, reflector, refractor, glass, or plastic.(LM-35-02)

9.2 Daylight Device Positioning

Refer to LM-72 for the guide of directional positioning of photometric data
The daylighting device must be properly positioned on the Photometer building to obtain correct luminous intensity distribution measurements at specific vertical angles and angular planes. The daylighting device must be centered over the nadir point.

Extreme care should be taken that the operator or other personnel involved in the test proceedings do not cast shadows on or block diffuse or direct light from making contact with the product being measured. In addition, access to the light measuring equipment room should be limited or avoided during the time of testing to maintain stable dark readings. In addition, mirrors should be maintained and cleaned in order not to diminish the readings.

9.3 Sun angles

Unlike electric luminaires, the photometric distribution of skylights change rapidly throughout the day, unless the sky is overcast to the extent that the sun component is almost totally obscured. Thus the rule set by IESNA for stabilization of the light output does not apply. Rather, the need is to perform testing as quickly as possible at a particular chosen angle of the sun. This is required to be conducted over a period where the sun movement can be considered negligible. Inevitably, once the test is completed, the facility must be ready to perform another test as the sun approaches the next selected angle, and so on.

It is desirable to conduct testing for every 10 degree increment of the sun's elevation over an entire day. Appendix C provides the method used to determine the exact times at which the desired solar angle is reached. Testing should be conducted in a location that receives and abundance of clear sunny days and that experiences solar elevations of at least 75 degrees. The testing latitude needs to be considered into the calculations.

In order to determine whether 10 degree steps in elevation are satisfactory for interpolation for different solar altitudes, test data measured at solar altitudes of 20° and 40° was then averaged. The resulting averaged data matched well with the results measured at a solar altitude of 30°. The resulting skylight efficiency of the averaged data is only 2% different from the actual test data. The maximum intensities of the averaged data and the actual data are in identical directions with magnitudes that differ by less than 1%. Clearly if averaging 20° and 40° data gives such a good 30° approximation, it can be expected that averaging 20° and 30° data will result in a reasonable 25° approximation. We therefore feel that collecting data for 10° altitude steps provides robust information that can be used for interpolation to find data applicable to intermediate solar angles.

The data for this interpolation were taken from tests of a white acrylic domed skylight and a white diffuse light well. It should be noted that the results of averaging data from more transparent skylights and more specular light wells might not result in approximations as good as this.

Regarding azimuth, comments have been made in the reference, “Skylights as Luminaires: PIER Skylight Photometric Test Results”, reference 5, as follows:

“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 under sunlight coming from a particular angle, one would need only pick the skylight photometrics tested under a solar elevation close to the modeled solar elevation. The solar azimuth in the model and photometric file can be aligned by rotating the photometrics azimuthally. This is accomplished by rotating the skylight in the lighting simulation software.” However, in order to accurately capture the effects of any optical geometry, photometric measurements should be measured at several azimuths for each corresponding sun angle. A good practice would be to position the daylighting device as it would be measured or installed and then rotate the skylight 30, 60, and 90 degrees from the normal positon to measure the effects of the optical elements.

The ambient temperature of the photometric daylight laboratory doesn’t have to be maintained at a certain level for accurately measuring the daylight produced by a particular product. However, air quality for the comfort of the employees may have some benefits.

9.4 Selection of Angles for Photometric Measurements Photometric Measurements (LM-46-04)

Angles of Measurement
The vertical increments around the source or luminaire under test shall be small enough so the recorded data describes the light distribution adequately. Within each vertical half-plane, intensity is measured at a minimum of 16 vertical angles with 0, 5, 15, 25, 35, 45, 55, 65, 75, and 85 degrees.

Planes for Measurement
Because of the angle of the sun in relation to the daylighting luminaire will vary over time and this will produce a wide range of results, daylight lumenaires are not considered symmetrical. A complete set of vertical planer angles are required to measure and accurately report the light distribution from daylight luminaires. In addition, the results from one sun angle are not valid for other sun angles.

The number of vertical angles at which the readings are taken will depend on the rate of change in the distribution of the luminaries luminous intensity. A complete set of vertical planer angles are needed to capture the results for the total 360 degree illuminous intensity distribution curve. To satisfy these requirements a minimum set of 16 vertical planer measurement need to be recorded at a minimum of every 22.5 degrees, with the 0 and 360 degree measurements being the first set of measurements.

The test measurements for one sun angle can not be used for another sun angle.

Angular relationships shall be considered as follows:
Vertically: Zero degrees at nadir and 90 degrees at horizontal.
Latterally: Measured counterclockwise

9.5 Testing start time in relation to sun angle times

In order to achieve an angular measurement at a given sun angle, measurements should be started prior to the desired sun angle in half the time it takes to capture a complete set of measurements for a daylight device. For example, if a tubular daylighting device or a skylight smaller than the daylight opening in the photometer building is being measured and the process time to complete on set of measurements is 2 minutes then start the test 1 minute prior to the desired sun angle time. If a larger skylight is being measured and four sets of test are needed to capture all the quadrants of the skylight and the process time is 2 minutes for each measurement for a total 8 minutes total start the test 4 minutes prior to the desired sun angle time. Refer to illustration 2 and figure 4 to see how the quadrants of a larger skylight can be measured separately.

The entire test for a 4’ x 4’ skylight requires 12 minutes. In the summer, this equates approximately to a change in solar elevation of + or - 3 degrees. By starting the test 6 minutes prior to the desired solar angle being reached, the sun's position for all data collection is accurate to plus or minus 1.0 degree. Note that any errors introduced by this small angular change would tend to be self-canceling when the tests for the four quadrants are added together, because of the plus and minus angles.

Tubular daylighting devices should be measured within 2 – 3 minutes or +/- 1 degree change in solar angle and skylights should be measured within 8 – 10 minutes or +/- 3 degree change in solar angle. In all cases, the shorter the measuring process time the better.

9.6 Reporting

Refer to LM-15-03 to provide a reference for use in the design of report forms to suggest a practical format and terminology for presenting the information obtained from a typical photometric test.

The subject matter of the photometric test report may be logically divided into the following three categories: General information, Photometric Data, and application engineering data. (LM-15-03)

In addition, a photometric report and output file should include the following:

SKYLIGHT DESCRIPTION

[_SKYLIHT or TDD] skylight or TDD detailed description
[Major_AXIS] ###.# in degrees (default is zero, 0 = major axis N-S) measured clockwise looking down
[EXTERIOR_GLAZING_TYPE] glazing description
[_INTERIOR_DIFFUSER_TYPE] diffuser description
[_GLAZING_Vt] 0.## visible transmittance of glazing material at normal incidence
[_GLAZING_HAZE] 0.## haze of glasing material
[_UNIT_TYPE] Feet or Meters
[_GLAZING_AREA] ##.# horizontal projection of glazing area
[_DAYLIGHT_DEVICE_WIDTH] frame width or tunnel width
[_DAYLIGHT_DEVICE_DEPTH] frame depth or tunnel depth
[_DAYLIGHT_DEVICE_LENGTH] Light tunnel length or tunnel length

TEST site time conditions

[_Test_Long] ###.# longitude of the test location
[_Test_Lat] ###.# latitude of the test location
[_TEST_ELEV] ##.# latitude of the test location
[_TEST_DATE] mm/dd/yyyy
[_TEST_TIME] standard local time of test
[_TEST_TZ] Time zone of test location relative ot the Greenwich Meridian (EST=5, PST = 8)

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, or overcast

10.0 Luminance Measurements

10.1 Angles of Measurements

a. The average luminance of the luminaire should be calculated for planes perpendicular, at 45 degrees and parallel to the lamp axis at the following angles from nadir: 0, 5, 15, 25, 35, 45, 55, 65, 75 and 85 degrees. The value at 0 degrees is seldom required. Average luminance is a quantity calculated from photometric data. It is given by the luminous intensity at a given angle divided by the projected area of the luminous surface at that angle in square meters or square feet.[27]

b. Maximum luminaire luminance can be determined using the methods described in the *IESNA Lighting Handbook*.[3, 28]

8.0 Testing Procedure

Step 1 Calibrate photometer

Step 2 Close off daylight opening and read dark room data. Subtract stray light from the measured results. These measured results should be very low or under 1% of the value measured during product testing.

Step 3 Install skylight or TDD.

Step 4 Determine sun angle times

Step 5 Based on the number of test needed for each sun angle, determine the number of minutes to start the test based on the amount of time needed to complete the test and divide these results by 2 to arrive at the number of minutes to start the testing prior to the desired sun angle.

Step 6 Measure sky readings, calculate and record the sky ratio.

Step 7 Start testing and recording horizontal illuminance for each reading.

Step 8 Rotate or move the skylight or TDD and continue testing.

Process reports

Step 9 open the PSO files and add the corresponding horizontal illuminance values.

Step 10 Process the pso files to creat IES files per the guidelines established in this LM and within the guidelines established in LM-63-02.

Step 11 Print the report and save the “.ies” file.

12.0 Problems of Skylight Photometry.

IESNA has developed numerous documents in its Light Measurement (LM) series that cover the photometry of most forms of lighting devices. While these lay out broad principles that can be applied to skylight photometry, there is no definitive recommended practice for such work. Moreover, there are aspects of the photometry of skylights that pose unique problems.

- Skylights form part of the building, and during testing, they must be illuminated by natural daylight. This natural light incident upon the upper surface of a skylight consists, of course, of that from a moving sun plus a significant sky component. The incident light therefore is by no means directionally uniform; duplicating its form by the use of some type of solar simulator would be very difficult and expensive. The authors therefore wished to develop a test system where the skylights operated under their natural conditions, being part of a building structure and illuminated by the natural source.

- Skylights are very often large, and exceed the size capabilities of typical intensity distribution photometers. As the goal of the program was to develop accurate data in standard IES photometric files, the test system must have the ability to collect intensity readings over an entire downward hemisphere. Further, the equipment must be accurate with regard to the effects of test distance.[6] It was desired to meet the IESNA rule-of-thumb of providing a distance from the skylight center to the photodetector of at least five times the largest dimension of the skylight.

- Unlike electric luminaires, the photometric distribution of skylights changes rapidly throughout the day, unless the sky is overcast to the extent that the sun component is almost totally obscured. Thus the rule set by IESNA for stabilization of the light output does not apply. Rather, the need is to perform testing as quickly as possible at a particular chosen angle of the sun. This is required to be conducted over a period where the sun movement can be considered negligible. Inevitably, once the test is completed, the facility must be ready to perform another test as the sun approaches the next selected angle, and so on.

The special requirements led to the development of a unique photometric test system.

Appendix A

Accuracy of the Quadrant Testing Method

The IES rule-of-thumb is that photometric errors are negligible as long as the test distance is more than five times the maximum dimension of the luminaire. By breaking a 0.6 x 0.6m (4 x 4 foot) skylight into 4 equal individual areas, the largest dimension of any test item will be less than one fifth of the test distance of the goniophotometer described. This therefore does not introduce any error related to source size greater than that which occurs in conventional photometry. It is, in fact, equivalent to doubling the test distance.

It has been queried what error this technique may introduce if different portions of the skylight produce different levels of intensity in given directions. Case 1 in Figure A1 shows where a 0.6 x 0.6m (4 x 4 ft.) skylight is tested at 8.5m (28 ft.) This illustrates measurement at an angle A. The skylight subtends an angular range B, and the intercepted vertical angles range from A1 to A2. Consider left and right equal portions of the skylight, marked LHS and RHS. Suppose LHS projects an intensity of 10 cd towards the photocell, and that RHS projects 100cd. Presume that the intensity from both sides decreases with increasing vertical angle.

The angular range projected for LHS to the photocell ranges from A to A1. This light is assigned to an angle A by the software. All light from LHS is at angles lower than A and therefore this light will be recorded and assigned to angle A at too high an intensity.

Similar logic applies to RHS, excepting that its light assigned to angle A will be too low an intensity.

Because light emission from LHS is much less than from RHS, the overall error will result in too low an intensity being assigned to angle A.

Cases 2 and 3 in Figure A1 illustrate where the photometry is performed separately on the two sections at a test distance that is half that used for case 1.

In case 2, the light assigned to A will actually be emitted over a range from A1 to A2. Providing the gradient of intensity change with angle is reasonably close to constant, the increased emission in the range A to A1 will be compensated by the decreased emission over the range A to A2. This will sharply reduce any errors.

In case 3, the same error cancellation occurs.

When the readings from cases 2 and 3 are summed, errors will be low because of the self-canceling tendency in the two individual cases. No such self-cancellation occurs in case 1. The summation method, case 2 + 3, is therefore inherently more accurate than case 1. Case 1 meets the requirements of the 5x rule, therefore the case 2 + 3 method exceeds the 5x rule requirements.

It is therefore logical to assume that errors introduced by spatial non-homogeneity of a 0.6 x 0.6m (4 x 4 ft.) skylight will be reduced by photometering in four quadrants, rather than the errors being increased.

Where intensity gradients versus angle change sharply, the self-canceling in cases 2 and 3 will be imperfect, but there will always be some self-cancellation of errors. In such cases, there is a possibility that errors will increase with cases 2 + 3 versus case 1 as the angular range of measurement for cases 2 and 3 is from A1 to A2, while that for case 1 is half that amount. Sharp changes in intensity gradient however, also are likely to introduce further errors in case 1.

Errors in the *application* of the skylight tests will exceed those from conventional luminaire tests to the degree that such non-homogenities are greater in the skylights. The extent of this effect is not known.

Appendix B

The Testing of Transparent Skylights

The testing of transparent skylights is something that is not recommended due to the inverse squared law. The inverse squared law assumption is invalid for transparent skylights. Imagine the sun shining directly through this tinted window to the 0° photocell. Let us assume that 6000fc illuminate the photocell. Our software will convert this to 1.5×10^6 cd. Now let us suppose that someone takes the IES file we generate and sets up an application where the skylight is only 10 feet above the floor. This will result in 15,000 fc Illuminance. This is brighter than broad daylight. This is wrong because the point source inverse squared law assumption is invalid for a transparent skylight. The illumination measured directly below the skylight 15 feet in the air will be the same as the illumination on the floor. This is true because the Sun is very far away compared to 15 feet. The transparent skylight is simply a form of filter over the photocell. Only skylights that are translucent and have absolutely no unscattered light from the Sun will fully obey the inverse squared law.

Appendix C

Accuracy Analysis of Reflections from Black Card

Errors likely to be generated by the use of black flocked cord over the three quadrants not being measured were examined in detail before use of the technique. Three assumptions were made in the analysis.

- Material is a black flocked surface, reflectance = 2.2%, as measured by a reflectometer in accordance with IESNA LM-44-1990, "Approved Method for Total and Diffuse Reflectometry."
- Pattern of reflected light is Lambertian.
- Consider average depth of skylight well = 0.9 m, (3.0 ft.)

Suppose 100 lumens reach the 1.2 x 1.2 m. (4 x 4 ft.) bottom of the well. Lumens intercepted by the shield, on average, = 75 lms., as 1.1 sq.m. (12 sq. ft.) out of 1.5 sq.m. (16 sq. ft.) are shielded.

By computing the intensity distribution from a given point on the shield, assuming a Lambertian diffuser, and the solid angle subtended by the skylight itself (top aperture), and the solid angle subtended by the skylight well surfaces, the proportion of reflected light from the point reflecting and then striking the well surfaces can be calculated. Computations indicated that for a typical point on the quadrant masking shield, 75% of the reflected light will strike the skylight well and 25% will strike the skylight itself from underneath.

Thus for the 75 lumens incident on the shield top surface, the lumens reflected and then intercepted by the well surfaces = 75 x 0.022 x .75 = 1.24 lumens.

For a ray striking the well surface, which has a diffuse reflectance of 85%, 50% will reflect upwards, 50% downwards.

Amount of light reflected downwards = 1.24 x 0.85 x 0.5 = 0.53 lumens.

Of this, one quarter is likely to be transmitted through the aperture. (0.4 sq.m. (4 sq. ft.) open out of the 1.5 sq.m. (16 sq. ft.) total).

Amount of light reflected through opening = 0.25 x 0.53 = 0.13 lm **Equation 1**

For the 100 lumens, lumens reflected from the shield and intercepted by the skylight itself = 75 x 0.022 x .25 = 0.41 lumens.

Amount of light reflected upwards from the skylight well surfaces (after reflection from the shield) = 0.53 lumens. (Identical to light reflected downwards). Assume worst case, that all of this hits skylight.

Therefore the total light striking the bottom of skylight itself after reflection from the shield top = 0.41 + 0.53 = 0.94 lumens.

The reflectance of a sample skylight has been measured to be 7%. However, assume a more diffuse skylight with a higher reflectance of 20% as a worst case.

Amount of light reflected by skylight after reflecting from shield top = 0.94 x 0.20 = 0.19 lumens.

Proportion of this light reaching 1.2 x 1.2 m. (4 x 4 ft.) bottom of skylight well = 0.25 (using same logic as 75/25% earlier).

Of this, one quarter will be transmitted through the 0.6 x 0.6 m. (2 x 2 ft.) aperture.

Therefore, light reflected from shield top and also reflecting from skylight itself = 0.19 x 0.25 x 0.25 = 0.01 lumens. **Equation 2**

From Equations 1 and 2, total light transmitted through 0.6 x 0.6 m. (2 x 2 ft.) aperture after reflecting from shield top = 0.13 + 0.01 = 0.14 lumens.

When data for the four quadrants are summed, this error will be increase by a factor of 4 to 0.56 lumens.

The approximate error introduced by reflection from the shield is therefore 0.56%, as the above calculations are for 100 lumens reaching the bottom of the 1.2 x 1.2 m. (4 x 4 ft.) well.

The error introduced from light reflecting of the masking shield is considerably less than the expected overall measurement error and no adjustment factor was felt to be needed to correct for the presence of the shield.

Appendix D

Calculation of Standard Time for Different Solar Elevations

See reference C1 for terminology definitions.

We wish to compute the standard time that the sun will be at certain specific elevations above the horizon. This can be accomplished by first computing the declination and right ascension of the sun. Declination and right ascension are the equivalents of latitude and longitude on the celestial sphere. Next the local sidereal time (LST) for the time of observation needs to be computed. The LST is the right ascension of the prime meridian. The prime meridian is the great circle that runs through the zenith and the celestial poles. Once the celestial coordinates of the sun and the LST of the observation time are known, the hour angle of the sun can be computed. The hour angle of any celestial object is the angle between the prime meridian and the great circle that runs through the object and the celestial poles. Hour angle and right ascension are normally expressed in terms of hours, minutes, and seconds. A full circle of 360° is converted to 24 hours so that 15° are equivalent to 1 hour. The elevation and azimuth of the sun can then be computed given the declination and hour angle of the sun, and the observer's latitude.

A BASIC language program was written incorporating two routines from outside sources and linked together with code written in-house. The two routines were for computing the declination and right ascension of the sun for a given calendar date and universal time, UT, and for computing LST from the calendar date, UT, and observer's longitude. Once the celestial coordinates of the sun, LST and observer's latitude and longitude are known, then the elevation and azimuth of the sun can be computed.

First the hour angle of the sun needs to be computed. The relationship between right ascension, RA, hour angle, HA, and local sidereal time, LST, is given by:

$$\mathrm{HA} = \mathrm{LST} - \mathrm{RA}$$

Once the sun's hour angle is known, the solar elevation can be computed. The relationship between an object's declination, δ, the observer's latitude, ϕ, the object's zenith distance, z, and the object's hour angle, H, is given by:

$$\cos z = \sin \phi \sin \delta + \cos \phi \cos \delta \cos H \qquad \text{(Reference C1)}$$

The zenith distance, z, is related to the elevation, e, by:

$$z = 90° - e$$

So the equation for elevation in terms of hour angle is:

$$e = 90° - \cos^{-1}(\sin \phi \sin \delta + \cos \phi \cos \delta \cos H)$$

Finally the sun's azimuth can be calculated. The relationship between an object's declination, δ, the observer's latitude, ϕ, the object's zenith distance, z, and the object's azimuth, A, is given by:

$$\sin \delta = \sin \phi \cos z + \cos \phi \sin z \cos A \qquad \text{(Reference C1)}$$

Solving the equation for azimuth gives:

$$A = \mathrm{Cos}^{-1} ((\sin \delta - \sin \phi \cos z) / (\cos \phi \sin z))$$

We wish to compute the standard time at which the sun's elevation would be a multiple of 10°. This was accomplished by computing the solar elevation at one-minute intervals over the course of the entire day. The times for which the solar elevation is a multiple of 10° could then be determined to a ± 1 minute accuracy. The software was verified against computations made using the U.S. Naval Observatory web site.

References

1. IESNA LM63- 1995

2 Heshong, l., Wright, R. and Okura, S. 2001. "Daylighting Impacts on Retail Sales Performance." IESNA 2001 Conference Proceedings, pp. 233-240.

3 McHugh, J., Burns, P. and Hittle, D. 1998. "The Energy Impact of Daylighting." ASHRAE Journal, May 1998. Vol. 40 No. 5. pp. 31-35.

3. *IESNA Lighting Handbook*, 8th Edition. New York: Illuminating Engineering Society of North America, 1993.

4 Available from the New Building Institute, http://www.newbuildings.org/pier/
Heshong Mahone Group. Construction and Calibration of Skylight Photometric Test Facility: Final Report for Task 5.3.5a Skylight Photometry Lab and Calibration. PIER Integrated Design of Commercial Building Ceiling Systems project report.

5 Murdoch, J.B. and Levin, R. E. "A Portable Sky Luminance Meter." Proceedings of the International Daylighting Conference, 1983.

6 Domigan, J.; Lewin, I.; O'Farrell, J.; McHugh, J. "Photometric Test System for Skylights and Luminaires." Leukos, 2005. Illuminating Engineering Society of North America, New York.
6

7 Approved Method for Photometric Testing of Indoor Luminaires Using High Intensity Discharge or Incandescent Filament Lamps. IESNA LM-46-98. Illuminating Engineering Society of North America, New York.

8 Method of Characterizing Illuminance Meters and Luminance Meters. Publication no. 69 of the CIE, Commission Internationale de l'Eclairage, Vienna, Austria. 1987.

9 Recommended Standard File Format from Electronic Transfer of Photometric Data. IESNA LM-63-95. Illuminating Engineering Society of North America, New York.

9. [C1]W.M. Smart, Textbook on Spherical Astronomy 6th ed., Cambridge University Press, 1979, p.35.

27. IESNA Testing Procedures Committee, *IESNA Guide for Determination of Average Luminance for* Indoor *Luminaires*, IESNA LM-37-97. New York: Illuminating Engineering Society of North America, 1997.

28. IESNA Testing Procedures Committee, "Guide for Measurement of Photometric Maximum Luminance," *Illuminating Engineering*, Apr. 1961, (LM-18).

[C1] W.M. Smart, Textbook on Spherical Astronomy 6th ed., Cambridge University Press, 1979, p.35.

Definitions

Average Luminance – Luminance as measured by conventional meters is averaged with respect to two independent variables, area and solid angle; both must be defined for a complete description of a luminance measurement.

Diffusers – are light control elements that scatter (redirect) incident light in many directions. Diffusers are used to spread light.