Visible Light Transmittance of Skylights

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March 2004

Submitted to:
New Buildings Institute
Integrated Energy Systems
Productivity & Building Science Program
Contract Product Number Deliverable #5.3.4b

On behalf of the
California Energy Commission
Public Interest Energy Research (PIER) Program
Contract Number 400-99-013

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Skylight effective visible transmittance testing and glazing visible transmittance testing was provided by David Tait of Tait Solar Inc. Skylight photometric testing was provided by Ian Lewin, John O'Farrell and Jim Domigan of Lighting Sciences Inc. Kathleen Eoff of DSET Laboratories tested glazing samples for visible transmittance and haze. We thank them for their conscientious efforts.

We wish to acknowledge members of the PIER Skylight Testing Advisory Group for their assistance. They include:

Dave Alexander, Sears; Dariush Arasteh, LBNL; Morad Atif, National Research Council Canada; Bill Beakes, Armstrong World Industries; Bob Berger, Independent Testing Laboratories; Gus Bernal, DayLite Company; Jim Blomberg, Sunoptics Prismatic Skylights; Yossi Vinograd, CPI; Doug Cole, Micron Vinyl; Hakim Elmahdy, National Research Council Canada; Charles Erhlich, Heschong Mahone Group, Sean Flanigan, Wasco Products; Joe Hayden, Pella Windows; Randy Heather, Naturalite Skylight Systems; Richard Heinisch, Lithonia Lighting; Lisa Heschong, HESCHONG MAHONE GROUP; Ivan Johnson, Accralight Skylights; Joe Klems, LBNL; Eleanor Lee, LBNL; Peter Lyons, Australian Window Association; Ross McCluney, FSEC; John Mors, Day Lite Company; Brad Prouty, California Daylight; Steve Richter, CrystaLite Inc.; Francis Rubinstein, LBNL; Stephen Selkowitz, LBNL; Bipan Shah, D&R International; Roland Temple, Velux; and Stephen Treado, NIST

The following companies provided generous in-kind support to this project:

- CrystaLite Inc.
- DayLite Natural Lighting Technologies LLC
- Naturalite Skylight Systems
- Sunoptics Prismatic Skylights
- Velux

We would also like to acknowledge the assistance provided by the Tool Lending Library at the Pacific Energy Center, which is owned and operated by the Pacific Gas and Electric Company. They have provided us with technical support and equipment necessary to complete our study.

About PIER

The Public Interest Energy Research (PIER) Program supports public interest energy research and development that will help improve the quality of life in California by bringing environmentally safe, affordable, and reliable energy services and products to the marketplace.

The PIER Program, managed by the California Energy Commission, annually awards up to $62 million to conduct the most promising public interest energy research by partnering with research, development and demonstration (RD&D) organizations, including individuals, businesses, utilities, and public or private research institutions.

PIER funding efforts are focused on the following six RD&D program areas:

1. Buildings End-use Energy Efficiency
2. Industrial/Agricultural/Water End-use Energy Efficiency
3. Renewable Energy
4. Environmentally Preferred Advanced Generation
5. Energy-Related Environmental Research
6. Strategic Energy Research.

This project contributes to the first topic area, the PIER Buildings Program Area. For more information on the PIER Program, please visit the Commission's Web site at: www.energy.ca.gov/pier or contact the Commission's Publications Unit at 916-654-5200. For other public reports within the *Integrated Energy Systems — Productivity and Building Science* project, please visit www.newbuildings.org/PIER.

The HESCHONG MAHONE GROUP has produced this report as part of the Integrated Design of Commercial Building Ceiling Systems research element of the *Integrated Energy Systems - Productivity and Buildings Science* energy research program managed by the New Buildings Institute. Cathy Higgins is the Director of this project for the New Buildings Institute.

The *Integrated Energy Systems - Productivity and Buildings Science* program is funded by the California Energy Commission under Public Interest Energy Research (PIER) contract No. 400-99-013. The PIER program is funded by California ratepayers through California's System Benefit Charges and is administered by the California Energy Commission (CEC). Donald J. Aumann is the CEC Programmatic Contact.

Legal Notice

Foreword

This research in this report has been designed to support the Integrated Design of Commercial Building Ceiling Systems research element. This research project consists of three related components:

1. Effectiveness of lay-in insulation
2. Comprehensive skylight testing
3. Culminating in a modular skylight well protocol for suspended ceilings that provide quality lighting (including daylight) and energy savings.

This report describes the measurement of skylight glazing transmittance and the effective visible transmittance of the skylighting system (skylight, light well, diffuser etc.) and the relationship between the two.

The purpose of this research element is to provide basic research input into a protocol for designing and specifying highly efficient ceilings that will incorporate effective placement of insulation, daylighting via toplighting and daylight-responsive electric lighting controls. This protocol is contained in the California Energy Commission design guideline titled, *Modular Skylight Wells: Design Guidelines for Skylights with Suspended Ceilings*.

Adoption of this protocol may lead to greater use of skylighting in conjunction with daylighting controls. Widespread use of skylighting with daylighting controls is estimated to have a significant impact on the energy consumption of commercial buildings.

EXECUTIVE SUMMARY

This report describes visible transmittance testing of skylight glazings and overall effective visible transmittance (EVT) of skylighting systems (skylight, light well, diffuser etc.). The effective visible transmittance is the ratio of light (luminous flux in lumens) impinging on the skylight opening to the light that exits the skylighting system into the interior space.

Two methods were developed to measure the light exiting the skylighting system:

1. A grid of illuminance meters below the light well opening measured the area-weighted illuminance exiting the light well.
2. A goniophotometer centered under the light well opening measured the luminous intensity (candelas) at regular intervals of horizontal (azimuthal) and vertical (from the nadir) angles.

The first method is more robust in that it does not rely on assumptions of the photometric method which assumes that the distribution of light is spherically expanding from the light well exit. Thus the grid of illuminance meters can be used to reliably measure light exiting the skylighting system for skylighting systems that have a significant amount of collimation of light such as is expected from clear or partially diffusing skylights.

Skylight EVT was measured while varying glazing type, skylight shape, light well height and light well material (diffuse white paint versus specular metallic film). This EVT data can be used to validate skylight transmittance models and develop new ones. Ideally these models ultimately impact both building energy and lighting simulation programs as well as the systems developed to rate the performance of skylights.

The primary finding of this study is that *both the visible transmittance of the glazing and the skylight shape affect the effective transmittance of the skylight*. This is especially important when we compare the effective visible transmittance of the skylighting system at the relatively low solar altitude of 30º above the horizon, the angle that the sun is most frequently near for most of the hours during the year.

Flat skylights mounted horizontally have a noted drop off in effective visible transmittance when the altitude of the sun is lower than 30º above the horizon as compared with normal incidence visible transmittance (90º solar altitude). In comparison, horizontal dome skylights have a visible transmittance that is relatively constant regardless of solar angle.

The existing NFRC (National Fenestration Rating Council) test protocols limit the visible transmittance rating of skylights to those with flat non-diffusing glazings. Building energy simulation programs typically model horizontal skylights as flat planar skylights regardless of skylight shape. However, these flat skylights are but a small fraction of the unit skylight market for commercial buildings. It is suggested that the NFRC consider a test method that can be applied to any shape and material of skylights and that they consider a simulation program (such as NRC Canada's SkyVision) that can simulate the visible performance of projecting skylights and TDD's (tubular daylighting devices). The research team has presented this information to NFRC staff. The algorithms in energy simulation programs are in need of modification to account for skylight shape. Some of the members of the EnergyPlus building simulation development team are on the technical advisory committee for this project. At this point in time we are not aware of any whole building energy simulation that accounts for skylight shape.

The need for such a test method and modeling method is quite imperative in that if everything else is equal, including normal incidence visible transmittance, the projecting skylight will yield greater energy savings. A lighting energy analysis performed using the angular EVT's of flat and dome skylights found that for the same skylight dimensions, a dome skylight typically saves 5% more lighting energy than a south facing 20° tilted skylight, 10% more lighting energy than a horizontal flat skylight and even greater savings as compared to a north facing flat skylight.

When skylights are used to displace electric lighting, they must have a means for diffusing daylight so that it is a useful source of light and not a source of glare. This project has identified a simple, inexpensive test that can identify on a gross level the level of diffusion from glazings. This test is the haze test administered in accordance with ASTM D1003. When glazing haze is greater than 90%, the glazing is considered to be relatively diffusing. This metric is useful to code developers and lighting designers when specifying a skylighting system that is intended to displace electric lighting and as a result of this project's work the glazing haze factor is included in California's 2005 Title 24 Standards.

INTRODUCTION

The primary purpose of skylights is to bring daylight into the interiors of buildings while keeping moisture out. As such the visible transmittance of skylights is of high importance when selecting skylights.

Approximately 60% of commercial buildings have a suspended ceiling between the roof and the occupied space. When buildings are designed with both skylights and suspended ceilings, a passageway from the skylight to an opening in the ceiling plane, called a light well, allows the light to enter into the room. Thus, the skylight does not work in isolation, the geometry and reflectance of the light well affects the overall luminous performance of the skylighting system.

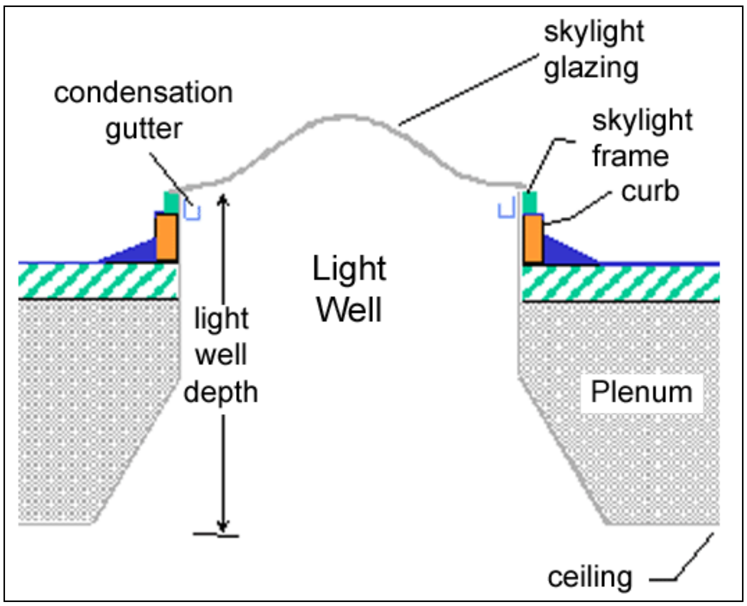

Figure 1. Skylight with light well

This report describes the testing of several types of skylights, their glazing and skylights with light wells. Commonly used calculation methods are compared with the test results. This comparison can help the designers in selecting the best methods for comparing skylighting system performance.

Economic Impact of Skylights with Suspended Ceilings

A casual observer might wonder why the performance of skylights is of interest to the Public Interest Energy Research (PIER program). The short answer is skylights installed with the appropriate lighting controls result in substantial reductions in electric lighting energy consumption. Table 1 illustrates the potential energy cost savings in California from installing skylights and lighting controls in five building types. (McHugh et al 2003c) This estimate considers only the fraction of spaces that are directly under a roof, have suspended T-bar ceilings and where adding skylights is feasible. This table shows that one year's worth of new and retrofit construction would save California ratepayers approximately $3.2 Million, or after adding skylights to 10 years of new construction, California commercial building owners would be saving $32 Million per year!

Table 1. Feasible energy cost savings potential from one year's new/retrofit construction for 5 selected building types

Occupancy	New or Retrofit M SF/yr	Under Roof	T-bar Ceiling	Feasible	Total Million SF/yr	$/SF-yr	Annual Savings ($Millions)
Lg Office	30.9	35%	45%	50%	2.4	$ 0.15	$ 0.4
Sm office	9.9	50%	45%	50%	1.1	$ 0.15	$ 0.2
Grocery	6.6	100%	46%	75%	2.3	$ 0.23	$ 0.5
Retail	24.8	80%	46%	75%	6.9	$ 0.23	$ 1.6
Education	12.6	60%	68%	75%	3.9	$ 0.16	$ 0.6
Totals	**84.8**				**16.5**		**$ 3.2**

The above estimate is only for low rise buildings with suspended ceilings. However, this research on visible transmittance of skylights impacts skylighting systems in all building types – even those without suspended ceilings such as big box retail and warehouses. Approximately 60 Million sf of new warehouses and big box retail is added to the California building stock per year. Thus the total impact of skylighting is two to three times the estimate of the impact on buildings with suspended ceilings or as much as a $100 Million/yr savings after ten years of aggressively adding skylighting to commercial construction.

However, the energy cost savings impacts may be but the tip of the iceberg in terms of the economic benefits of greater use of skylighting. As shown above the energy cost savings from daylighting are between $0.15/SF and $0.23/SF. In contrast, the salary and overhead costs of office workers range from $100 - $400/SF. The average salaries and overhead of Federal government workers is around $165/SF (Harris et al. 1998). Annual retail sales are of a similar magnitude; the average annual sales for non-food retail is $153/SF of floor area and for supermarkets $579/SF of sales floor area (Food Marketing Institute 2002). Thus, building features that can reliably increase human performance or retail sales even 1 percent would have around a $1.50/SF to $5.00/SF impact on sales or office labor costs. The effect of increases in productivity or sales on profits would vary by industry.

Recent reports on the value of daylighting have correlated full daylighting to 21% higher test scores in schools (HMG 1999a) and up to 6% increase in retail sales (HMG 2003). Thus there is growing evidence that daylighting is linked to a probability of higher productivity in different work environments. In addition, the magnitudes of the productivity gains indicate an economic impact on profits that are as large as or larger than the energy cost savings impact of daylighting. To the extent that these effects are related to building occupants receiving daylight, this result highlights the importance of being able to predict the amount of light transmitted by the skylight and light well system.

Focus on commercial buildings

When calculating the energy savings impact of skylights in Table 1, all of the occupancy types were nonresidential. This exclusion of residential skylighting is due to a qualitative difference between residential and commercial skylighting. Commercial and industrial occupancies are good targets for energy savings from skylights since they have high lighting power densities, extensive lighting use during daytime hours, and whole building energy consumption that is relatively insensitive to envelope thermal transmittance (U-factor). Residential buildings, on the other hand, are not likely to see energy savings from skylights for the opposite of all the reasons listed above.

This qualitative difference in residential versus commercial skylighting results in different products being used; residential skylighting relies on a substantially greater fraction of flat glass skylights than commercial skylighting which uses plastic dome skylights. A tabulation of the differences in commercial and residential skylighting in Table 2 illustrates factors that have driven commercial skylighting toward diffusing plastic domes and residential skylighting towards clear flat glass glazing.

Table 2. Differences between Commercial and Residential skylighting

Topic	Commercial Skylighting	Residential Skylighting
Energy	Displace electric lighting	Minimize heat loss and gain
Roof slope	Often flat roof	Often sloped roof
Profile	Profile not important	Low profile desired
Clarity	Diffusion desired for glare control	Often clear for view of sky
Cost	Cost-effectiveness consideration	Aesthetic amenity

Glass is more expensive than plastic, but it can accept low-e coatings, which reduce both heat gains and losses, and flat glass skylights have a lower profile than domes, which are projecting. Dome skylights can be placed on flat roofs without requiring a slanted curb or adapter. As will be quantified later on in this report, dome skylights are better at intercepting low angle sunlight.

Importance of Light Transmittance to Skylight Performance

Understanding the luminous performance of skylighting systems is of great importance because these systems have the potential to substantially increase California's economic efficiency. The most evident benefit of skylighting is the energy savings that can be realized by reducing of lighting energy consumption and cooling loads in commercial buildings. This benefit is realized when photocontrol systems are used in conjunction with skylights. Photocontrol systems measure the amount of light inside of a space and turn off or dim electric lights during peak daylight hours while maintaining as much or more light than the design light levels. Cooling loads can go up or down depending upon the trade-offs between less internal gains from electric lights and increased solar gains or thermal conduction through the skylights. Heating loads are almost always increased by skylights due to increased thermal conduction of the roof and reduction in electric lighting internal gains.

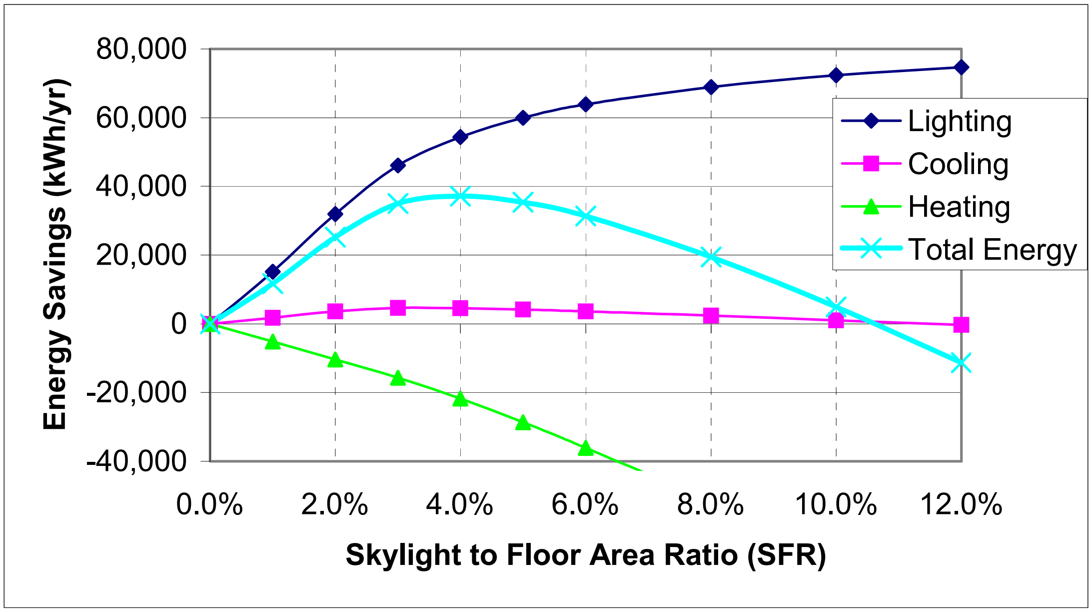

Figure 2. Components of energy savings due to skylights[1].

Figure 2 illustrates the results of a SkyCalc calculation of the components of energy savings resulting from adding skylights and a photocontrol system to a 25,000 square foot retail store in San Francisco, CA. Energy savings are described in relation to the skylight area to floor area ratio (SFR) of double glazed plastic skylights. It should be noted that one of the key assumptions in SkyCalc is that the skylights are perfectly diffusing and that they are spaced for relatively uniform illuminance (typically no further apart than 1.5 times the ceiling height). Lighting energy savings increase as more skylights are added, cooling savings increase at first but after 3%, decrease as additional skylights add more solar heat than the reduction in heat from electric lighting. Overall energy savings are maximized at 4% skylight to floor area ratio. The optimum energy savings varies by climate, occupancy type, lighting power density etc., but the main point illustrated by this figure is that the primary benefit from skylighting is bringing in enough daylight to turn off or dim electric lighting.

[1] Figures calculated using SkyCalc®, a free skylight design spreadsheet application developed by the Heschong Mahone Group. A copy of the program can be accessed from http://www.h-m-g.com.

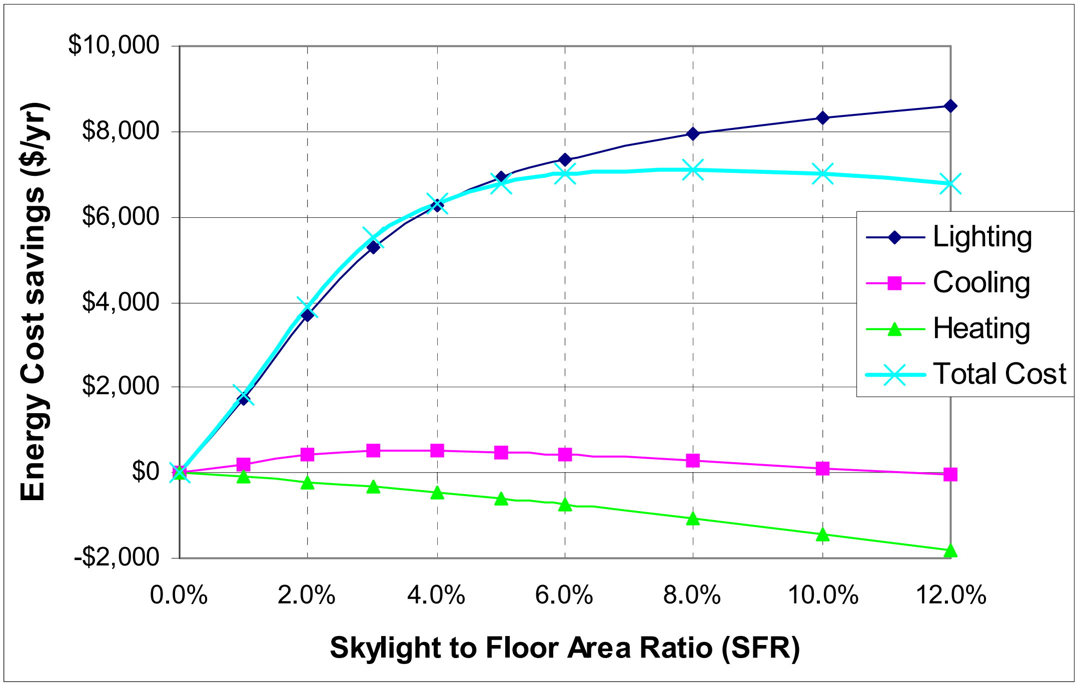

Figure 3. Energy cost savings due to skylights[2].

Figure 3 illustrates the components of energy cost savings as natural gas rates are applied to heating energy and electricity rates are applied to lighting, and cooling. In California, the gas costs per unit of energy are approximately a fifth of the cost of electrical power; this results in the heating losses, though relatively large, having a small impact on the overall cost savings from an optimal skylighting system with a 6% skylight to floor area ratio. The primary lesson to be learned from this is that the key parameter of a skylighting system is how well it can deliver daylight so that electric lighting can be turned off. The secondary lesson is that heat losses are less important in California's mild climates and with the substantial cost differences between electricity and natural gas.

Angular Transmittance – Accounting for a Moving Sun

Over the course of the day, the sun moves azimuthally from east to west and it rises in solar elevation (the angle between the horizon and the sun) to a maximum at solar noon and falls again. The arc of the sun's trajectory across the sky is called the "sun path". As shown in the Figure 4, the sun path varies by time of year in response to the tilt of the earth's axis relative to the sun. The solar azimuth and altitude angles are readily calculated for any date and time at given latitude and longitude (ASHRAE 2001).

[2] Figures calculated using SkyCalc®, skylight sizing software developed by the Heschong Mahone Group. A copy of the program for California cities can be accessed from http://www.energydesignresources.com for additional climates go to http://www.h-m-g.com

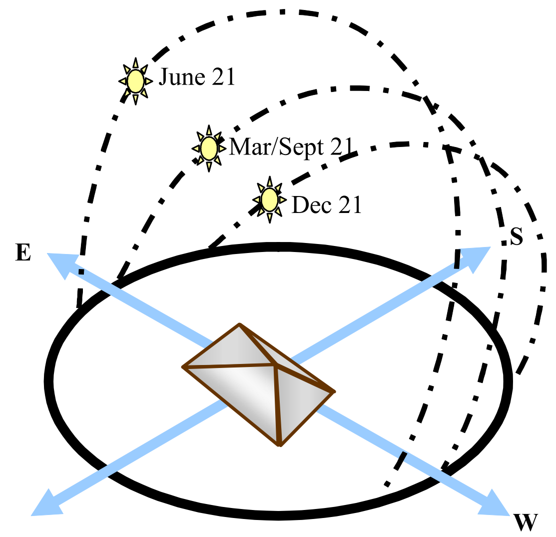

Figure 4. Sun path at winter and summer solstice and equinox

Figure 5 illustrates the sun angles on a flat skylight that is horizontal and facing straight up. This is how skylights are often modeled. In this case, the angle of incidence of direct beam sunlight is the complement of the solar altitude, also as known as, the zenith angle. In this case the angle of incidence in degrees is:

Angle of incidence = 90° - Solar Altitude = Zenith Angle

For a flat piece of glass, or even multiple layers of glass, the change in transmittance as incident angle varies is very well characterized as these equations were developed over a century ago (Stokes 1862). Presumably a variant on these equations can be used to model the visible transmittance of skylights of other shapes. The primary differences in modeling projecting skylights and flat glass is:

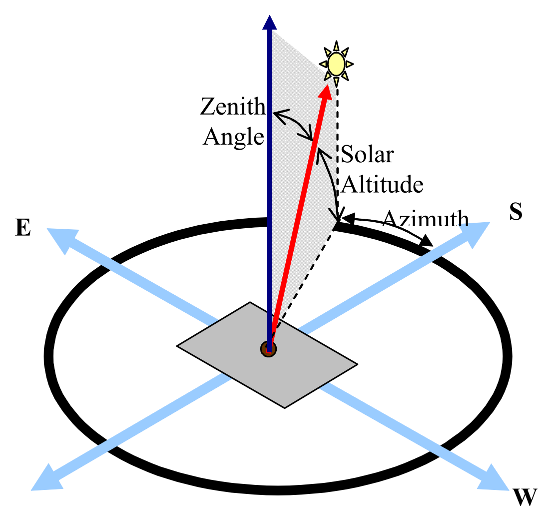

Figure 5. Sun angles on a flat horizontal skylight

- The angle of incidence of collinear sunlight is the same over the entire area of flat glass, whereas the angle of incidence on a projecting skylight varies over the surface of the skylight.
- Light transmitted by flat glass is considered transmitted whereas some fraction of light transmitted through a projecting skylight may also intersect with another section of glazing and be retransmitted outside, absorbed or reflected.
- These equations do not account for diffusing or light redirecting glazings.

Thus it is desirable to know if projecting and diffusing skylights can be readily approximated as a flat piece of glass over the range of sun angles encountered in a year. Alternatively, if the flat glass approximation is not very accurate, what improvements are needed to model the light transmitting performance of skylights. As described in the section on the Importance of Light Transmittance to Skylight Performance, correctly characterizing the visible light transmittance is of paramount importance in estimating the energy impacts of skylights over the course of a year.

The daylight availability model in IESNA Handbook calculates horizontal illuminance as a combination of horizontal direct beam illuminance and horizontal illuminance as produced by the sky. Both the beam and sky illuminance terms increase with solar altitude. Thus there is less sunlight available when sun is lowest in the sky. When the sun is high in the sky, there is an excess of sunlight available. Thus the highest consideration for skylight transmittance is at low solar altitudes.

San Diego Average Global Horizontal Illuminance (fc) from TMY2 data file												
Hour	**Jan**	**Feb**	**Mar**	**Apr**	**May**	**Jun**	**Jul**	**Aug**	**Sep**	**Oct**	**Nov**	**Dec**
1	0	0	0	0	0	0	0	0	0	0	0	0
2	0	0	0	0	0	0	0	0	0	0	0	0
3	0	0	0	0	0	0	0	0	0	0	0	0
4	0	0	0	0	0	0	0	0	0	0	0	0
5	0	0	0	0	0	0	0	0	0	0	0	0
6	0	0	0	195	402	519	346	225	75	0	0	0
7	0	97	476	1,229	1,393	1,548	1,360	1,116	840	506	207	0
8	601	1,053	1,990	3,019	3,148	3,509	3,002	2,685	2,329	1,866	1,262	749
9	2,009	2,706	3,718	4,917	4,968	5,394	5,083	4,738	4,116	3,422	2,877	2,036
10	3,360	4,195	5,121	6,418	6,413	6,946	6,872	6,993	5,502	5,117	4,280	3,220
11	4,602	5,337	6,508	7,790	7,635	8,195	8,474	8,538	7,057	6,433	5,206	4,318
12	5,056	5,954	7,154	8,345	8,493	8,904	8,931	8,895	7,977	6,953	5,549	4,823
13	5,199	6,003	7,260	8,584	8,793	8,393	8,982	9,134	8,030	6,834	5,337	4,756
14	4,516	5,490	6,680	7,827	7,908	7,805	8,230	8,314	7,080	6,047	4,516	4,100
15	3,386	4,307	5,421	6,643	6,585	6,470	7,088	6,790	5,536	4,432	3,191	2,932
16	1,980	2,829	3,832	4,802	4,728	4,882	5,543	5,253	3,755	2,649	1,585	1,396
17	531	1,198	2,070	2,703	2,931	3,226	3,593	3,239	1,794	844	329	285
18	0	173	458	842	1,167	1,510	1,661	1,252	404	35	0	0
19	0	0	0	31	194	333	348	149	0	0	0	0
20	0	0	0	0	0	0	0	0	0	0	0	0
21	0	0	0	0	0	0	0	0	0	0	0	0
22	0	0	0	0	0	0	0	0	0	0	0	0
23	0	0	0	0	0	0	0	0	0	0	0	0
24	0	0	0	0	0	0	0	0	0	0	0	0

Figure 6. Average exterior illuminance in San Diego by month and hour

Figure 6 illustrates the average outdoor illuminance by hour for each month of the year in San Diego. The plot is progressively shaded depending upon the amount of light available. If we have a skylighting system that could deliver 1% of exterior light to the floor of the interior space and one was turning off 1/3 of lights when the interior daylight light levels were above 25 fc (exterior illuminance greater than 2,500 fc) and turning off a total of 2/3 of the lights when the internal daylight light levels were above 50 fc (exterior illuminance greater than 5,000 fc), this would be represented by the hour and month matrix in Figure 6. Cells with greater than 5,000 exterior fc are shaded white – 2/3 s of the lights could be tuned off. Cells with less than 5,000 fc and greater than 2,500 fc are shaded light grey (blue in color images) – enough light to turn off 1/3 of the lights. What one can also see is that there is usually more than enough light to turn off electric lighting in the middle of the day for most months. The key determinate of how much the system saves is how many hours the building interior is daylit enough in the mornings and during the winter months.

San Diego Average Solar Altitude (degrees)

Hour	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec
1	0°	0°	0°	0°	0°	0°	0°	0°	0°	0°	0°	0°
2	0°	0°	0°	0°	0°	0°	0°	0°	0°	0°	0°	0°
3	0°	0°	0°	0°	0°	0°	0°	0°	0°	0°	0°	0°
4	0°	0°	0°	0°	0°	0°	0°	0°	0°	0°	0°	0°
5	0°	0°	0°	0°	1°	1°	1°	0°	0°	0°	0°	0°
6	0°	0°	1°	4°	7°	9°	7°	4°	2°	1°	0°	0°
7	1°	2°	6°	14°	19°	21°	19°	15°	11°	6°	3°	1°
8	7°	10°	18°	26°	32°	33°	31°	27°	23°	18°	12°	8°
9	17°	22°	30°	39°	44°	46°	44°	40°	35°	29°	22°	18°
10	26°	31°	40°	50°	57°	58°	56°	52°	46°	38°	30°	26°
11	33°	39°	49°	60°	68°	70°	68°	63°	55°	45°	36°	31°
12	36°	43°	54°	66°	76°	80°	77°	70°	59°	47°	38°	34°
13	36°	44°	54°	65°	73°	77°	76°	69°	57°	45°	37°	33°
14	32°	39°	49°	57°	63°	66°	66°	60°	50°	39°	31°	29°
15	25°	32°	40°	46°	51°	53°	54°	49°	40°	30°	23°	21°
16	16°	22°	29°	34°	38°	41°	41°	37°	29°	20°	13°	12°
17	6°	11°	17°	22°	25°	28°	28°	24°	16°	8°	4°	4°
18	1°	3°	5°	9°	13°	16°	16°	12°	5°	1°	0°	0°
19	0°	0°	0°	1°	3°	5°	5°	3°	0°	0°	0°	0°
20	0°	0°	0°	0°	0°	0°	0°	0°	0°	0°	0°	0°
21	0°	0°	0°	0°	0°	0°	0°	0°	0°	0°	0°	0°
22	0°	0°	0°	0°	0°	0°	0°	0°	0°	0°	0°	0°
23	0°	0°	0°	0°	0°	0°	0°	0°	0°	0°	0°	0°
24	0°	0°	0°	0°	0°	0°	0°	0°	0°	0°	0°	0°

Figure 7. Average solar altitude in San Diego by month and hour

Figure 7 shows the average solar elevations by month and hour in San Diego having the same hours shaded for 2/3's of the lights and 1/3 of the lights on as in Figure 6. The solar altitudes of interest are those which might affect the number of hours that lights are controlled. These solar altitudes of interest are those where there is a transition of one control state to another in Figure 7, this is the transition from the white center cells to the light gray (blue in color images) and the transition from light gray to medium gray. These transitions for this skylighting system occur at solar altitudes of around 25° for turning the first third of lights off and around 40° for turning the second bank of lights off. Not only are the hours of relatively low light levels and low solar elevations the times when visible transmittance of the system needed the most to gain savings, it turns out that most of the daytime hours of the year have solar altitudes less than 30°. The histograms in Figure 8 show that from Southern California (San Diego) to the Oregon border (Eureka), the mode and the median of daylit hours are around 30° to 35°.

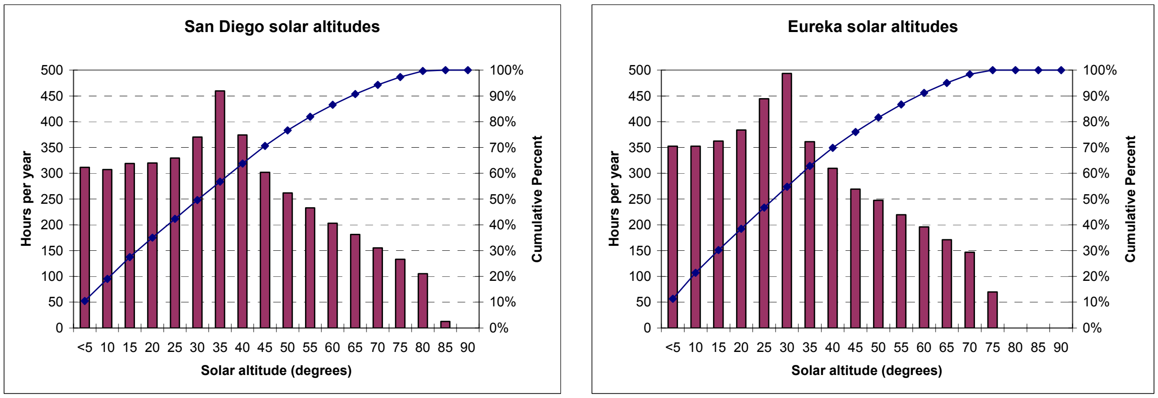

Figure 8. Frequency of solar altitudes in San Diego, CA and Eureka, CA.

Thus the measurement and rating of skylight visible transmittance should predict well the visible transmittance of skylights around 30° solar altitude or 60° angle of incidence from directly above the skylight.

The Value of Diffusing Skylighting Systems

For the proper design of skylighting in workspaces, such as schools or offices, it is essential that light leaving the skylighting system be diffused. Non-diffusing light sources, whether they are electric lights or skylights, will cause excessive glare on the task surface and cause visual discomfort for the occupants.

Diffusely transmitting skylight systems distribute light across a wider area, thus requiring fewer skylight installations. They also result in less "hot spots" within the space that might cause thermal discomfort for the occupants. (See Figure 9). If skylights are going to be used to displace electric lighting it is important that they are sufficiently diffusing.

Figure 9. Clear skylight with "hot spot" and diffuse skylights with even lighting

Skylight Visible Light Transmittance and Well Efficiency

Overall visible light transmittance of the combined skylight and light well system is a product of the visible light transmittance of the skylight and the transmittance of the light well, called the well efficiency.

The visible transmittance of a product is the fraction of light from the sun that passes through the product. To measure visible transmittance, only the fraction of solar radiation within this "visible" wavelength on the surface of the glazing material or passing through is considered.

$$T_{vis} = \frac{\textbf{Light passing through glazing}}{\textbf{Light incident on glazing}}$$

Visible light transmittance is usually tested with the incident light "normal" or perpendicular to the glazing material. Calculation models are then used to estimate transmittances at other incident angles. A simplifying assumption is that the skylight glazing is flat and thus transmittance decreases at lower solar elevations. This report will investigate the error that results when this assumption is applied to domed and other projecting skylights.

The well efficiency, WE, is the fraction of light that is transmitted by the light well and is given by the relation:

$$\mathbf{WE} = \frac{\textbf{Light exiting bottom of light well}}{\textbf{Light entering the top of light well}}$$

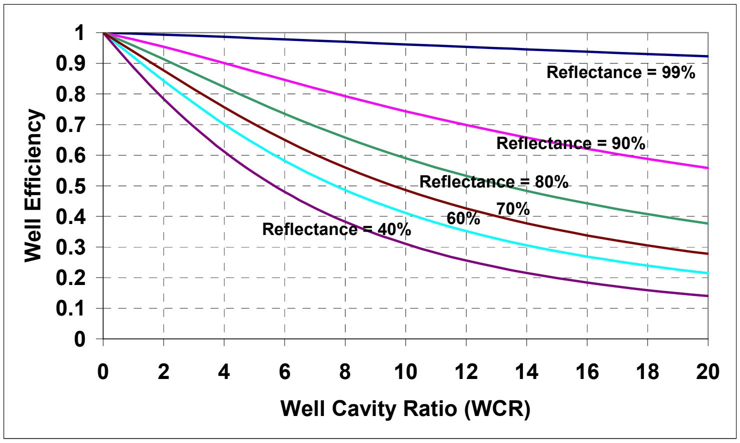

Figure 10. Well efficiency as a function of well cavity ratio and reflectance

For light wells that are under diffusely transmitting skylights and have diffusely reflecting surfaces, the well efficiency can be calculated using the Lumen Method. The IESNA Handbook publishes a well efficiency graph that is a function of the well geometry (well cavity ratio), and the average well surface reflectance. The well cavity ratio, RCR, is given by the equation below, where, well perimeter and well area are measured at the bottom of the light well.

$$\mathbf{WCR} = \frac{\mathbf{2.5} \times \textbf{well height} \times \textbf{well perimeter}}{\textbf{well area}}$$

The graph of well efficiency shown in Figure 10, is based upon a Lumen Method calculation with a top of cavity reflectance of 99% and a bottom of cavity reflectance of 0%. (Heschong & McHugh 2000) This matches closely the well efficiency figure published in the IESNA handbook.

If the well efficiency nomograph were applied to light wells with specular (mirror-like) surfaces, the resulting well efficiency estimate would be lower than its actual performance. The performance of such light wells is best estimated using an alternate calculation method. Since tubular skylights typically make use of a specular light well, further discussion of the methods used to calculate specular light well efficiency are contained in the section on “Transmittance of Tubular Daylighting Devices (TDD’s)”

Existing Light Transmittance Testing and Modeling Methods

As described above, the key determinant of the energy performance of a skylighting system is its ability to transmit useful energy from the outdoors to where tasks are being performed. To predict how much useful light makes it from the outdoors to the task requires reliable methods of measuring the physical properties of skylighting system components and a method of calculation that results in fidelity to real results.

The definition of "useful light" is a function of both is quantity (lumens) and its quality (distribution). The total quantity of light entering the room through a skylight and light well is the product of the skylight visible transmittance and the well efficiency. The distribution of light can be approximated by two different methods, measurement of glazing diffusion or by photometric measurements of the skylighting system. A companion report also created for the PIER program describes photometric testing in detail.[3] However, this report will touch upon the measurement of glazing diffusion and will also make use photometric measurements as they relate to measurements of total quantity of light admitted though the skylight/light well system.

NFRC 300: Solar Optical Properties of Glazing Materials and Systems

The National Fenestration Rating Council (NFRC) has adopted a procedure for determining Visible Transmittance (VT) for simple fenestration products. The visible transmittance of a fenestration product is rated at an incidence angle of 0º degrees, or normal to the flat glazing surface. It does not cover strongly diffusing materials, patterned or textured materials, complex glazing like prismatic panels, and curved skylights.

The NFRC test method is based upon solar optical measurements using a spectrophotometer equipped with an integrating sphere as described in ASTM E903. These test measurements of individual glazing layers are then combined together to form the overall skylight transmissivity using the LBNL Window 5 program or as calculated using the equations contained in the NFRC 300 test method.

The benefit of taking measurements in an integrating sphere is that the sphere "integrates over all transmitted angles" that is captures light leaving the sample in all directions and measures the total transmitted light. Thus it may seem incongruous that the NFRC 300 method does not allow diffusing glazings to be tested according to this method. The reason for this prohibition is that the calculation methods embedded in the LBNL Window 5 program and in the test method assume that for multiple layer glazings the path of light remains unaltered as it is transmitted through the glazing assembly. This is important as both reflectance and absorptance vary with respect to angle. *If this is the only reason for the prohibition on strongly diffusing glazing, the prohibition should be reduced so that it only applies when the diffusing glazing is not on the bottom (inside) layer.*

Both the NFRC-300 calculation method and the LBNL WINDOWS model represent the performance of a flat glazing surface with a single angle of incidence over the entire skylight surface. Thus neither of these methods will accurately predict the performance of any projecting skylight (domes, pyramid, catenary arch etc.). Doming causes the angle of incidence of the direct sunlight

[3] Jon McHugh, *Skylight Photometry Test Methods and Results*, PIER Report for Contract Number 400-99-013, June 2003

to vary over the dome's surface, and increases the light gathering surface area relative to a flat sheet at low solar elevations.[4]

Thus the NFRC-300 standard test method cannot be used to rate the visible transmittance of the most popular commercial skylighting product – domed plastic skylights. This is particularly troublesome in that projecting skylights tend to have higher overall transmittances than flat skylights when the sun is low on the horizon and yet there is no NFRC test method to capture this effect.

NRC – SkyVision

The inability of the LBNL Window 5 program to model projecting glazing has been a major obstacle towards an NFRC rating of projecting skylights. The National Research Council Canada has been working on a visible light transmittance and solar heat gain transmittance simulation tool for projecting skylights called SkyVision (Laouadi et al. 2003). This software is currently in a Beta (draft) version. It may be that SkyVision or its algorithms may play a role in getting past the current simulation roadblock for projecting and diffusing skylights.

If this program were used to rate skylights, a rule set would have to be crafted that would address:

- required inputs and test data
- sun position and fraction of diffuse daylight
- method of calibrating simulation to tested results

Transmittance of Tubular Daylighting Devices (TDD's)

Tubular daylighting devices typically have a clear hemispherical dome on top of a specularly reflecting tubular light well which terminates at a round diffuser or a round to square adapter and a square diffuser at the ceiling level. The benefits of these devices are:

- Light well can be offset easily to get around obstructions using the same type of angle adapters used for circular vent pipe.
- Roof flashing is well developed – the design is similar to "roof jacks" used to flash piping penetrations in roofs.
- For the relatively high roof cavity ratios encountered in tubular skylights, well efficiencies are kept relatively high by the use of specular reflecting materials with high reflectances. Advances in material science have made it possible to have specular reflectivities very close to 100%. (Weber et al. 2000)

[4] IESNA Handbook, 9th ed., p. 8-11.

- Labor costs can be reduced by prefabricated light wells and curbs. This has a trade-off with the increased number of roof penetrations needed to provide the same aperture area as larger square unit skylights.

There has been a desire to rate the overall transmittance of the entire TDD assembly as the TDD is sold as a single product. In addition, traditional well efficiency calculations based upon the lumen method would underestimate the well efficiency of TDD's.

In response to this need, a draft of NFRC 202 "Calculation of Tubular Daylighting Device SHGC and T_{vis}" contains a proposal for rating the solar heat gain coefficient (SHGC) and visual transmittance of tubular daylighting devices based upon a calculation method. This calculation method is based upon the solar optical transmittance of the top glazing and bottom diffuser materials and the solar and visible reflectance properties of the surface of the tube. No testing of the overall transmittance of a representative system is required to calibrate the results.

This calculation method is limited to tubular skylight systems with the following properties:

- hemispherical skylights with curvature within ±10%
- limited to a specific incident angle of 30°, which for horizontally mounted skylights is equivalent to a solar altitude of 60%
- insignificant diffusion of glazing
- specularly reflective tubular light well

This calculation method does not cover TDD's with top domes that have a significant reflecting or lensing systems, or systems with light wells having a diffuse reflectance greater than 5% of specular reflectance.

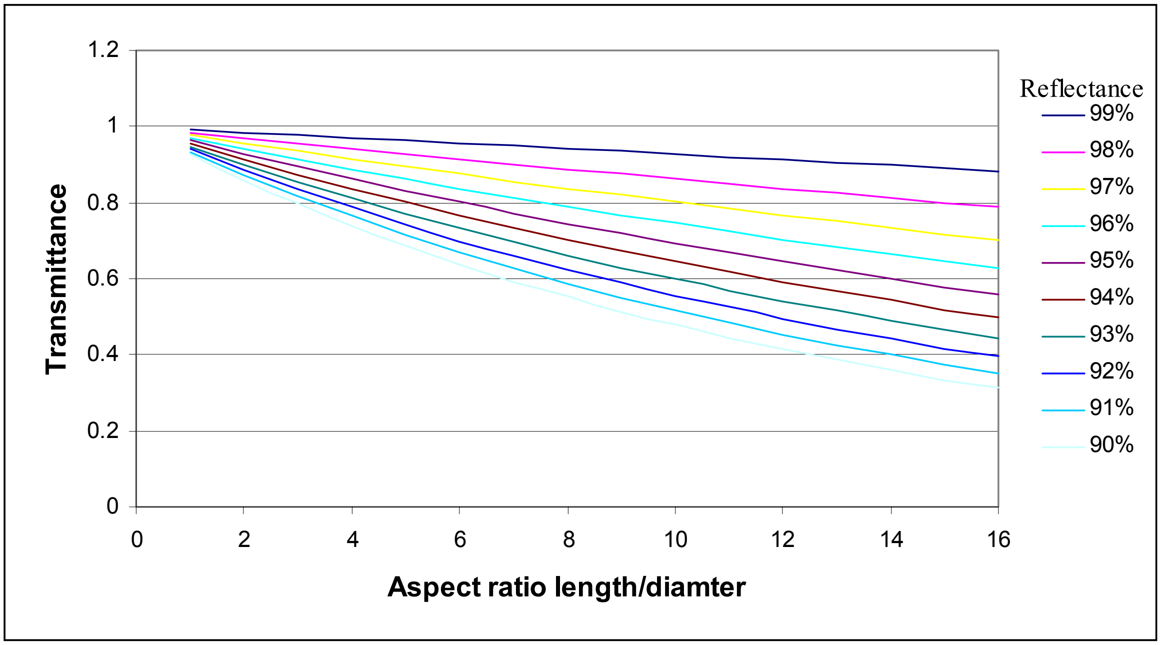

Figure 11. NFRC 202 reflective tube transmittance (30° incidence)

Total system transmittance is the product of transmittance of skylight, well and diffuser. Transmittances of the skylight glazing and diffuser are measured from planar sheets of the glazing material, with calculations accounting for curvature of the top dome. The transmittance of the tubular well is based upon ray tracing simulations for different material reflectances and different aspect ratios of tube diameter to length.

The equations and ray tracing simulations in this draft NFRC standard for TDD's assume a direct beam solar incidence angle of 30°, or for a horizontal TDD, a solar altitude of 60° above the horizon. From discussion with Dr. Ross McCluney, the author of the draft standard, this incident angle was chosen because at this high sun angle the performance of TDD's with reflectors or refractor devices on the bottom third of the dome is similar to those without such devices.

However, as shown earlier in this report in Figure 8 for San Diego in the southern tip of California to Eureka on the northern end of California, the most common solar altitudes over the course of the year are in the range of 10° to 40°. Using the NFRC performance ratings based upon a 60° solar altitude overestimates the light transmittance of tubular daylighting devices for most of the hours in a year.

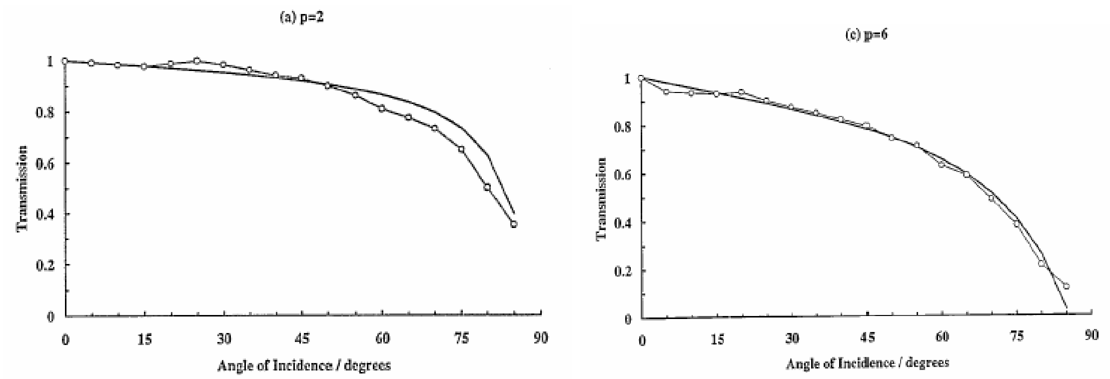

Figure 12. Light pipe transmittance as a function p (l/dia.) and angle of incidence

(Source: Smith & Swift 1995)

How much greater is the visible transmittance of a light pipe with the assumption of a 30° incident angle as compared to the more common sun angles experienced during the year such as 60° angle of incidence (30° solar altitude)? Smith and Swift (1995) have developed an analytical solution to the transmittance of tubular light pipes and validated this work with measurements of transmittance of light pipes using a Helium Neon laser as the collimated light source and an integrating sphere to measure the exiting luminous flux. Figure 12 shows variability in transmittance of a cylindrical light pipe having a 95% reflectance with respect to the incident angle of light and the characteristic aspect ratio, p, of length divided by diameter. When the length of the tube is 6 times greater than its diameter, the transmittance at 30° incident angle (60° solar altitude) is 35% greater than at a 60° incident angle.[5] For a tubular skylight with a length to diameter ratio of 6:1, the NFRC proposal would provide a rating that is met or exceeded during solar elevations that are experienced 15% of the daylit hours and overestimates light transmittance by at least 35% for half of the daylit hours in the year.

Thus this proposed rating method does not provide information regarding the skylight's performance during the more frequently occurring solar elevations when daylight availability is lower. The calculated overall transmittance of a diffusing skylight over a diffusely reflecting light well is the product of the skylight glazing transmittance and the light well efficiency. As we will see later, the transmittance of dome skylighting is fairly constant over the course of a day and if the skylight is sufficiently diffusing, the well efficiency of a diffusing well will also remain constant. Thus the TDD rating which overestimates its transmittance for most of the hours of the year does not provide a comparable metric to that of unit skylights when combined with diffusing light wells. This rating system is bound to cause confusion to specifiers when comparing between different skylight types.

[5] From personal communications with Paul Jaster at Solatube, proprietary software owned by 3M predicts lower light tube transmittances than predicted by Smith & Swift.

Existing Skylight Design Simulations

DOE-2 and Window 5 Software

DOE-2 is a whole building energy analysis program that can model daylighting, daylighting controls, building space conditioning loads and the energy consumption of building environmental systems (lighting, HVAC and appliances). To calculate the energy savings from daylighting, DOE2 must make the following calculations:

- Total amount of visible light incident on the glazing and the angle of incidence from weather file and geometric model.
- Visible transmittance of daylight with respect to angle of incidence from glazing library or internal calculations.
- Fraction of light transmitted through glazing that illuminates the reference task position in the zone from geometric model of zone (Winkelmann 1983). This uses the "split-flux" calculation algorithms in DOE-2 and models the distribution of light through a glazing as either perfectly specular (clear) perfectly diffusing (Lambertian). One can also create sun position specific daylight factors, import this into DOE-2 and DOE-2 will interpolate between these daylight factors by sun angle and sky condition to simulate interior daylight availability over the course of a year. [6]
- Reduction in electric lighting energy, based upon the electric lighting control strategy and setpoint.

DOE-2.1E calculates the angular transmittance of glazing in two ways:

1. For a few glazings, the angular transmittance is calculated as a cubic polynomial in the cosine of the solar incidence angle. The coefficients in this polynomial are a function of the glass type and number of panes. This method is a legacy of older versions of DOE-2 and is based on the assumption of flat homogenous glazing layers.
2. Most of the glazings are contained in a glazing library, which contains angular transmittances pre-calculated by the WINDOW[7] program. This program can convert normal incidence transmittances into angular transmittances based on the assumption of flat glazing (Rubin et al. 1988).

DOE-2 is the simulation engine for many other building energy simulation programs including Energy10 and VisDOE. The skylight sizing spreadsheet SkyCalc adjusts pre-calculated DOE-2 simulations and thus has an angular transmittance model that is also based upon flat perfectly diffusing glazing.

The compliance software for the Alternative Compliance Method (ACM), California's building efficiency standards (Title 24) is currently EnergyPro.

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[6] P. 2.50 F. Winkelmann et al, DOE-2 Supplement Version 2.1E, Lawrence Berkeley Laboratory, 1993.

[7] Window 5.1, Windows & Daylighting Group, Lawrence Berkeley National Laboratory.

EnergyPro though based upon DOE-2 does not calculate daylight availability for calculating energy savings from daylighting controls but rather reduces the installed lighting power density (LPD) as a function of the effective aperture of the glazing systems. The effective aperture is the product of the transmittance of the skylighting system and the ratio of skylight area to daylit floor area.

Radiance

Radiance is a ray-tracing computer program that can model just about any material surface that one can create a probabilistic function of its behavior. (Ward 1994) It also has a library of pre-defined material properties for common types of surfaces with user control over reflectance, absorptance, transmittance and other properties. Radiance traces the paths of light backwards from the viewer to the light source in a "backwards ray tracing" method. Radiance can be used to model skylights in four ways[8]:

1. as a geometric model with the material properties of reflectance, absorptance and transmittance defined for each glazing layer of for the assembly of layers; or
2. as a virtual luminaire based upon the luminous intensity distribution as published in IES skylight photometric files from goniophotometric measurements;[9]
3. as a virtual luminaire generated from a geometric model of a skylight through the use of the mkillum program within Radiance.
4. as a combination of the above approaches where the virtual luminaire provides the general illumination of the space and the more complex geometric model is used to describe the appearance of surfaces (the underside of the skylight and the skylight well) that are behind the virtual luminaire

The first method requires the most computations and the most user inputs as it requires generating a physically accurate representation of the skylight and carefully defining the surface properties which sometimes includes a detailed bi-directional reflectance (or transmittance) function, BRDF, of the glazing material. Usually BRDF's are not available and the user must make an estimate of diffuse versus specular transmittance based upon the measured quantity haze. For some materials such as prismatic and light-redirecting surfaces the location of the solar disk must be known to provide an accurate simulation.

The second method is the least computationally intensive and does not require a detailed representation of geometry or material properties. However, this method does not provide a rendering of the geometric shape of the skylights and only

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[8] Personal communication Charles Erhlich, Heschong Mahone Group

[9] Skylight photometric files resulting from PIER testing available from www.newbuildings.org or www.h-m-g.com

approximates the light distribution in near field situations when the light is impinging on surfaces closer than 5 times the largest dimension of the skylight. Skylight photometric files derived from goniophotometric measurements were only recently created as part of this same PIER skylight testing program (McHugh et al. 2002). Photometric files from 7 different skylights on a variety of light wells were published. It is our hope that this method will become widespread, but in the short term there are not many skylight photometric files available.

The third method while requiring the same detailed inputs of the first method is less computationally intensive than a combined Radiance calculation as the problem has been broken down into two pieces: 1) the transfer of light from the sky to the skylight and 2) the transfer of light to the skylight to the room. This is a welcome addition since this can substantially reduce the computational time needed. This path has the shortcoming of the first method in terms of the time needed to generate the skylight geometry and the little detailed glazing properties information available.

The fourth method is similar to the second method in that the source of the light is a virtual luminaire having a measured photometric distribution. What differs is that a geometric representation of the skylight is created – not as a source of light but as part of the room surfaces, so that one can visualize the room geometry including the underside of the skylight. The approach avoids some of the computational overhead associated with a complex, lighting-accurate model of the skylight system. Computational savings for this approach depend upon the complexity of the skylight and result from having fewer rays traced from the room surfaces toward the origin of the light. This hybrid modeling approach also allows the simulation of skylight systems that are computationally intractable, such as light-redirecting and prismatic lenses, because pre-computed (as with a forward ray-tracing program) or lab-measured photometric distribution is used with the virtual luminaire to provide the general illumination for the space.

Radiosity Programs

Most of the electric lighting design software that visualizes spaces does so by solving a matrix of the radiosity (combined emitted and reflected light) of each surface in a modeled geometry. The radiosity matrix simultaneously solves the fraction of light exiting each surface that impinges on other surfaces through the use of form factors. These form factors (as known as in thermal radiation transfer theory as view factors) are calculated based upon the assumption that all surfaces are diffusely reflecting. As a result, radiosity programs are unable to model specular surfaces accurately and semi-specular surfaces are approximated as diffuse (matte) (Ashdown 2002).

Electric lighting design software if it has a daylighting module at all, will treat skylights as being either perfectly clear or perfectly diffusing and as flat. However, real diffusing skylights are not perfectly diffusing. This type of skylight model thus can only differentiate between diffusing skylights based upon published transmittance but not in terms of the distribution of light. One lighting program that we tested did not vary skylight transmittance with sun angle. As it turns out, this is a reasonable thing to do for dome skylights, which have relatively constant visible transmittance with respect to sun angle. But for flat skylights, the assumption of constant transmittance overestimates transmitted light at low sun angles.

If skylight photometric files are available in IESNA LM-63 format, the skylight can be modeled as an electric lighting luminaire. However, the sun position and the solar illuminance on the day the skylights are tested may vary from the conditions one wants to model for their project. The process of "tricking" the electric lighting design software to model daylighting with skylights by adjusting the "lamp lumens" and the "luminaire rotation angle" is described in McHugh et al. (2002).

As described above, only a few tested skylight photometrics exist outside of those created as part of the PIER Integrated Ceiling skylight testing research. Additional limitations of this method are:

- far field photometric measurements will only approximate the near field interactions with wall and well surfaces
- calculations are based upon the distribution of light expanding spherically under the skylight (inverse square law assumption); light that is collinear violates this assumption

Thus this method does not work well for situations where there are large skylights over fairly low ceilings. In addition, using skylight photometry for poorly diffusing skylights will not provide accurate results. However, this method is acceptable for modeling diffusing skylights, which are desirable in commercial skylighting due to lower glare and better distribution of light.

Description of the Study

Skylights come in a variety of shapes, with many different glazing types and are placed over a variety of light wells (heights and surface properties) and in some cases have a separate diffuser. Often the only transmittance data available is the visible transmittance of the glazing material. This study attempts to provide guidance on what information is needed to accurately predict the hourly visible transmittance of skylighting systems for daylighting commercial buildings. Since most commercial buildings have low slope (less than 1/12 pitch) roofs, the skylights are mounted horizontally.

Thus we will be comparing skylight transmittance according to these test methods:

- Visible transmittance testing of single layers of flat glazing samples and glazing assemblies tested on a laboratory apparatus (BYK Gardner Haze Gard Cat. #4725) according to ASTM D1003.

- Visible transmittance testing of the skylight glazing in the form of the skylight using sunlight as the light source based upon the test methods in ASTM E1084.
- Effective Visible Transmittance (EVT) of the skylight, its light well and diffuser (if any) by the use of a regular grid of illuminance meters placed at the bottom of the light well.
- Skylight (luminaire) efficiency calculated from goniophotometric measurements that are based upon the IESNA LM-41 standard for photometric testing of indoor fluorescent luminaires.

This comparison will help us to identify what level of testing is required to accurately predict visible transmittance of skylights. This comparison will also help validate calculation algorithms for the transmittance of skylights.

METHODOLOGY

This section describes the luminous transmittance tests performed on new skylights and their light wells. These tests do not describe what the long term visible light performance might be after weathering. It should also be noted that these tests were performed on a small subset of the skylight products that are currently available.

DSET Laboratories Standard Visible Transmittance (T_{vis}) Test

This test was conducted to determine the light transmission of diffusive flat skylight materials, such as used by the NFRC. Test results from this test will be compared to the results from the standard light transmittance test for curved skylights (conducted by Tait Solar Laboratories).

Methodology

Visible transmittance and transmission haze measurements are performed on the specimens in accordance with ASTM D1003-00 *Standard Test Method for Haze and Luminous Transmittance of Transparent Plastics*, Procedure A. The measurements are made using BYK Gardner Haze Gard Cat. #4725. The transmission haze values were determined by the ratio of the diffuse transmittance to the total transmittance for each specimen. See Figure 13 for a diagram of the visible transmittance test apparatus.

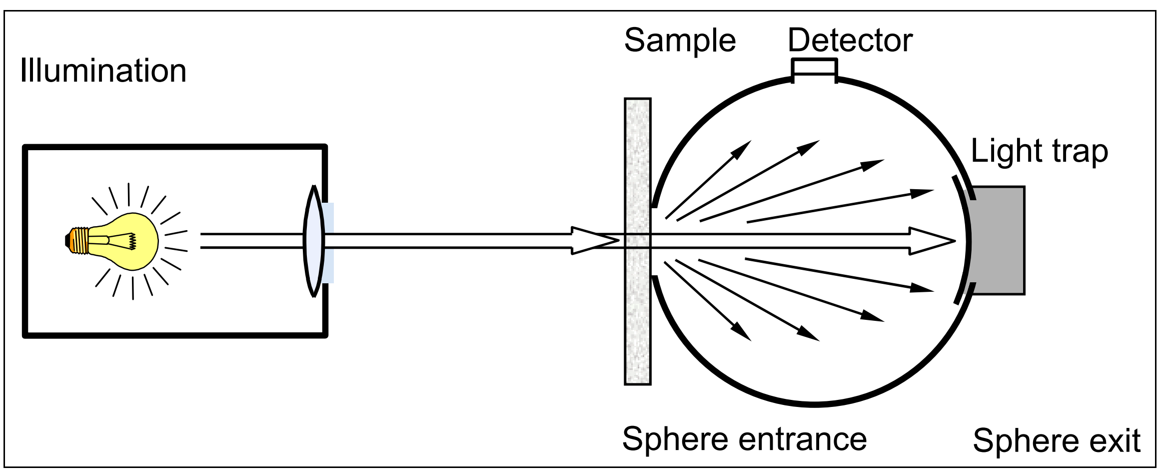


Figure Courtesy of BYK-Gardner

Figure 13. Measurement of Total Transmittance with light trap covered

The Haze Gard consists of a light source, and integrating sphere with a light trap a light trap shield and three detectors. The light source matches the spectral distribution of CIE illuminant C. The light trap captures all light that is within a 2.5° acceptance angle of the beam of light emitted by the light source. If there is no glazing in place and the light trap is unshielded virtually all of the light is captured by the light trap. When there is no glazing in place and the light trap is shielded the integrating sphere detector shown on the top of Figure 13 measures the maximum amount of light reflected in the integrating sphere.

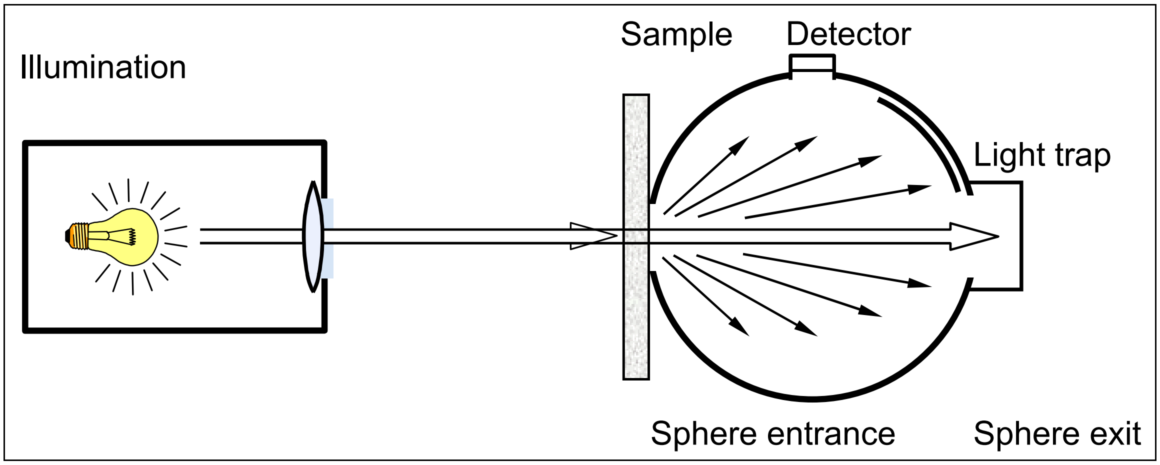


Figure Courtesy of BYK-Gardner

Figure 14. Measurement of Diffuse Transmittance with light trap open

Total light transmitted by the glazing is measured with the light trap obstructed by a cover having the same reflectance as the rest of the integrating sphere (see Figure 13). Total transmittance is the ratio of the measured illuminance by the sphere detector with the glazing sample in front of the sphere aperture and the light trap covered, to measured illuminance by the sphere detector with the glazing sample removed and the light trap covered.

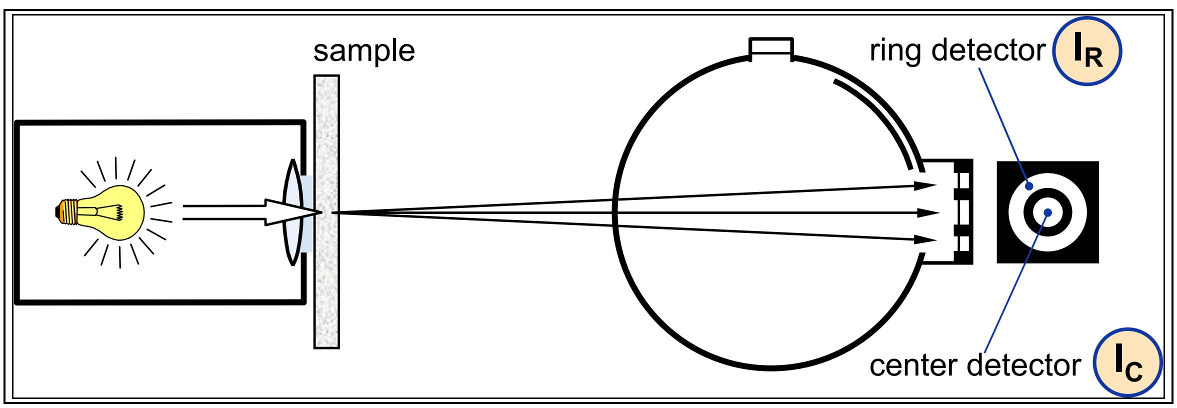


Figure Courtesy of BYK-Gardner

Figure 15. Center sensor and ring sensor in light trap

Diffuse transmittance, $T_{Diffuse}$, is measured with the light trap uncovered as shown in Figure 14. In this configuration the sphere detector measures only the light not trapped – light which is scattered more 2.5°. Diffuse transmittance is used to quantify transmission haze, which is the wide-angle scattering of transmitted light through transparent and translucent materials. Haze is the ratio of diffuse transmittance to total transmittance and is expressed by the following relation:

$$\textbf{Haze} = \frac{T_{Diffuse}}{T_{Total}}$$

The center detector, as shown in Figure 15, is located in the center of the light trap and measures the amount of light that is transmitted without any scattering. The ring detector, in the shape of a ring that surrounds the center detector, measures the amount of light that is scattered within 2.5° of the center detector. These two sensors are used to measure clarity which is the relative intensity of light that is directly transmitted with no scattering to scattered light observed in a 2.5° acceptance angle. Clarity is defined in terms of the measured center detector intensity, I_C, and the ring detector intensity, I_R.

$$\textbf{Clarity} = \frac{I_C - I_R}{I_C + I_R}$$

Thus, a glazing sample that resulted in equal intensities of light being measured by the center detector (direct transmittance) and the ring detector (narrow angle scattering) would have a clarity of 0%. Conversely, if the light were sensed by the center detector and no light was sensed by the ring detector, the glazing clarity would be 100%. The clarity measurement by the Haze Gard instrument is not in accordance with any recognized test standard, but is of interest as it indicates the narrow angle light scattering caused by the glazing sample. Clarity measurement procedures are not part of the ASTMD1003 test standard.

Thickness measurements are taken as the average of four readings taken with a Starrett Digital Caliper No. 722.

The ASTM D1003 standard states that "material having a haze value greater than 30% is considered diffusing and should be tested in accordance with practice E167," *Standard Practice for Goniophotometry of Objects and Materials, American Society for Testing and Materials*. The problem with ASTM E166 (for transmitting materials) and E167 (for reflecting materials), is that this standard has no simple term for diffusing or non-diffusing glazing. There is no concept of haze in ASTM E166, it merely defines the method of generating a photometric distribution. This result of a measurement of a photometric distribution is not particularly useful in a code or a specification context where an unambiguous criteria is desired. If ASTM E166 were used as a method of defining diffusion, some derivative metric would need be created such as a root mean square error from a Lambertian (perfectly diffusing) distribution.

The concern with measuring haze from a highly diffusing sample is that it does cause some error but this error is small. In a paper by Weidner and Hsia (1979), the uncertainty in percentage haze is on the order of 0.2% of full scale for a highly diffusing (Lambertian) sample and as high as 2% if the haze samples have a concentrated directional scattering. As we will see later, 2% error is acceptable for the very gross distinctions in haze we are interested in.

Test Specimens

Ten specimens were tested in the 17 configurations tabulated in Table 3. The ten specimens were provided by the skylight manufacturers and are flat samples of the plastics used in the manufacture of skylights or well bottom diffusers. The samples were not formed but in the case of prismatic materials were already embossed with their prismatic pattern. The configurations were selected as match the configurations of glazing in the skylights.

In selecting these glazing types we had several criteria:

- Common commercial skylight glazings. White acrylic is perhaps the most popular glazing used. Most of the other glazing types are also commonly used.
- Different methods of diffusion. The white skylights scatter light by pigments, the fiberglass skylights scatter light by fibers, and the prismatic and structured polycarbonate skylights scatter light by refraction.

The interest in different methods of diffusion is due to the recognition that higher visible transmittance is desirable but so is good diffusion of light. When pigments are used to diffuse light, higher diffusion results in lower transmittance. In the past, focusing solely on transmittance had led to high transmittance, low diffusion white skylights. These skylights produced excessive contrast causing glare and because the light was not spread enough, resulted in *lower light levels between skylights* than lower transmitting but better diffusing medium white skylights.

Diffusing light via refraction or other methods offers the possibility of having both high visible transmittance and high diffusion. Some skylight manufacturers are combining diffusion methods e.g. creating prismatic or structured glazings with small amounts of pigment. For simplicity of analysis, this sample of glazing types does not contain products with combined diffusion methods. There are several commercially available skylights that combine light diffusion methods such as skylights that have either prismatic or twinwall glazings that contain pigments.

Table 3. DSET Laboratories test specimens.

Tests	**Material 1 (outside)**	**Material 2 (inside)**	**Description**
1	White Acrylic (0.118 in)	--	
2	Clear Acrylic (0.118 in)	--	
3	Clear Acrylic	White Acrylic	Assembly with 1/16” air gap.
4	Clear Acrylic	White Acrylic	Same as above with 1” gap
5	Bronze Acrylic (0.116 in)	--	

Tests	Material 1 (outside)	Material 2 (inside)	Description
6	White PET (0.117 in)	--	
7	Thicker (0.225 in) prismatic	--	Prisms facing light
8	Thicker (0.225 in) prismatic	--	Prisms away from light
9	Thinner (0.117 in) prismatic	--	Prisms facing light
10	Thinner (0.117 in) prismatic	--	Prisms away from light
11	Thicker (0.225 in) prismatic	Thinner (0.117 in) prismatic	Material 1 prisms facing away from light, 1/16" gap, Material 2 with prisms facing light
12	Thicker (0.225 in) prismatic	Thinner (0.117 in) prismatic	Same as above with 1" gap
13	Twinwall (0.241 in) polycarbonate	--	
14	Fiberglass (2.75 in) assembly	--	Side with no fill (more transmitting)
15	Fiberglass (0.67 in) sheet	--	Avoid scratch
16	Prismatic (0.18 in) diffuser	--	Prisms facing light
17	Prismatic (0.18 in) diffuser	--	Prisms away from light

In combining more than one glazing layer in a test, we are deviating from the ASTM D1003 test procedure. The test procedure is developed for single layers of glazing only. We wanted to know if we could get reasonable results by combining the layers and altering the spacing of the gap between layers.

We also wanted to compare the performance of prismatic glazings with the prisms pointed towards and away from the source of light. It was hypothesized that pointing the prismatic side towards the light source would increase visible transmittance as the prisms may act like light traps similar to those used to boost the output of photovoltaic cells. (Campbell & Green, 1987, Parretta et al. 2003)

When the twinwall polycarbonate glazing (test No. 13) was tested, it was measured twice – once with the "flutes" or tubes facing up and another with the tubes oriented horizontally – the results were then averaged. It was thought this may reduce any systematic error related to orientation.

Standard Visible Transmittance (T_{vis}) Test using Sunlight

Tait Solar conducted the Standard Visible Transmittance tests on skylights outdoors using the sun as the light source. The purpose of measuring the standard visible transmittance values of the skylight products was to compare the difference in light transmittance performances of flat glazing samples (DSET Laboratories Standard Visible Transmittance Test) to the transmittance of glazing after it has been formed and installed in a skylight. Does the skylight glazing forming process or the different test procedure result in vastly different measured transmittances?

Methodology

The Standard Visible Transmittance Test was conducted according to ASTM E972-88 *Standard Test Method for Solar Photometric Transmittance of Sheet Materials Using Sunlight* and ASTM E1084 *Standard Test Method for Solar Transmittance (Terrestrial) of Sheet Materials Using Sunlight.* It should be noted that the standard calls for flat, single layered product samples. Therefore these test results cannot be officially referenced as "tested according to the ASTM E972-88 standard". There is no equivalent ASTM test standard for the complex skylight glazing systems tested.

ASTM E972-88 requires that visible transmittance be tested at direct-normal incident angle. The procedure requires measuring the illuminance values, with the sample in place, and then without the sample. This is referred to as the "full sun" value. The ratio of these two measurements determines the visible transmittance.

When the measurement is taken with the sample in place, the illuminance sensor is held 50mm (2") from the inner surface. According to an Advisory Group member, this method can result in a significant loss (as much as 15%) in transmissivity as compared to placing the sensor directly touching the inner surface.

The light meters used were LI-COR Model LI-210SA Photometric Sensors. These light sensors are cosine corrected up to 80° angle of incidence and have a sensitivity response function that is within 5% of the CIE $V\lambda$ photometric efficiency function.

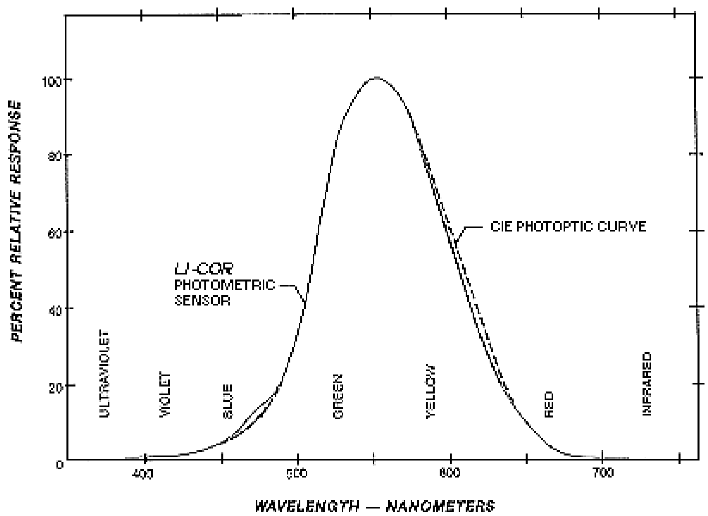


Figure 16. Spectral response of LI-COR photometric sensor and the CIE photometric curve.

Both flat glass and curved glazing products were measured. For the skylight products that had curved glazing materials, the measurements were made from the inside and outside surfaces of the skylight to minimize possible errors from the concentration or spreading of the transmitted light due to the material curvature. Five measurements were made from both the concave (interior) side and five were made from the convex (exterior) side (see Figure 17). These ten readings were averaged. These five measurements were taken on relatively flat sections of glazing that were as close as possible to the four corners and the center of the skylight glazing to account for the varying thickness of the material around the curvature.

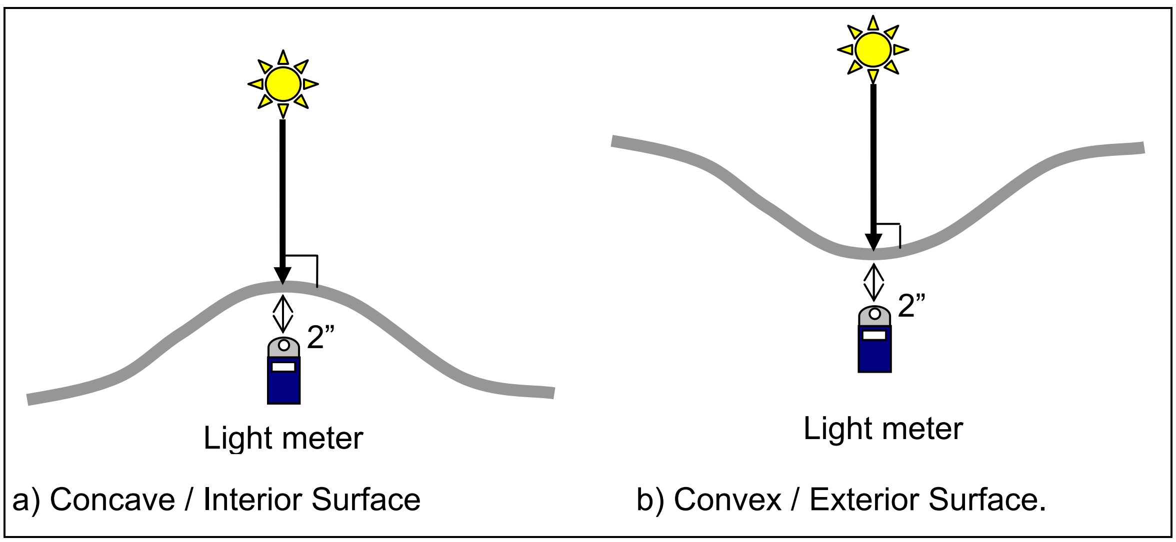


Figure 17. Light meter position in Standard Visible Transmittance test

Since the ASTM E 972-88 standard requires normal direct incident angle conditions, the skylight has to be rotated so that the section of the skylight glazing being measured is perpendicular to the rays of the sun (see Figure 18).

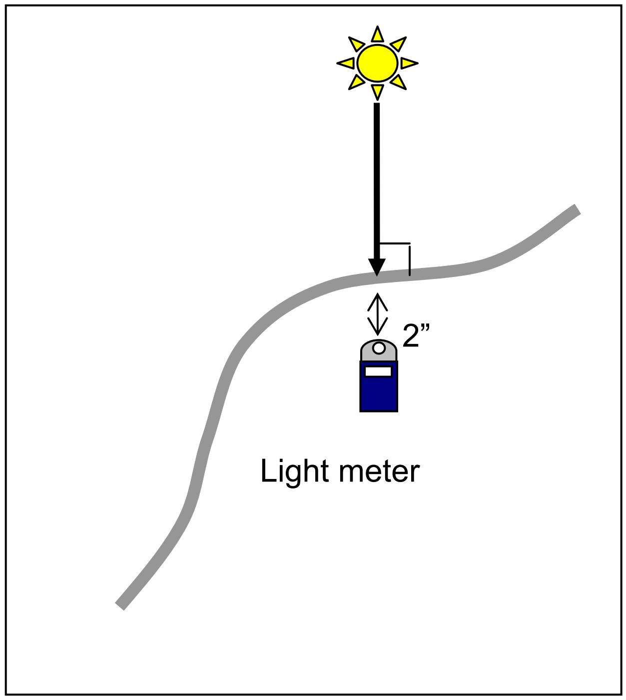


Figure 18. Diagram of Standard Visible Transmittance test with sunlight at normal incidence to the glazing.

Test Specimens

Table 4. lists the eight sample skylights tested. These are the same skylights that also were tested for Effective Visible Transmittance of the skylighting system including the skylight and light well. This sample of skylights includes a variety of commercial skylight shapes and glazing materials. For images of the test samples, refer to Figure 19 to Figure 25 below.

Table 4. Standard Visible Transmittance test -- description of skylights

Type	Dimension	Material	Color	Shape
A	4' x 4'	Double-glazed Low-E glass	Clear	Flat - horizontal
B	31" x 39"	Double-glazed Low-E glass	Clear	Flat - 20° slope
C	4' x 4'	Single-glazed Acrylic	Medium-white (color 2447)	Dome
D	4' x 4'	Double-glazed Acrylic	Outer – clear Inner – medium white (color 2447)	Dome
E	4' x 4'	Double-glazed Prismatic Acrylic	Clear, with 12 prismatic pattern on the inside surfaces.	Catenary Arch Dome
F	4' x 4'	Fiberglass insulating panel, with no fiberglass batt filling between sheets	Crystal over Crystal	Pyramid
G	4' x 4'	Structured Polycarbonate "Twinwall" Glazing	Clear	Pyramid
H	4' x 4'	Non-diffusing Acrylic Sheets	Bronze	Pyramid

Figure 19. Double-glazed low-e flat skylight – Type A

Figure 20. Single-glazed white acrylic dome skylight – Type C.

Figure 21. Double-glazed white acrylic dome skylight – Type D.

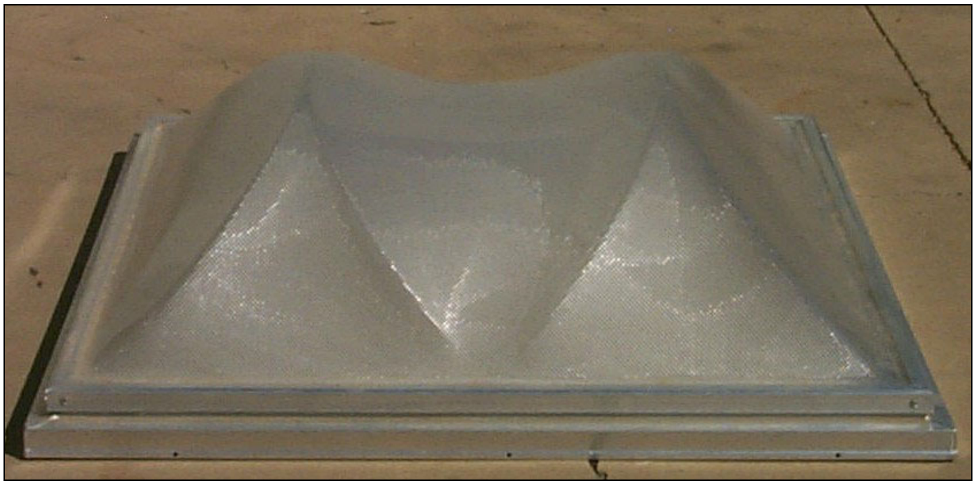


Figure 22. Double-glazed prismatic acrylic arch skylight – Type E.


Figure 23. Fiberglass pyramidal skylight – Type F.


Figure 24. Twinwall polycarbonate pyramidal skylight – Type G.

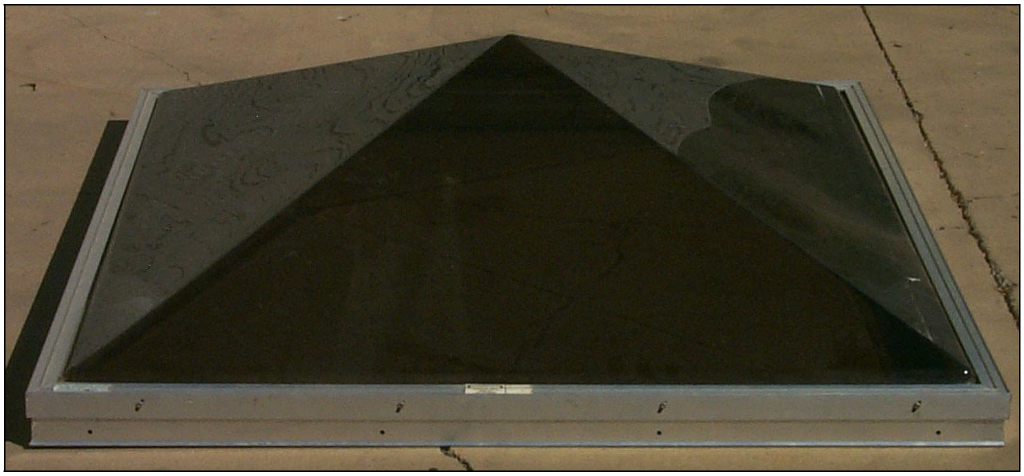


Figure 25. Bronze acrylic pyramidal skylight – Type H.

Effective Visible Transmittance (EVT) Skylight Test

The effective visible transmittance, EVT, test describes the light transmittance of the skylighting system including the skylight, the light well and any diffusers that may be in the light well. Thus EVT testing accounts for the effects of skylight shape, skylight framing, well efficiency and diffuser transmittance. By testing skylights in installed configurations, it also gives results of varying solar conditions and typical skylight installations that reflect "real life" conditions. This provides information on how skylights tested in various rating protocols actually perform as installed in buildings.

Since we were interested in configurations typical for commercial buildings, we obtained commercial sized skylights and mounted them as they would be on the roof of a commercial building. In general, the unit skylights installed on commercial buildings are at least 4 foot wide, thus we tested 4 foot by 4 foot skylights. Most commercial buildings have low slope roofs, thus we mounted the skylights horizontally. We also varied the light well height from 1 foot (essentially no well, just the curb depth) to 6 feet (a moderately deep well). Some commercial skylights have prismatic diffusers placed at the bottom of the light well so we tested diffusers in a couple of cases.

Methodology

We did not find any predefined test standard for measuring EVT. However the concept is relatively simple. The EVT is the ratio of the luminous flux exiting the bottom the light well to the ambient luminous flux impinging on the horizontal projection of the skylight rough opening.

The ambient luminous flux impinging on the horizontal projection of the skylight rough opening is the product of the ambient total horizontal radiation and the rough opening area of the skylight. The ambient luminous flux in lumens is given by:

$$\text{Ambient Luminous Flux} = E_{TH} \times A_{RO}$$

where,

E_{TH} = Total ambient (outdoor) horizontal illuminance, footcandles (lux)

A_{RO} = Horizontal projection of skylight rough opening, sf (m^2)

The luminous flux exiting the bottom the light well is the product of the average illuminance measured at the bottom of the light well and the area of the opening at the bottom of the light well. The exiting luminous flux in lumens is given by:

$$\text{Exiting Luminous Flux} = \frac{\sum_{i=1}^{N} EG_i}{N} \times A_{Grid}$$

where,

EGi = the illuminance at the i^{th} sensor of the grid of sensors at the bottom the light well, footcandles (lux)

N = number of illuminance sensors that make up the illuminance grid at he bottom the light well

A_{Grid} = area of the bottom of the light well, sf (m^2)

Given the definitions of Exiting Luminous Flux and Ambient Luminous Flux, Effective Visible Transmittance is readily calculated as:

$$EVT = \frac{\text{Exiting Luminous Flux}}{\text{Ambient Luminous Flux}} = \frac{\frac{\sum_{i=1}^{N} EG_i}{N} \times A_{Grid}}{E_{TH} \times A_{RO}}$$

To measure EVT accurately, it is important that ambient total horizontal illuminance, E_{TH}, and average illuminance exiting the light well be measured simultaneously. Since there can be substantial gradients in the illuminance exiting the bottom of the light well, the greater the number of sensors in the grid of interior illuminance meters, the better.

Since diffusing glazings smooth the distribution of light to a wider range of angles, the spatial gradient of illuminance at the bottom of the light well will be diminished. Thus measurement error will be less for diffusing skylights as compared to clear (non-diffusing) skylights. Diffusers placed at the bottom of the light well will have less impact because the diffuser is 2” away from the sensor and cannot spread the light in such a small gap. Tall diffusely reflecting light wells will have better exiting luminous flux measurement accuracy than specularly lined light wells due to the light distribution smoothing effect of diffuse reflections.

Test Equipment

The EVT of different skylights and skylight well combinations were measured simultaneously with measurements of solar heat gain. A description of the solar gain measurements is the topic of another PIER report (McHugh, Saxena & Dee 2002). The main impact of measuring solar gains is that the grid of light sensors was placed at the bottom of the skylight well at the opening of the Skylight Solar Calorimeter. Figure 26 illustrates the position of the light sensor grid relative to the other components that comprised the Skylight Solar Calorimeter Test System (SSCTS).

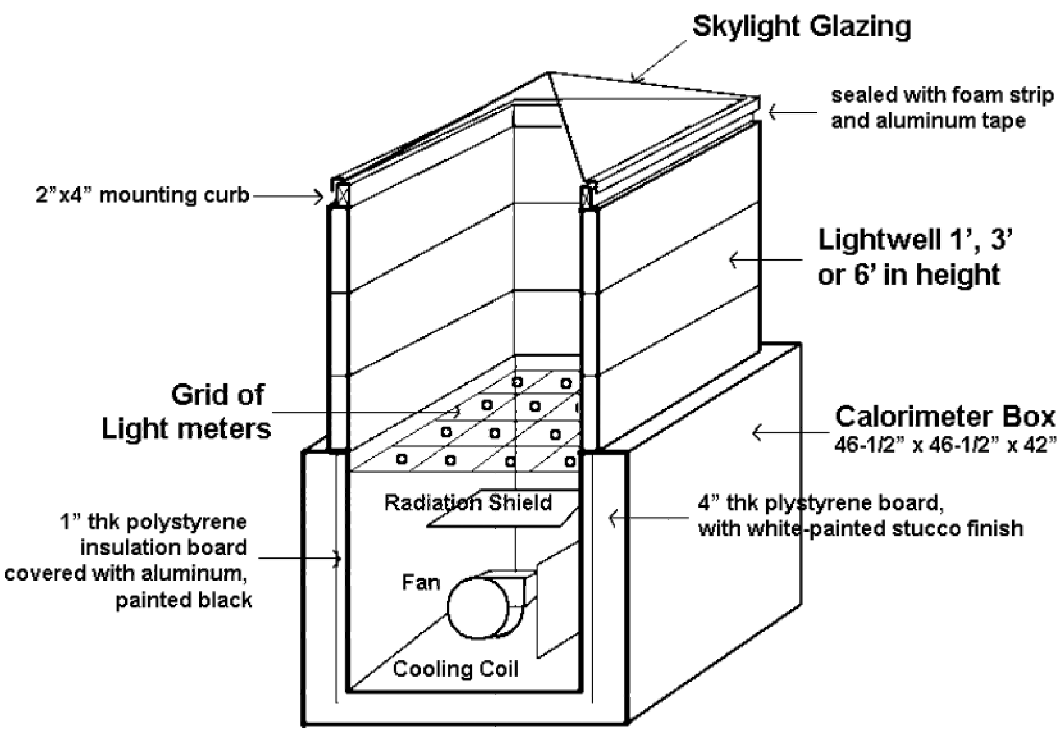


Figure 26. Cut-away isometric of the Skylight Solar Calorimeter Test System (SSCTS)

The calorimeter box is a heavily insulated test box with inside dimensions of 46-1/2" length by 46-1/2" width by 42" height. The inside box wall surfaces are made of 1" thick high-density polystyrene insulation board that has been covered with an aluminum sheet, and painted flat black for absorption. The bottom of the box has an additional ½" thick high-density polystyrene board. The outside box structure is made of 4" thick high-density polystyrene board finished with white-painted stucco for weather-protection. The 16 light sensors in the light well are held in place by an aluminum grid that kept the sensors evenly spaced. This light sensor grid was located above a radiation shield that was painted black – thus the grid of light sensors is above a black cavity.

The skylight samples were equipped with an attached 2"x4" mounting curb. The bottom edge of the skylight curbs had an adhesive-backed foam strip to prevent air and light leakage. The skylight samples were placed on the top of the skylight well and secured in place with mechanical fasteners to prevent movement.

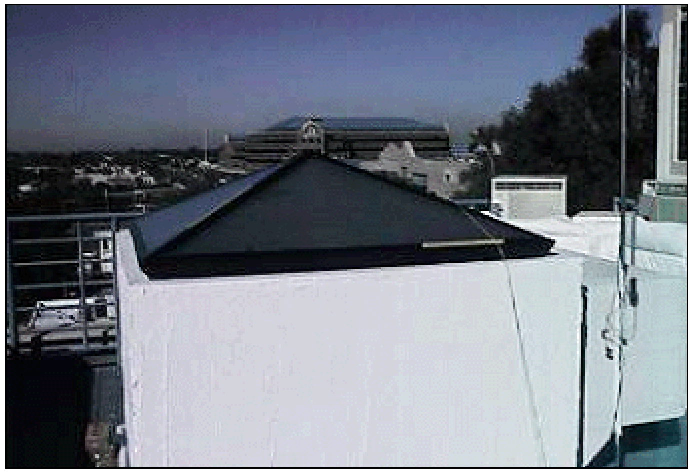


Figure 27. Photo of exterior of calorimeter box.

Sixteen light meters were mounted inside the calorimeter box, slightly below the ceiling diffuser level. The spacing of the interior light meters is shown in Figure 28.

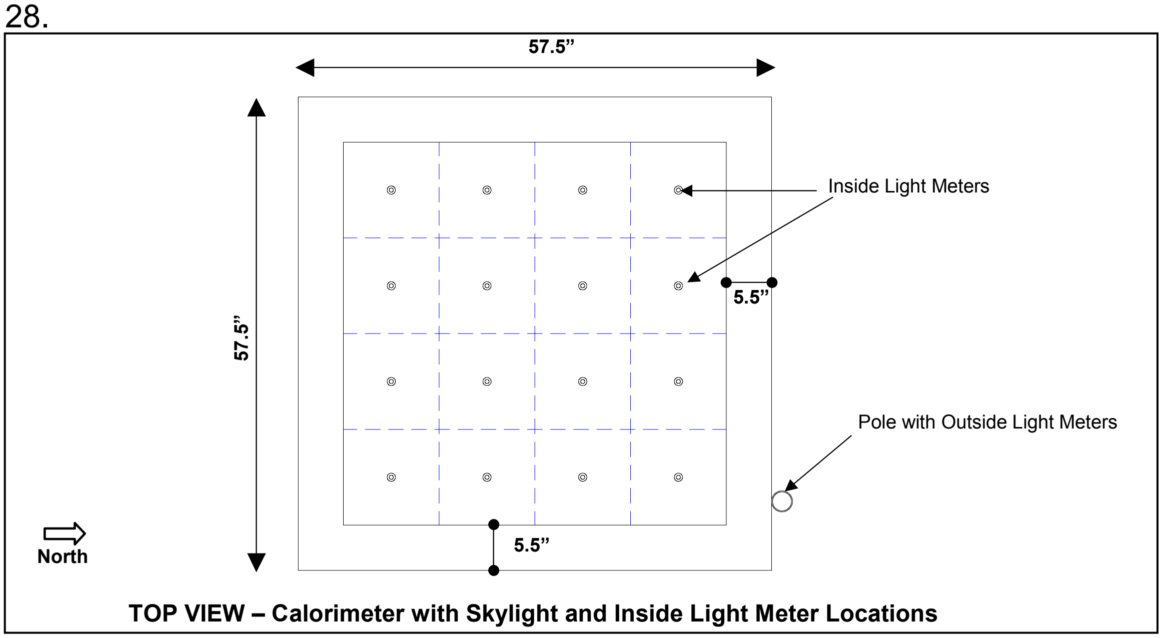
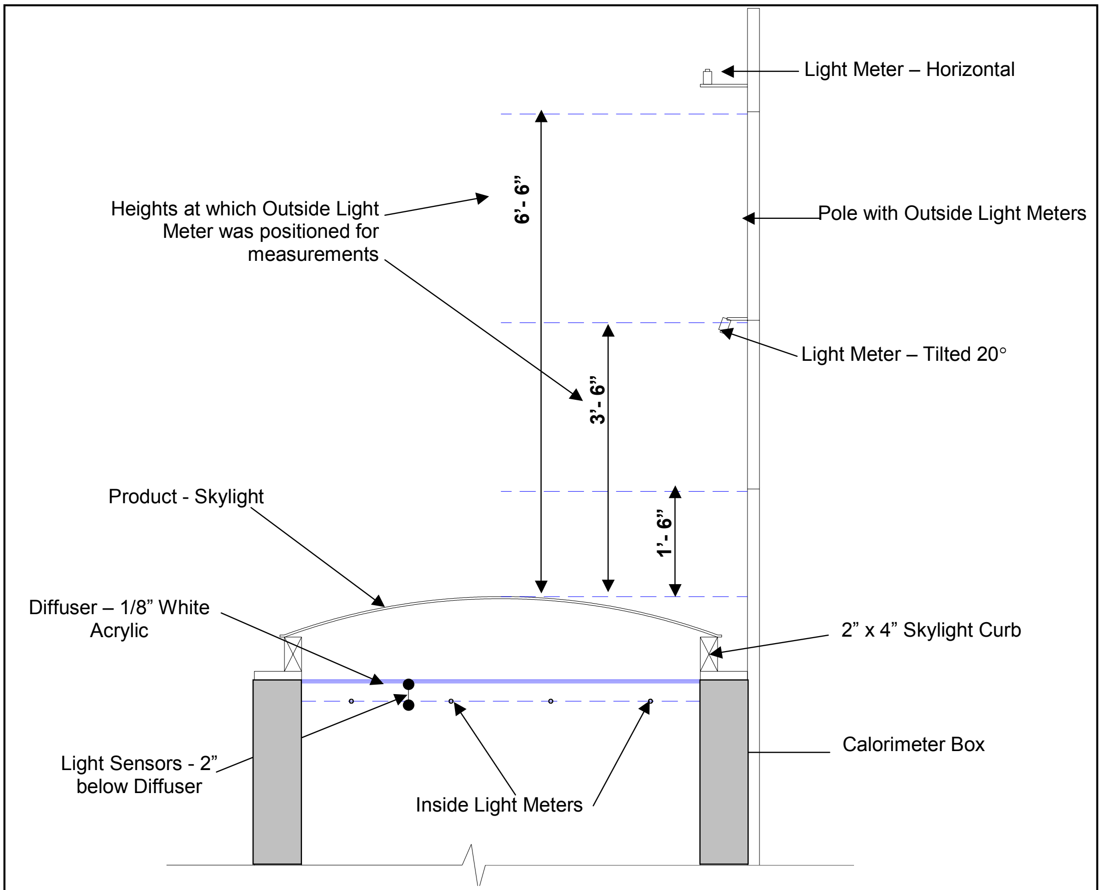


Figure 28. Grid of light meter installed in the calorimeter box (plan view).

Two additional light meters were mounted on the outside of the test system to take ambient illuminance measurements. One meter is measuring total horizontal illuminance and the other meter is measuring illuminance on a 20° tilted plane. The tilted light meter measures the light incident on the one flat skylight that has an adapter to impart a 20° tilt to the skylight. See Figure 29 for light meter configurations. As shown is that horizontal light meter height is maintained at a constant 6 inches above the top of the skylight.



Sectional Side View – Calorimeter with Skylight showing location of Inside and Outside Light Meters and Diffuser Location

Figure 29. Diagram of light meter installations in EVT skylight testing (side view).

The light meters used were Licor Model LI-210SA Photometric Sensors. As can be seen in Figure 16, the spectral response of these sensors is very close (within 5% under most light sources) to the spectral response of the eye as represented by the CIE photometric curve. This sensor is also cosine-corrected up to an 80° angle of incidence. The current signals from the sensors were converted into voltages as they passed through a precision resistor. These voltages were measured and recorded by a HP 34970A data acquisition system.

Test Specimens

Table 5 lists the descriptions of the 24 VLT tests that were conducted on the eight sample skylights. Twenty of the tests used a white diffusing inner surface on the skylight wells leaving four tests with a highly reflective inner skin on the skylight well surfaces. The conditions unique to each skylight test are the tilt, well height, well surface (reflective / specular or flat white), and whether a diffuser was installed at the bottom of the lightwell.

Table 5. Tait Labs Standard Light Transmittance test configurations.

Test No.	Material	Well Height	Well Surface	Diffuser (yes or no)
1	Double-glazed Low-E glass - flat	3'	Diffuse	No
2	Double-glazed Low-E glass - tilt	3'	Diffuse	No
3	Double-glazed Low-E glass - flat	3'	Specular	No
4	Double-glazed Low-E glass - tilt	3'	Specular	No
5	Single-glazed White Acrylic Dome	1'	Diffuse	No
6	Single-glazed White Acrylic Dome	3'	Diffuse	No
7	Single-glazed White Acrylic Dome	6'	Diffuse	No
8	Double-glazed Acrylic Dome	1'	Diffuse	No
9	Double-glazed Acrylic Dome	3'	Diffuse	No
10	Double-glazed Acrylic Dome	6'	Diffuse	No
11	Single-glazed White Acrylic Dome	3'	Specular	No
12	Single-glazed White Acrylic Dome	6'	Specular	No
13	Single-glazed White Acrylic Dome	3'	Specular	Yes
14	Single-glazed White Acrylic Dome	6'	Specular	Yes
15	Double-glazed Prismatic Acrylic, Catenary Arch	1'	Diffuse	No
16	Double-glazed Prismatic Acrylic, Catenary Arch	3'	Diffuse	No
17	Double-glazed Prismatic Acrylic, Catenary Arch	6'	Diffuse	No
18	Fiberglass Panel - Pyramid	1'	Diffuse	No
19	Fiberglass Panel - Pyramid	3'	Diffuse	No
20	Fiberglass Panel - Pyramid	6'	Diffuse	No
21	Polycarbonate “Twinwall” Pyramid	1'	Diffuse	No
22	Polycarbonate “Twinwall” Pyramid	3'	Diffuse	No
23	Bronze Acrylic Sheets	3'	Diffuse	No
24	Bronze Acrylic Sheets	3'	Diffuse	Yes

Skylight Photometry Test

Photometric information, a description of the angular distribution of light from a source, is the basis of predicting how that light source will light a space. Photometric distributions describe the directionality and the magnitude of light from a given lighting source. Almost all electric light fixtures sold in the United States have a photometric report. This photometric information allows one to calculate how the light fixtures shall distribute light in a room. As part of this same PIER skylight testing program, Lighting Sciences Inc. conducted photometric tests on 22 skylight/light well combinations which resulted in photometric data files and reports for each of these combinations at various sun angles (McHugh 2003b). One metric generated by the photometric report is the “luminaire” efficiency which is equivalent to the effective visible transmittance of the skylight/light well system.

Methodology

The Illuminating Engineering Society of North America (IESNA) has documented the photometric test practices for most lighting devices in its Light Measurement (LM) series. However, there is no established test standard for measuring the photometric distributions from skylights. The essence of measuring photometric distributions is to measure the luminous flux (lumens) of the source and once stabilized to install this source in a luminaire. The luminous intensities (candela) that are emitted by the luminaire are measured at regular angular intervals on a goniophotometer. The goniophotometer as shown in Figure 30 has sensors that measure light at 10º vertical angle intervals and the goniophotometer is rotated in 22.5º increments to capture these measurements in a full hemisphere beneath the skylight opening. (McHugh 2003b)

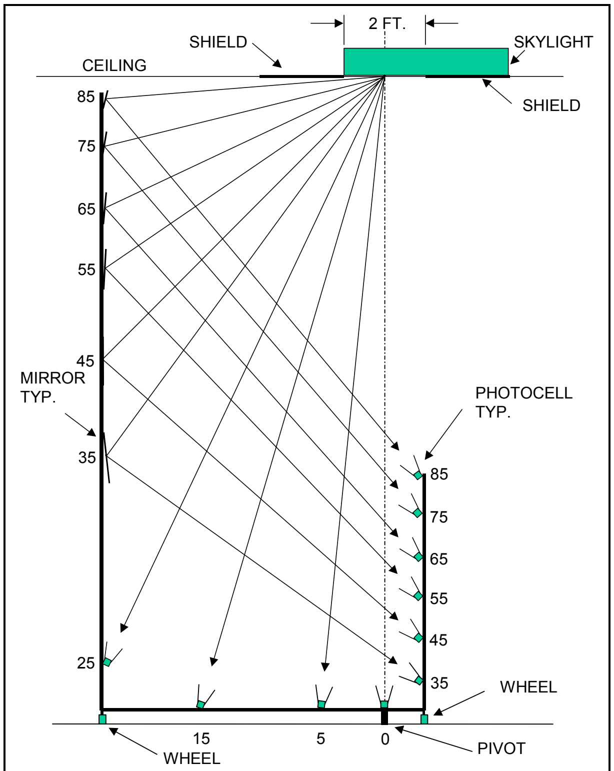


Figure 30. Skylight Goniophotometer

In general, the light output of the source is stabilized and well defined before the luminous intensities are measured from a luminaire. However, in this case the source, the sun, is constantly changing. Instead of measuring absolute values of luminous intensities for a source of a fixed luminous flux, the luminous intensities exiting the bottom of the skylight and the luminous flux impinging on the horizontal projection of the skylight surface are simultaneously measured. These luminous intensities are then normalized by the luminous flux so that the photometric distribution intensities are in units of candelas per 1,000 lumens impinging on the top of the skylight. (Domigan et al 2002)

Test Specimens

Similar to the other tests, the single glazed white acrylic skylight was combined with the most permutations of light well conditions. In addition to measuring the total luminous flux beneath the skylight, the primary purpose of these tests was to document the effect skylight shape and light well configuration have on distribution of light from the skylighting system. Most of these specimens are the same as the skylights tested by Tait Solar for EVT except that this series of tests also includes a white PET compound parabolic arch skylight.

Table 6. Photometric testing – Skylight description and well conditions

Test No.	Skylight Description	Well and other description
1	Flat glass double low-e, double glazed, clear low-e glass	1 ft deep white light well
2	Flat glass double low-e, double glazed, clear low-e glass	3 ft deep white light well
3	Flat glass double low-e, double glazed, clear low-e glass	6 ft deep white light well
4	Flat glass double low-e, double glazed, clear low-e glass	6 ft deep white light well w/ bottom diffuser
5	Dome, single glazed, white acrylic glazing	1 ft deep white light well
6	Dome, single glazed, white acrylic glazing	3 ft deep white light well
7	Dome, single glazed, white acrylic glazing	6 ft deep white light well
8	Dome, single glazed, white acrylic glazing	3 ft deep silver light well
9	Dome, single glazed, white acrylic glazing	6 ft deep silver light well
10	Dome, single glazed, white acrylic glazing	3 ft deep silver light well with bottom diffuser
11	Dome, single glazed, white acrylic glazing	6 ft deep silver light well with bottom diffuser
12	Dome, double glazed, clear acrylic over white acrylic glazing	1 ft deep white light well
13	Compound parabolic, clear prismatic acrylic over clear prismatic acrylic glazing	Major axis perpendicular to ridges, 1 ft deep white light well
14	Compound parabolic, clear prismatic acrylic over clear prismatic acrylic glazing	Major axis perpendicular to ridges, 6 ft deep white light well
15	Compound parabolic, clear prismatic acrylic over clear prismatic acrylic glazing	Major axis perpendicular to ridges, 1 ft deep white light well
16	Pyramid, fiberglass insulating panel glazing with no fill	1 ft deep white light well
17	Pyramid, fiberglass insulating panel glazing with no fill	6 ft deep white light well
18	Pyramid, twinwall structured polycarbonate glazing	1 ft deep white light well
19	Pyramid, twinwall structured polycarbonate glazing	6 ft deep white light well
20	Pyramidal, single glazed, bronze acrylic glazing	3 ft deep white light well
21	Compound parabolic, single glazed, medium white PET glazing	Major axis perpendicular to ridges, 1 ft deep white light well
22	Compound parabolic, single glazed, medium white PET glazing	Major axis perpendicular to ridges, 1 ft deep white light well

RESULTS

DSET Laboratories Standard Visible Transmittance (T_{vis}) Test

As shown in Table 7, prismatic acrylic (except double-glazed prismatic with a 1" gap), clear acrylic and twinwall polycarbonate glazings have the highest transmittances, T_{vis}. The bronze acrylic skylight and the fiberglass assembly have the lowest transmittances.

Table 7. Results of DSET Laboratories' Standard Visible Transmittance test.

Test	Materials	Thickness in Inches	% T_{vis}	% Haze	% Clarity
1	White Acrylic	0.118	62.6	100	18.7
2	Clear Acrylic	0.118	94.9	0.3	99.8
3	Clear Acrylic outside, White Acrylic inside – 1/16" gap	0.298	59.4	100	17.7
4	Clear Acrylic outside, White Acrylic inside – 1" gap	1.236	58.0	100	17.0
5	Bronze Acrylic	0.116	28.2	1.5	99.7
6	White PET	0.117	48.8	100	6.4
7	Thicker prismatic prisms facing light	0.225	95.3	96.7	57.2
8	Thicker prismatic prisms away from light	0.225	84.8	98.1	61.1
9	Thinner prismatic prisms facing light	0.117	96.6	97.2	13.9
10	Thinner prismatic prisms away from light	0.117	87.7	97.2	15.0
11	Thicker prismatic outside, thinner inside – 1/16" gap	0.404	80.0	99.7	7.5
12	Thicker prismatic outside, thinner inside – 1" gap	1.342	45.5	100	9.3
13	Twinwall polycarbonate (clear)	0.241	83.6	33.2	80.9
14	Fiberglass assembly (crystal over crystal no fill)	2.750	29.2	92.2	13.4
15	Fiberglass sheet (crystal)	0.067	79.1	69.0	23.5
16	Prismatic diffuser prisms facing light (clear)	0.180	93.3	97.4	4.9
17	Prismatic diffuser prisms away from light (clear)	0.180	85.8	97.2	5.1

The materials that provide best wide-angle diffusion are those with high haze values and include prismatic glazing and diffusers, white acrylic, double-glazed acrylics, white PET, and fiberglass assembly. Those samples with the lowest measured haze are the clear acrylic and the bronze acrylic. Though not measured, the glass used in the skylights test would have extremely low haze values. Many of the materials that provide high levels of wide angle scattering, also provide high levels of narrow angle scattering as defined by clarity. The lower the clarity number, the greater the narrow angle scattering. Ideally a diffusing glazing provides both high levels of haze and low levels of clarity.

The following analysis were derived from the data:

- Prismatic lenses with prisms facing the light perform about 10% better than when the prisms face away from the light.
- Layered diffusing materials have a higher tested visible transmittance when the gap between layers is smaller. This is an artifact of the test method and not an actual reduction in the amount of light transmitted. The reasons for this are discussed later in this section.
- Though they are a commonly used skylight glazing material, pigmented white acrylic materials perform satisfactorily, with a T_{vis}. around 60%.

Table 8. Ranking of test specimens according to haze rating.

Test	Material	Specimen Code	% Haze
1	White Acrylic	A	100
3	Clear and White Acrylic 1/16" gap	A + B	100
4	Clear and White Acrylic 1" gap	A + B	100
6	White PET	D	100
12	Thinner and Thicker prismatic 1" gap	E + F	100
11	Thinner and Thicker prismatic 1/16" gap	E + F	99.7
8	Thicker prismatic prism away fr light	E	98.1
16	Prismatic diffuser prism facing light	J	97.4
9	Thinner prismatic prism facing light	F	97.2
10	Thinner prismatic prism away from light	F	97.2
17	Prismatic diffuser prism away from light	J	97.2
7	Thicker prismatic prism facing light	E	96.7
14	Fiberglass assembly	H	92.2
15	Fiberglass sheet	I	69
13	Twinwall polycarbonate	G	33.2
5	Bronze Acrylic	C	1.5
2	Clear Acrylic	B	0.3

As can be seen in Table 8, there is a very obvious demarcation in haze ratings of existing skylight materials. Most of the test specimens are either above 92% or below 70% haze. The haze properties of less diffusive materials fall rapidly below 70%. Thus the concern expressed about the 2% error generated by measuring the haze of highly diffusing glazings is not important when making a clear separation between diffusing and non-diffusing glazings.

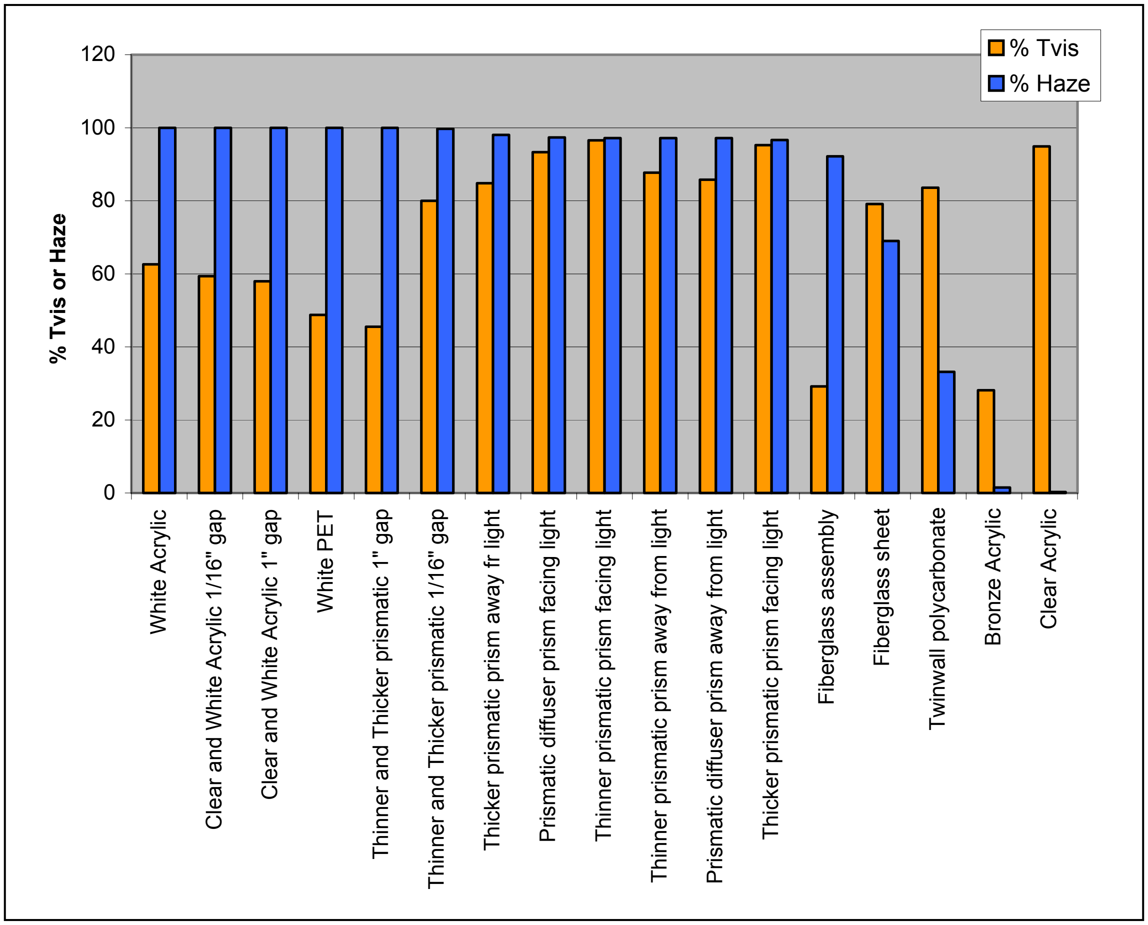


Figure 31. T_{vis} and haze rating of test specimens.

Figure 31 plots the visible transmittance and haze values from the DSET Labs tests and is sorted by haze, from greatest haze on the left to the least diffusing on the right. On the left side of the plot is medium white plastic, the traditional commercial glazing material, which provides moderate transmittance and very high diffusion (haze = 100%). The clear prismatic materials provide significantly higher visible transmittance but somewhat less diffusion (haze in upper 90 percentile).

When multiple glazings are measured together as an assembly, changing the spacing from 1/16” to 1” reduced measured transmittance slightly for clear over white acrylic but reduced measured transmittance significantly for prismatic over prismatic glazings.

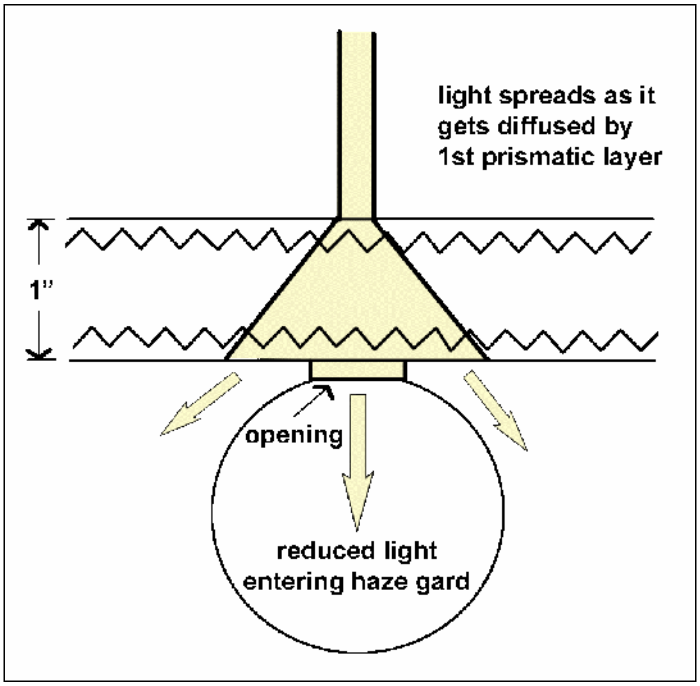


Figure 32. Light transmission of double-glazed prismatic glazing (1" gap).

When the outer layer is diffusing, as with a prismatic 1st layer, the light is not directly transmitted in a straight line but is spread due to the diffusing prismatic surface. The wider the gap between layers, the wider the light has spread before impinging onto the 2nd prismatic layer for light measurement (see Figure 32). The wider the gap between diffusing glazing layers, the greater the fraction of light that is spread beyond the opening in the Haze-Gard measurement apparatus. This reduction in measured light is an artifact of the measurement process not of the transmittance of the glazing assembly. Thus if one wishes to test the visible transmittance of multiple layers, one must minimize the gap between layers. Thus in Figure 31, the tests with the 1/16" gap should be used as representative of the transmittance of double glazed assemblies, even if the spacing between glazings is further apart as installed in a skylight.

Standard Visible Transmittance (Tvis) Test

The results of the standard transmittance test are contained in Table 9. To determine whether it is important to measure both front side and backside transmittance, we have included the transmittance measured from the interior of the skylight, T_{vis} interior, and the average of the transmittances of tested from the inside and the outside, T_{vis} average. The difference in values of the T_{vis} interior and T_{vis} average is minimal, with a maximum of 4.2% difference

Using this test method, we achieved results similar to the results using ASTM D1003. In both tests bronze skylights have the lowest light transmittance, while prismatic skylights have the highest transmittance.

Skylight B, the double Low-E glass skylight tested at a 20° slope has a higher transmittance than the larger horizontally mounted skylight. The larger glass skylight, skylight A, has a lower transmittance due to a plastic interlayer added for more strength.

Table 9. Results of Standard Visible Transmittance Test.

Skylight Code	Dim	Material	Color	Shape	Tvis interior	Tvis average
A	4' x 4'	Double-glazed Low-E glass	Clear	Flat - horizontal	0.467	0.459
B	31" x 39"	Double-glazed Low-E glass	Clear	Flat - 20 deg slope	--	0.583
C	4' x 4'	Single-glazed Acrylic	Medium-white (color 2447)	Dome	0.542	0.531
D	4' x 4'	Double-glazed Acrylic	Outer – clear Inner – medium white (color 2447)	Dome	0.505	0.474
E	4' x 4'	Double-glazed Prismatic Acrylic	Clear, with prismatic pattern 12 on the inside surfaces.	Catenary Arch Dome	0.671	0.713
F	4' x 4'	Fiberglass insulating panel	crystal over crystal fiberglass glazing, without batt filling	Pyramid	0.443	0.474
G	4' x 4'	Structured Polycarbonate "Twinwall" Glazing	Clear	Pyramid	0.634	0.667
H	4' x 4'	Non-diffusing Acrylic Sheets	Bronze	Pyramid	0.254	0.239

Effective Visible Transmittance (EVT) Skylight Test

Though Tait Solar tested the EVT of skylights over the course of a day, the EVT summary in Table 10, is for a solar elevation of 30 degrees. This angle was selected for two reasons:

1. It was desired to compare skylights at the same solar elevations as the EVT changes with respect to sun angle. The skylight/well configurations were tested at different times of year and data for 30° was available for all the tests.
2. As shown in Figure 8 "Frequency of solar altitudes in San Diego, CA and Eureka, CA." The most frequent solar elevation is around 30°. Thus the EVT at a sun elevation of 30º is more representative of annual skylight performance than measurements taken at higher or lower elevations.

Table 10. Results of calorimeter box EVT test at 30° solar elevation.

Test No.	Material	Well Height	Well Surface	Diffuser (yes or no)	EVT
1	Double-glazed Low-E glass - flat	3'	Diffuse	No	0.151
2	Double-glazed Low-E glass - tilt	3'	Diffuse	No	0.056
3	Double-glazed Low-E glass - flat	3'	Specular	No	0.253
4	Double-glazed Low-E glass - tilt	3'	Specular	No	0.111
5	Single-glazed White Acrylic Dome	1'	Diffuse	No	0.445
6	Single-glazed White Acrylic Dome	3'	Diffuse	No	0.291
7	Single-glazed White Acrylic Dome	6'	Diffuse	No	0.26
8	Double-glazed Acrylic Dome	1'	Diffuse	No	0.367
9	Double-glazed Acrylic Dome	3'	Diffuse	No	0.269
10	Double-glazed Acrylic Dome	6'	Diffuse	No	0.144
11	Single-glazed White Acrylic Dome	3'	Specular	No	0.462
12	Single-glazed White Acrylic Dome	6'	Specular	No	0.409
13	Single-glazed White Acrylic Dome	3'	Specular	Yes	0.354
14	Single-glazed White Acrylic Dome	6'	Specular	Yes	0.31
15	Double-glazed Prismatic Acrylic, Catenary Arch	1'	Diffuse	No	0.298
16	Double-glazed Prismatic Acrylic, Catenary Arch	3'	Diffuse	No	0.218
17	Double-glazed Prismatic Acrylic, Catenary Arch	6'	Diffuse	No	0.113
18	Fiberglass Panel - Pyramid	1'	Diffuse	No	0.139
19	Fiberglass Panel - Pyramid	3'	Diffuse	No	0.12
20	Fiberglass Panel - Pyramid	6'	Diffuse	No	0.058
21	Polycarbonate “Twinwall” Pyramid	1'	Diffuse	No	0.311
22	Polycarbonate “Twinwall” Pyramid	3'	Diffuse	No	0.193
23	Bronze Acrylic Sheets	3'	Diffuse	No	0.079
24	Bronze Acrylic Sheets	3'	Diffuse	Yes	0.061

An analysis of the test results above can be summarized as follows:

- With four foot wide by four foot long vertical light wells with diffusing surfaces, EVT is reduced on average by 28% from a 1 foot tall light well to a 3 foot tall light well and by 56% from 1 feet to a 6 foot tall light well (See Figure 33).
- With the same skylight unit and light well depths, specular light wells are more efficient than diffusive light wells at directing daylight into the space. Measured EVTs of systems with specular light wells are 57% greater than those with diffusing light wells.
- Predictably, diffusers decrease the EVTs of skylight systems. In the systems tested above, the EVT decreased by 23%. This is close to what would be expected since the measured transmittance of the diffuser is 86%.

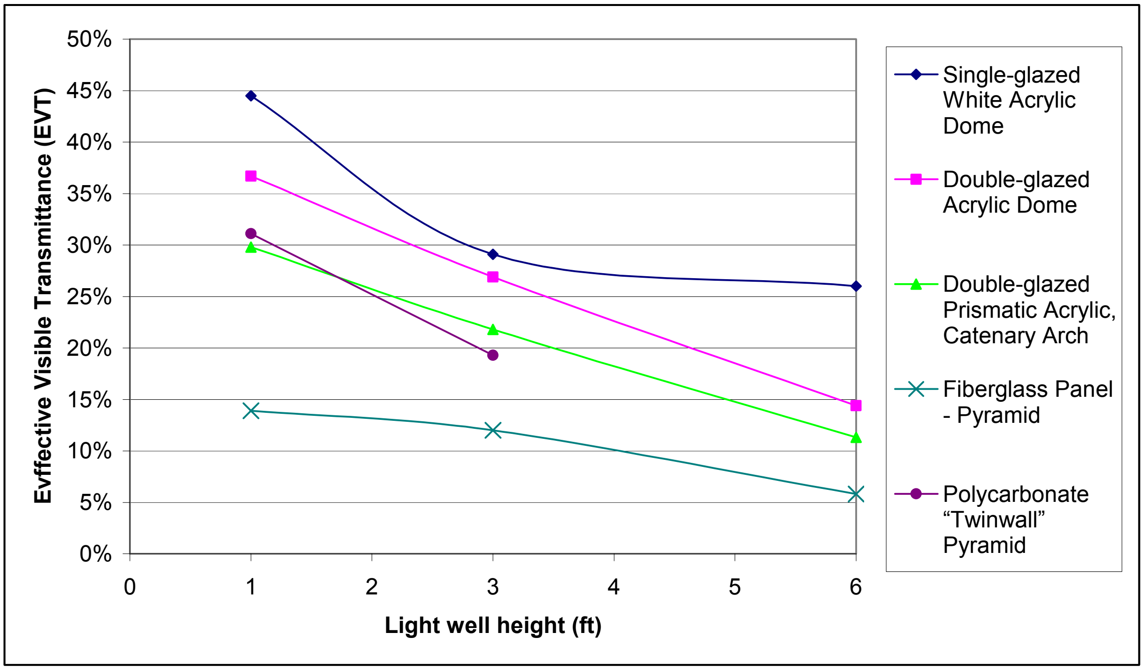


Figure 33. EVT as a function of diffusing well height at 30 solar altitude.

As mentioned in the introductory section of the report, existing test protocols assume that skylights are flat glass, without consideration for varying solar angles. The results in Table 11 and plotted in Figure 34 show that different skylights have a marked different relationship between effective visible transmittance and solar altitude. This is perhaps the most important finding is this report.

The EVT for Test 1, a flat horizontal glass similar to the assumptions used in current calculation methods, show results that are very similar to simulated skylight performance. When the skylight is horizontal as it was for these tests, the incident angle to the glazing is simply the zenith angle. The angular transmittance of the flat glass skylight drops off significantly as solar altitude decreases (incident angle increases). In contrast, the visible transmittance for the dome skylights is relatively constant with respect to solar elevation

Table 11. Results of Tait Labs EVT tests over a range of solar altitudes

EVT By 10 Degree Solar Altitude Angles										
Sample Test No.	**Solar Altitude Angle ***									
	0	**10**	**20**	**30**	**40**	**50**	**60**	**70**	**80**	**90**
1		0.116	0.116	0.151	0.190	0.263	0.355			
2		0.048	0.042	0.056	0.074	0.086	0.153			
3		0.144	0.191	0.253	0.460	0.535				
4		0.077	0.074	0.111	0.153	0.203	0.280			
5		0.529	0.479	0.445	0.431	0.430	0.432			
6		0.437	0.327	0.291	0.281	0.282	0.290			
7		0.505	0.299	0.260	0.244	0.224				
8		0.394	0.385	0.367	0.372	0.388	0.408	0.426		
9		0.343	0.288	0.269	0.258	0.275	0.284			
10		0.175	0.151	0.144	0.147	0.155				
11		0.582	0.494	0.462	0.457	0.459				
12		0.545	0.445	0.409	0.402	0.390				
13		0.442	0.377	0.354	0.351	0.354				
14		0.412	0.337	0.310	0.308	0.314				
15		0.456	0.312	0.298	0.341	0.414	0.508	0.636		
16		0.257	0.214	0.218	0.241	0.301	0.381			
17		0.129	0.111	0.113	0.132	0.175				
18		0.127	0.120	0.139	0.176					
19		0.161	0.122	0.120	0.128	0.146	0.174			
20		0.059	0.054	0.058	0.066	0.077				
21		0.330	0.298	0.311	0.384	0.469	0.619			
22		0.223	0.186	0.193	0.223	0.257	0.376			
23		0.078	0.070	0.079	0.092	0.128	0.149			
24		0.056	0.053	0.061	0.069	0.091				

Projecting skylights have shapes that are not flat, and thus, there is no single angle of incidence for any sun angle. The angle of incidence of beam sunlight for any solar elevation changes with respect to location on the surface of the skylight. Thus calculations models that attempt to base projecting skylight transmittance on glazing transmittance are necessarily complex because of the changing incident angles with respect to position on the skylight. Laouadi & Atif (2001) have done just this and have calculated EVTs as shown in Figure 35, that were greater than 100% for dome skylights at low incidence angles. The results for our set of skylights were not that extreme but we did find that the EVT of projecting skylights was dramatically different from flat skylights and approached the shape that Laoudi and Atif have calculated. This is an important finding since the work of Laoudi and Atif is the basis of the dome skylight model in the skylighting software SkyVision.

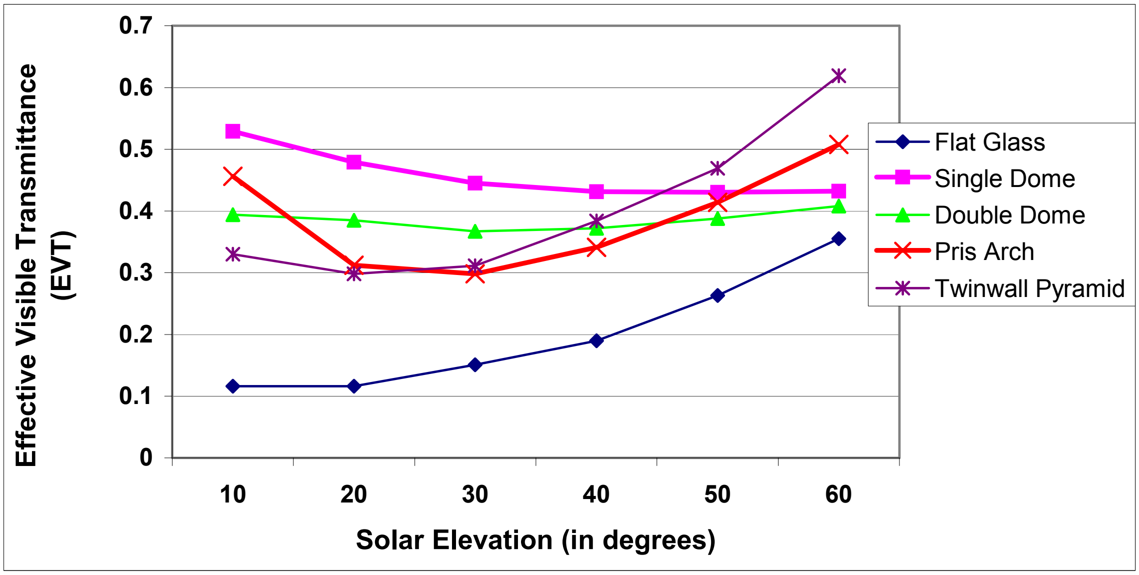


Figure 34. Performance of various skylights over varying sun angles.

When the sun is at a lower elevation, ambient daylight illuminance is also lower. Thus higher visible transmittances are needed at low solar elevations and lower visible transmittances are desirable at high solar elevations when there is an overabundance of daylight illuminance.

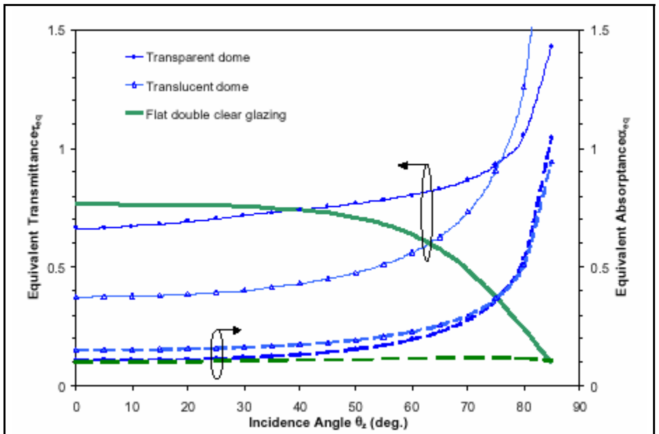


Figure 35. Dome Skylight Equivalent Transmittance (Laouadi & Atif 2001)

By graphing the EVTs of different skylight glazings at varying sun angles, we can predict that projecting skylights will yield better visible transmittance at low solar elevations when it is needed the most (see Figure 34).

- Dome skylights had higher EVTs at low sun elevations than at moderate of high sun elevations.
- Compound arch skylights had higher EVT's at low and high sun elevations than at moderate solar elevations.
- Glass and pyramidal twinwall polycarbonate skylights have lower transmittance at low sun angles and higher transmittance at high sun angles.

ANALYSIS

Comparison of Test Methods

This section compares the various test methods and whether they provide mutual verification. For instance, if one performs goniophotometric measurements to develop photometric files, when is it desirable to take a separate measurement of effective visible transmittance?

Flat Sample Testing (DSET) vs. Curved Sample Manual Testing

For all test materials, the measured T_{vis} of flat samples consistently showed higher values than samples of complex shapes. This may be due to a systematic error in the calibration of the measurement equipment for either test. The notable exception to this rule is the Haze Gard measurements on the fiberglass insulating panel. The effect of multiple glazing layers spreading the light away from the integrating sphere opening and how it reduces the measurement of visible transmittance is illustrated in Figure 32 and described in the accompanying text.

For most of the test samples, T_{vis} measured from the interior resembles the DSET test results more closely than T_{vis} average.

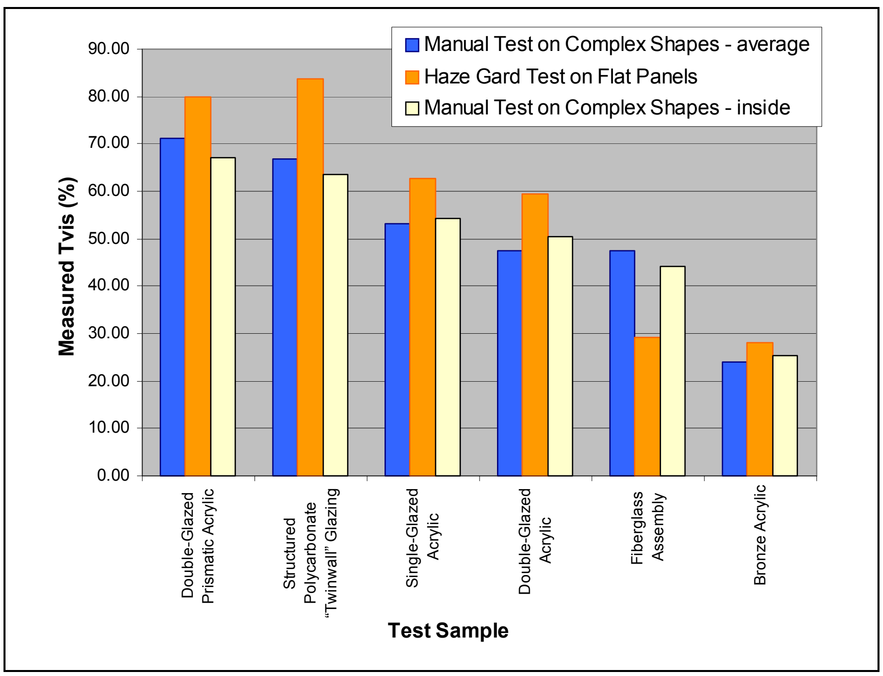


Figure 36. Comparison of T_{vis} of flat samples and curved samples.

Calculated T_{vis} of Flat Glass vs. Window 5.0 model

This analysis allows us to determine whether the test methods we used in this research yield results similar to the Window 5.0 software's calculated results. Since Window 5.0 assumes flat glass models, we compare its calculated results to the measured data for the double-glazed flat glass samples.

The first T_{vis} value is calculated from the EVT for varying solar angles as measured using ASTM E972. The second Tvis value is calculated from the EVT for varying solar angles as measured using photometric testing.

The general trend of T_{vis} is that it is increasing as the solar elevation increases, and this is consistent for all three measures. The difference among the different methodologies is the shape of the curve. Window 5.0 and T_{vis} from photometric testing show similar trends, except that Window 5.0 values flatten out as the sun gets higher overhead. T_{vis} from ASTM E972 testing shows the reverse pattern, with flatter T_{vis} at lower sun angles.

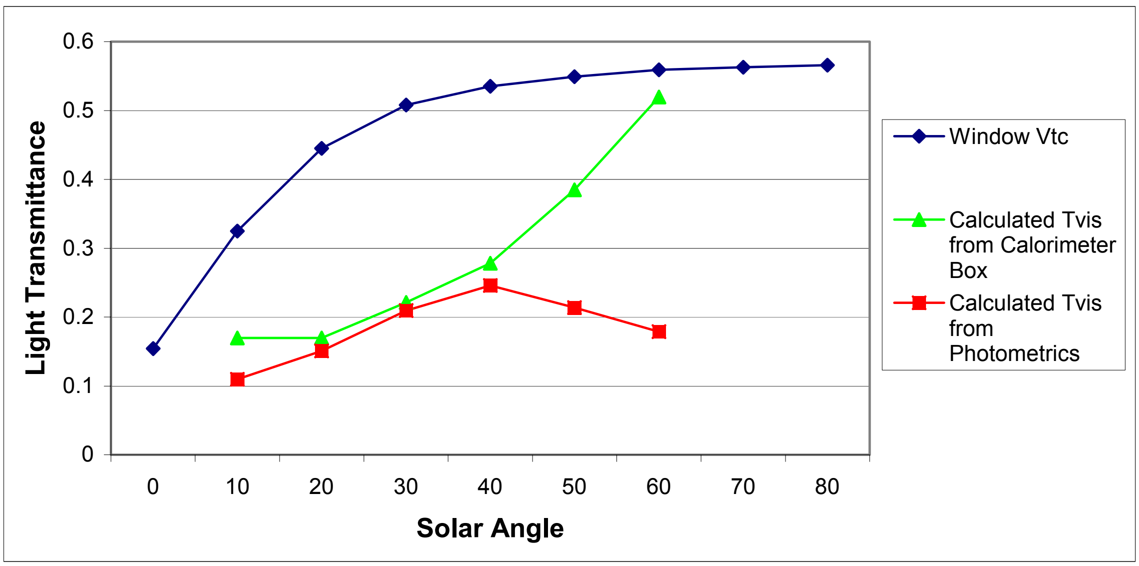


Figure 37. Comparison of T_{vis} over varying solar angles - Window software vs. calculations from calorimeter box and photometric testing.

EVT from Calorimeter Box vs. Photometric Efficiency

Both the EVT measured via a grid of photometers and the skylight efficiency measured by the goniometric test refer to the same physical effect which is the fraction of light that impinges on the horizontal projection of the skylight opening that makes it through the bottom of the light well. In both tests, the amount of light (lumens) that impinges on the horizontal projection of the skylight opening is measured the same way: horizontal illuminance (foot-candles) is measured and multiplied by the horizontal projection of the skylight opening (square feet).

The two tests differ in how they measure the light (luminous flux in lumens) exiting the bottom of the light well. The EVT test measures the illuminance at the opening at the bottom of the light well by a grid of 16 illuminance meters. Each illuminance meter is representative of one square foot of light well opening. By multiplying the foot-candles of each illuminance meter by their representative area and summing this up across all 16 meters, yields the overall luminous flux (lumens) that leaves the bottom of the light well.

The goniophotometer sweeps an array of photometers mounted at different vertical angles azimuthally underneath the skylight. Measurements of luminous intensity (candela) are taken at regular intervals in positions that describe a hemisphere centered at the light well opening. Each measurement of luminous intensity has a solid angle (steradians) to which it corresponds. Multiplying the luminous intensity measurements by their corresponding solid angles yields the luminous flux (lumens) for a patch on the goniometric hemisphere that corresponds to the measurement taken at a given vertical and horizontal angle. Summing all of the luminous fluxes (lumens) on the hemisphere yields the total light in lumens leaving the bottom of the light well.

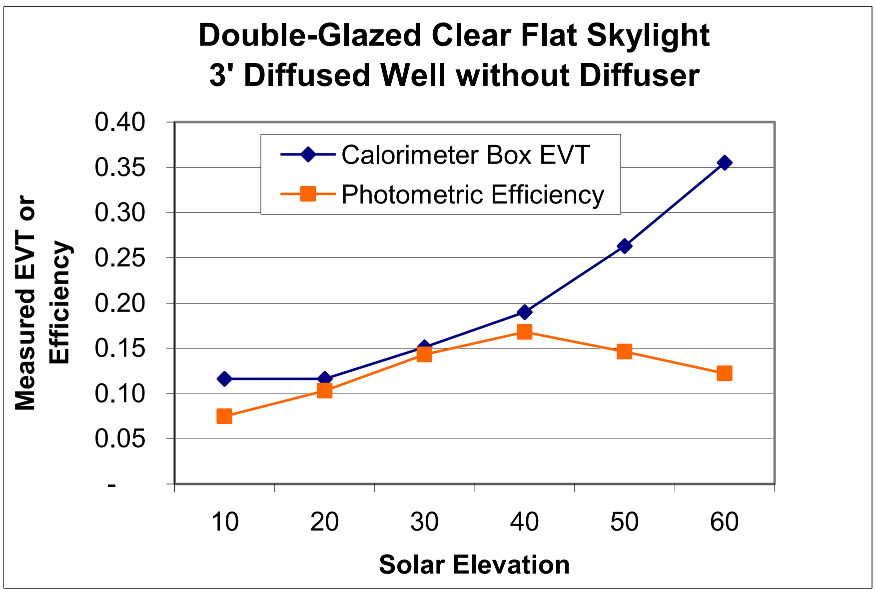


Figure 38. Plot of EVT and photometric efficiency of flat glass skylight

An evaluation of Calorimeter Box EVT values shows more consistent performance over varying solar elevations than do photometric efficiency values which tend to fluctuate more. The EVT and photometric efficiency graph in Figure 38 is for a clear skylight over a 3 foot tall light well and with no bottom diffuser. This figure shows clearly the problems that result from applying photometric principles to a non-diffusing source. At low sun elevations, all the sunlight is reflected off of the diffusing white surfaces of the light well. Under this situation, the light is well diffused and obeys the assumption of far field photometry reasonably well and the photometric efficiency matches reasonably well with EVT effective visible transmittance measured in the calorimeter. At higher sun elevations, collimated light directly enters the room below the calorimeter and is registered by the calorimeter. Thus the EVT and photometric efficiency start to diverge.

Since the solid angle represented by the sensors near the nadir are smaller than the solid angles higher up on the goniometric sphere, the luminous flux calculated by measurements at the bottom of the goniometric sphere are smaller than those on the sides. As the solar elevation increases and shafts of light are registered by these lower sensors, the photometric efficiency decreases. Since the distribution of light violates the assumptions underlying the photometric test method, the photometric efficiency results for a clear skylight are erroneous.

The Appendix contains plots of photometric efficiency and EVT with respect to sun angle for other skylight and light well combinations.

Table 12. Comparison of Effective Visible Transmittance values using calorimeter box and photometrics testing at 30° solar altitude.

Ref No.	Material	Well Height	Well Surface	Diffuser (yes or no)	Calorimeter Box EVT	Photometric Efficiency
11	Single-glazed White Acrylic Dome	3'	Specular	No	0.462	0.362
5	Single-glazed White Acrylic Dome	1'	Diffuse	No	0.445	0.464
12	Single-glazed White Acrylic Dome	6'	Specular	No	0.409	0.345
13	Single-glazed White Acrylic Dome	3'	Specular	Yes	0.354	0.493
21	Polycarbonate "Twinwall" Pyramid	1'	Diffuse	No	0.311	0.239
14	Single-glazed White Acrylic Dome	6'	Specular	Yes	0.310	0.427
15	Double-glazed Prismatic Acrylic, Arch	1'	Diffuse	No	0.298	0.437
15r	Double-glazed Prismatic Acrylic, Arch Rotated	1'	Diffuse	No	0.291	0.379
6	Single-glazed White Acrylic Dome	3'	Diffuse	No	0.291	0.289
7	Single-glazed White Acrylic Dome	6'	Diffuse	No	0.260	0.160
1	Double-glazed Low-E glass - flat	3'	Diffuse	No	0.151	0.143
18	Fiberglass Panel - Pyramid	1'	Diffuse	No	0.139	0.178
17	Double-glazed Prismatic Acrylic, Catenary Arch	6'	Diffuse	No	0.113	0.462
23	Bronze Acrylic Sheets	3'	Diffuse	No	0.079	0.069
20	Fiberglass Panel - Pyramid	6'	Diffuse	No	0.058	0.085

It should be noted that though the solar elevation was the same for each of these comparisons, the measurement of photometric efficiency and calorimeter EVT were not taken on the same day. Thus the azimuthal location of the sun will be different for the calorimeter EVT and photometric efficiency tests. In general, there is a good match between calorimeter EVT and photometric efficiency. Only test 17 (double glazed prismatic arch) shows a marked difference, this is likely due to testing error and should be considered an outlier. However the other tests on the prismatic skylight (tests15 and 15r) result in a fairly large deviation between the results from the two test methods. The transmittance of the prismatic arch may have more sensitivity to azimuthal sun position than other shapes. Alternatively the refracted light from the prismatic glazing is somewhat collimated and thus this violates a key assumption of the photometric test method that the object measured is a source that has light expanding spherically from its center. If this is indeed the issue, this would imply that the calorimeter EVT method is a more robust method of measuring system overall transmittance as it is less impacted by the distribution of light exiting the light well.

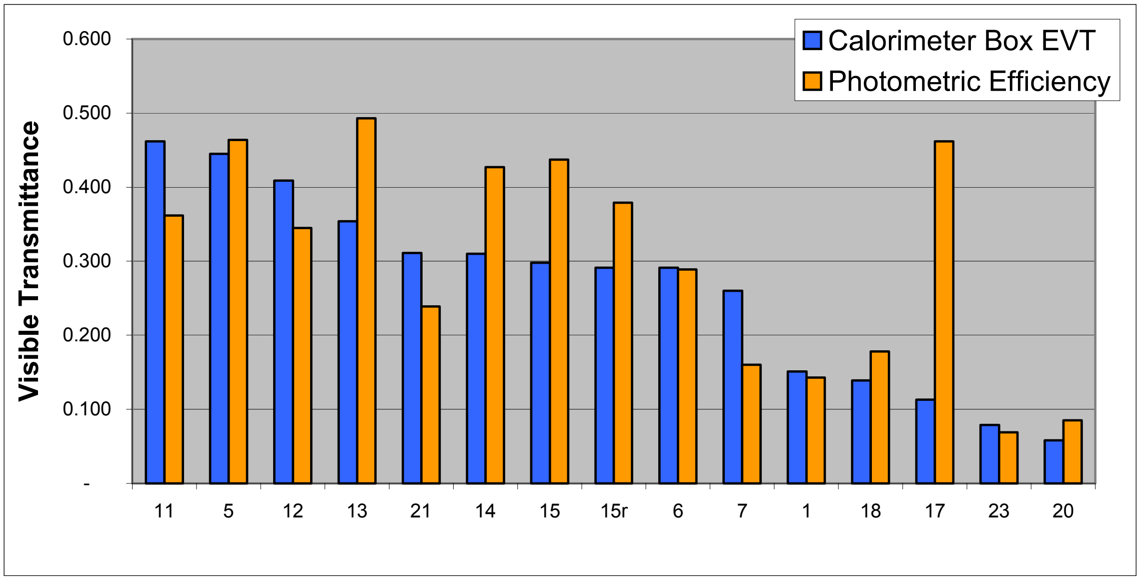


Figure 39. Comparison of Effective Visible Transmittance values using calorimeter box and photometrics testing at 30° solar altitude.

Relationship between Visible Transmittance of Glazing and EVT

One would expect that the visible transmittance of glazing would correlate well with the EVT of a skylighting system. In general this is true but as illustrated earlier in Figure 34, the shape of skylights has a significant effect on their EVT. Table 13 tabulates the measured glazing visible transmittance and the effective visible transmittance (EVT) of the same skylight over a 3 foot light well with white diffusing surfaces. As described earlier the EVT was measured at a solar elevation of 30º as this sun angle is near the median and mode of solar elevations over the course of the year in the lower 48 United States.

The data in Table 13 has been sorted by EVT in descending order from highest EVT to lowest. Though the single glazed acrylic dome had the third highest glazing visible light transmittance, its shape is more efficient at capturing light at 30° solar elevation (60° angle of incidence from the skylight normal) than the other skylights and thus it has the highest EVT. Though the dome's visible transmittance is only 16% greater than that of the flat glass skylight, its effective visible transmittance at a 30 solar elevation is almost twice that of the glass skylight.

However, when compared to a similar shape, such as the comparison between the double and single glazed dome, EVT correlates well with T_{vis}. The single dome has a 12% greater visible transmittance and a 7% greater EVT. The structured polycarbonate glazing has a 40% greater visible transmittance than the fiberglass insulating panel and a 58% greater visible transmittance. Since the shape of the two skylights is similar, it is thought that the lower EVT for the fiberglass insulating panel pyramid is due to framing members inside each of the fiberglass insulating panels being opaque and not very reflective. As the incident angle increases, the transmittance of the assembly drops off rapidly.

Table 13. Comparison of Glazing T_{vis} and Skylight EVT

Skylight Code	Dim	Material	Shape	Tvis interior	Tvis average	EVT 3 ft well, sun 30 deg
C	4' x 4'	Single-glazed Acrylic	Dome	0.542	0.531	0.29
D	4' x 4'	Double-glazed Acrylic	Dome	0.505	0.474	0.27
E	4' x 4'	Double-glazed Prismatic Acrylic	Catenary Arch	0.671	0.713	0.22
G	4' x 4'	Structured Polycarbonate "Twinwall" Glazing	Pyramid	0.634	0.667	0.19
A	4' x 4'	Double-glazed Low-E glass	Flat - horiz.	0.467	0.459	0.15
F	4' x 4'	Fiberglass insulating panel	Pyramid	0.443	0.474	0.12
H	4' x 4'	Non-diffusing Bronze Acrylic	Pyramid	0.254	0.239	0.08

Thus the primary lesson to be gained from this comparison is that visible transmittance of glazing is important but so is skylight shape on the performance of the skylighting system. The bronze glazing, with the lowest visible transmittance, was also the poorest performer in terms of EVT.

Validation of EVT Measurements with Well Efficiency

The effective visible transmittance of the skylight/light well system can be thought of as combining the transmittance of two elements that are in series with each other. Thus the overall EVT is the product of the EVT of the skylight itself and the fraction of light that is transmitted by the light well, otherwise known as the well efficiency.

$$\mathrm{EVT}_{\mathrm{Skylight+Well}} = \mathrm{EVT}_{\mathrm{skylight}} \times \mathrm{Well\ Efficiency}$$

The effective visible transmittance of the skylight alone can be found by measuring the effective visible transmittance of the skylight with no light well. The well efficiency for a light well with diffuse (matte) surfaces can be calculated using the Lumen Method algorithm as published in the IESNA Lighting Handbook. The key assumptions of this method are:

- Light emanating from the bottom of the skylight is perfectly diffuse (Lambertian distribution)
- Each surface in the skylight well is diffusely reflecting
- Each major surface of the skylight is uniformly illuminated

Since the calculation method is fairly involved, a nomograph of well efficiency with respect to light well reflectance and well cavity ratio (WCR) is published in the daylighting chapter of the IESNA Handbook (2000). The well cavity ratio quantifies the relative depth of a light well (actually surface area of side walls as compared to its cross-sectional area). The well cavity ratio is given by the following relation:

$$WCR = 5 \times \frac{Height \times (Length + Width)}{Length \times Width}$$

A tall narrow light well has a high WCR and a wide, short light well has a low RCR. For the same reflectance, a light well with a high RCR will have a lower well efficiency than one with a low RCR.

The IESNA nomograph provides curves for 40%, 60% and 80% well surface reflectance. To calculate well efficiency at other reflectances, one must interpolate between the lines and no guidance is given for extrapolating at reflectances higher than 80%. We made use of the well efficiency calculations that are contained in the SkyCalc freeware, to calculate the well efficiency very accurately. SkyCalc calculates the light well efficiency as a coefficient of utilization for a cavity that has a Lambertian emitter as the top plane (the underside of the skylight), a ceiling reflectance of 99%, a wall reflectance equal to the average reflectance of surfaces in the light well and a floor reflectance of 0%. (Heschong & McHugh 2000)

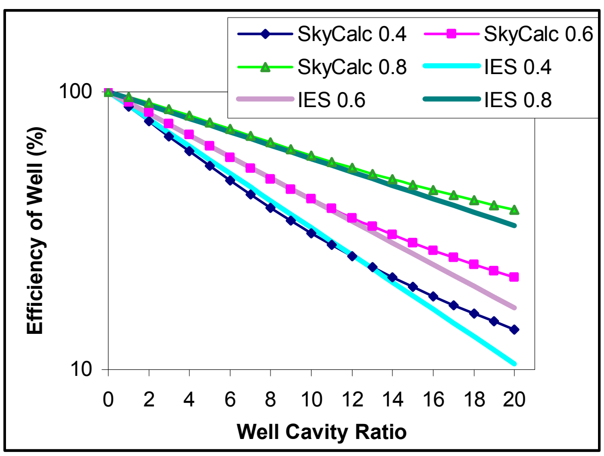


Figure 40. Well efficiencies for various well reflectances in SkyCalc *and in the IESNA Handbook*

As shown in Figure 40, this method of calculating well efficiency closely correlates with the well efficiency table in the IESNA Handbook (2000) at low well cavity ratios. At high well cavity ratios, the shape of the divergence from the values in the IESNA handbook is similar to that published by Serres and Murdock (1990). This method allows for a direct calculation of well efficiency without interpolation of a non-linear function. Thus we can calculate the well efficiencies at reflectances higher than 80%.

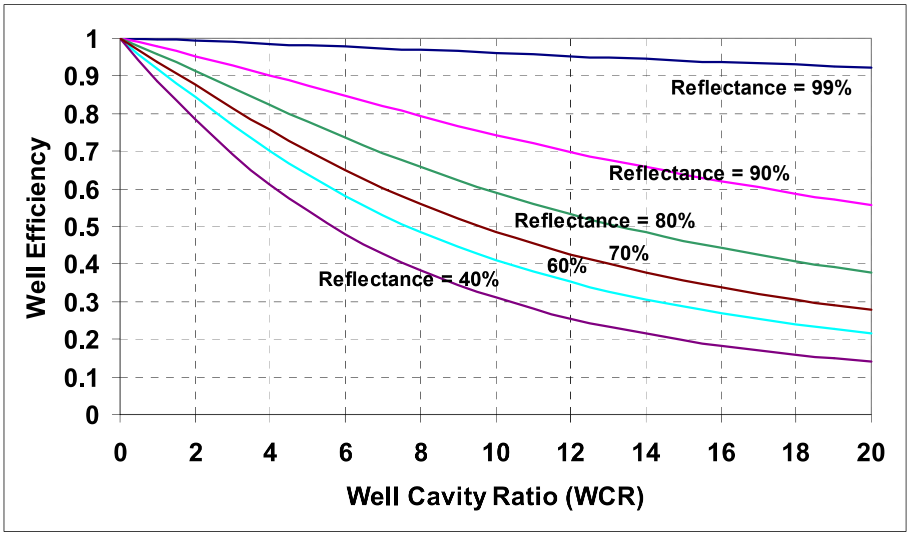


Figure 41. Well efficiency graph

Given that we have the EVT for a given light well and skylight combination, one should be able to calculate what the EVT should be for the same skylight over a light well with a different height or reflectance. Since the calculation of light well efficiency is pretty well established, one way of validating the EVT measurements is to compare the overall EVT for a given skylight over light wells of different heights and see how closely the change in EVT matches the change in light well efficiency.

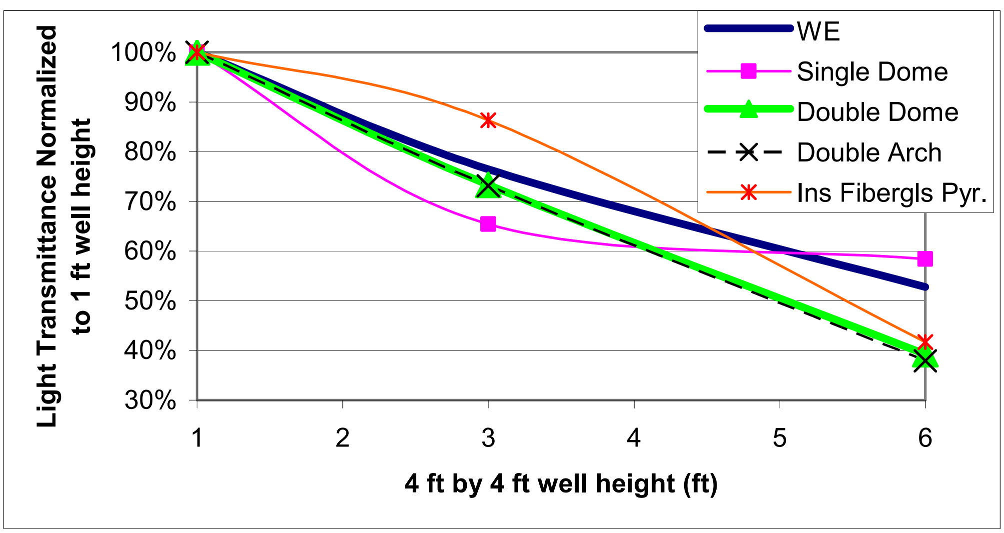


Figure 42. Comparison of well efficiency to normalized EVT

Such a comparison is illustrated in Figure 42, for four skylights that were tested over 1, 3, and 6 foot tall light wells painted with white diffusing paint with a reflectance of 81%. These light wells, which are 4 feet wide and 4 feet long and have heights of 1, 3, and 6 feet, have well cavity ratios of 2.5, 7.5 and 15 respectively. The EVT's of each skylight type were normalized relative to the light transmittance of the skylight over a 1 foot well; the EVT's of each skylight/light well combination were divided by the EVT of that skylight over a 1 foot light well. Thus the normalized light transmittance of each skylight over a 1 foot light well is 100%. The same normalizing process was applied to the calculation of well efficiency for different light well heights.

In viewing Figure 42, one can see that the EVT's of skylights over diffusing wells diminish according to an increase in well height at approximately the same relative decrement as does the well efficiency. The maximum error for a 3 foot well height is 14% and the maximum error at 6 foot well height is 28%.

Overall the skylight normalized EVT's are distributed around the normalized well efficiencies. Thus without testing at other light well heights, extrapolating EVT's using well efficiency appears to be method that yields reasonable results without excessive error.

Well Efficiency and Solar Altitude

This analysis compares the angular response of well efficiency. The hypothesis being that diffusing skylights over a diffusing light well will have fairly constant well efficiency regardless of sun angle. Figure 43 shows that the EVT's are relatively constant with respect to solar altitude except for 10 degrees. As a result the ratios of EVT are relatively constant. The dome skylight was chosen in that the dome is relatively insensitive to changes in solar azimuth that could confound the results.

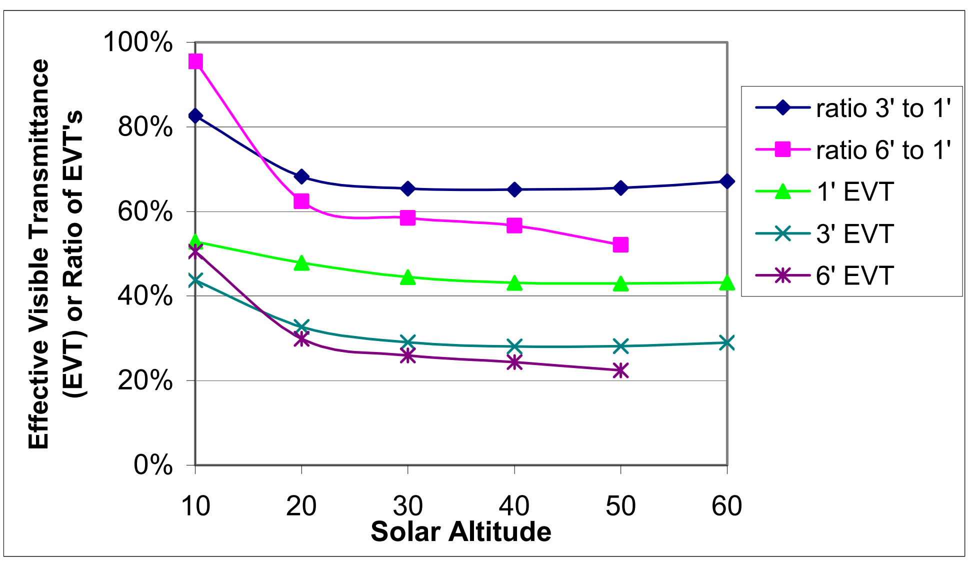


Figure 43. EVT ratios of single white dome over white diffusing wells

If the light well were specular but covered with a white diffusing skylight, would the same results be obtained? Implicit in this question is, were the above results because the light well efficiency is relatively insensitive to the luminous distribution of the skylight or does the relatively constant luminous distribution with respect to solar altitude result in relatively constant well efficiencies. The results in Figure 44 indicate that in the case of a highly diffusing skylight, the constancy of the light distribution renders the well efficiency relatively constant regardless of the specularity of the light well.

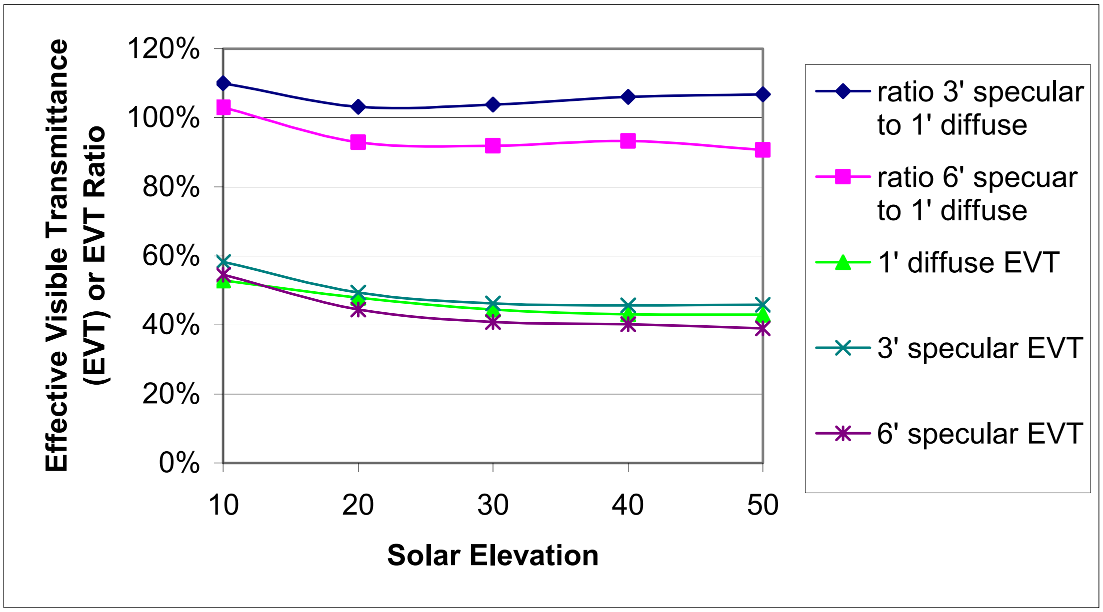


Figure 44. Ratios of EVT of single white dome over 3' and 6' specular light wells to EVT over 1' diffuse light well

These results vary significantly from the prior research on tubular daylighting devices that illustrate that when specular light wells are beneath clear skylights, their well efficiency is highly dependent on incident angle especially for surface reflectances less than 90%.

Prediction of EVT from Visible Transmittance and Shape

Given that the data collected, can one develop a simple model of skylight EVT based solely on visible light transmittance of the glazing and the skylight shape? How much error will result, if the model is simply the glazing transmittance times the well efficiency and some function of solar elevation? Figure 45 plots the normalized EVT as a fraction of the glazing T_{vis} times the well efficiency. Thus we can easily tell how closely EVT matches a simplistic model of glazing transmittance representing skylight transmittance adjusted for well efficiency. This plot indicates that for dome skylights, that the Tvis and well efficiency would be derated by around 10% to more closely match the measured EVT results and that no adjustment is needed for angle of incidence for most incident angles.

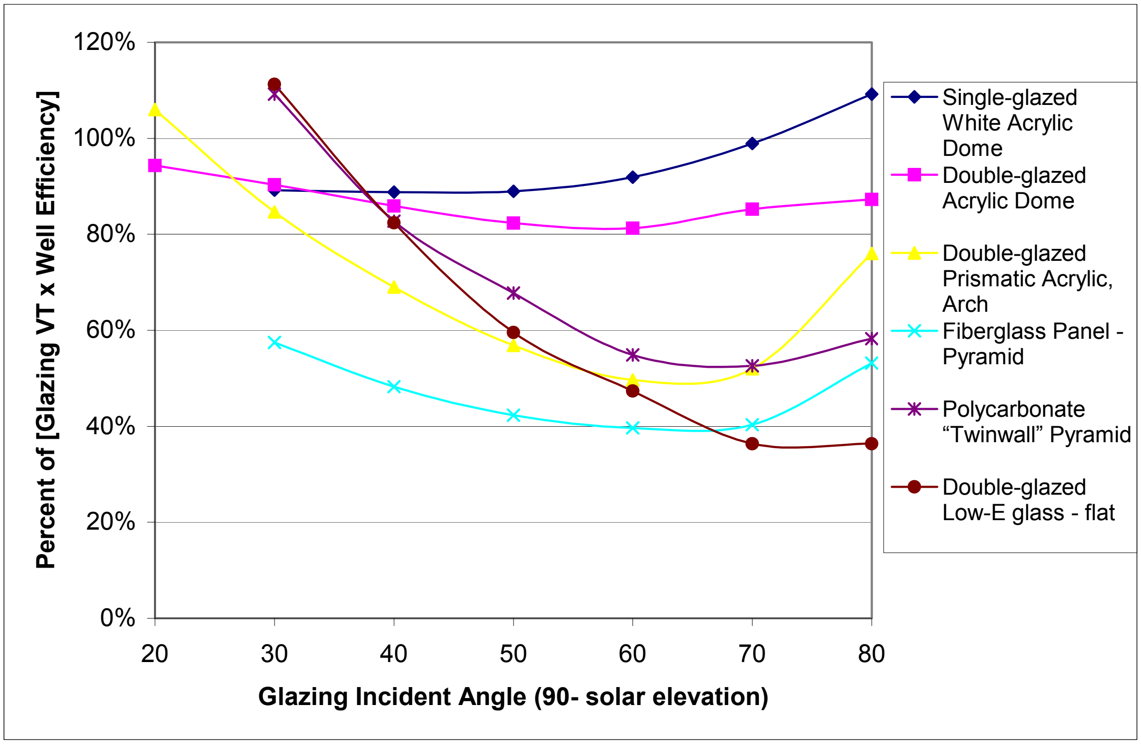


Figure 45. EVT as a fraction of glazing T_{vis} x well efficiency

All of the other skylight shapes need a model that accounts for solar altitude (incident angle). Except for the fiberglass insulating panel pyramid skylight, all the other skylights come close to the predicted EVT as calculated by Tvis and well efficiency at low incident angles. Unfortunately the lowest incident angle for which we have EVT data for the fiberglass pyramid is 30 degrees. However, we would expect the drop off in angular transmittance to be quite high for this glazing as the internal framing members would absorb light at off angles. Thus empirical correlations could be easily fit to this data. Second order curve fits all matched the data in the Figure to an R^2 or 95% or better. However, more confidence would result from an analytic solution that is calibrated to measured test results.

Table 14. Curve fit of EVT normalized to glazing transmittance

Material	EVT Curve Fit as a function of incident angle (x) in deg	R2
Single-glazed White Acrylic Dome	$y = 0.0001445087x^2 - 0.0120856443x + 1.1302348251$	99.4%
Double-glazed Acrylic Dome	$y = 0.000091457x^2 - 0.010434570x + 1.123106557$	95.2%
Double-glazed Prismatic Acrylic, Arch	$y = 0.0003889x^2 - 0.0451225x + 1.8343432$	96.1%
Fiberglass Panel - Pyramid	$y = 0.00024476x^2 - 0.02829199x + 1.21271589$	94.8%
Polycarbonate "Twinwall" Pyramid	$y = 0.0003775x^2 - 0.0517604x + 2.3039051$	99.8%
Double-glazed Low-E glass - flat	$y = 0.00034238x^2 - 0.05265429x + 2.38231016$	99.9%

Flat versus Dome Annual Lighting Energy Comparison

The results of this study clearly identify that skylight shape has an impact on the angular transmittance of skylights. As shown in Figure 45, the effective visible transmittance of flat glass is very incident angle dependent whereas the effective visible transmittance of a dome skylight is relatively insensitive to sun angle. This section investigates how skylight shape impacts lighting energy consumption for a big box store in two California cities, Sacramento and San Diego.

Sacramento and San Diego were selected for representative cities as both cities have TMY2 (Typical Meteorological Year) hourly climatic data including outdoor beam and diffuse illuminance. (Marion & Urban 1995) Illuminance values in the TMY2 data are derived from hourly irradiance data, solar altitudes and dewpoint temperatures using a correlation developed by Perez et al. (1990). San Diego is representative of the mild and sunny climate of southern coastal California and Sacramento is representative of the less sunny and more extreme climates encountered in California's central valley.

The calculation of lighting energy impacts is accomplished by calculating the hourly lighting energy consumption over the course of a year. Lighting energy consumption for each hour is the product of the installed lighting power, the lighting schedule for that hour and the daylight control factor. The daylight control factor reduces lighting power as a function of lighting control type (dimming versus switching, number of stages etc.), the control setpoint and the interior daylight illuminance. The lighting schedule and daylight control factors used in this analysis are the same as those found in the SkyCalc software and described in a paper by Heschong and McHugh (2000). This analysis assumes that 50 fc of general lighting is provided by linear fluorescent sources. The retail lighting schedule used has lights on from 8 am to 10 pm. The analysis was performed with two common daylight control types for retail applications: 10% minimum light output dimming and 2/3's off switching control.

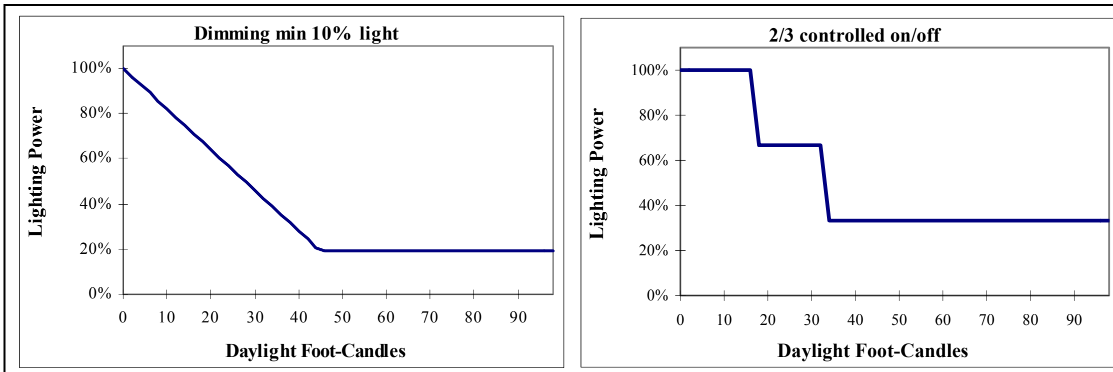


Figure 46. 10% dimming and 2/3's off switching daylight controls

The calculation method used here is conceptually the same as that presented in the IESNA Handbook for finding interior illuminance under skylights , E_i, when exterior horizontal diffuse illuminance, $E_{xh\ sky}$, and exterior horizontal beam illuminance, $E_{xh\ sun}$, are known:[10]

$$E_i = \left(E_{\text{xh sky}}\ \tau_d + \text{E}_{\text{xh sun}}\ \tau_{\text{D}}\right)\text{CU N}\frac{\text{A}}{\text{A}_{\text{W}}}$$

where,

τ_d	=	net diffuse transmittance
τ_D	=	net direct (beam) transmittance
CU	=	skylight system coefficient of utilization for a given room geometry and reflectances, assuming perfectly diffuse (Lambertian) distribution
N	=	number of skylights
A	=	area of each skylight
A_w	=	area of workplane

In the analysis here we have reorganized some of the terms so that the mechanisms of light transfer are grouped by design elements. As an example net diffuse transmittance, τ_d, is a function of the glazing type as well as the light transfer efficiency of the light well (well efficiency). Thus the term τ_d, is broken into three terms, $EVT_{diffuse}$, WE (well efficiency) and DF (dirt factor). Similarly τ_D, is broken into DF, WE and $EVT_{beam}(\theta)$. Note that EVT_{beam} is a function of incident angle θ. Since tilted surfaces will also be evaluated, exterior horizontal beam illuminance, $E_{xh\ sun}$, will be converted into the product of direct beam illumination, E_{db}, and the cosine of the incident beam angle θ. For tilted surfaces the diffuse component is also reduced by R_d, the ratio of diffuse light on a tilted surface to that on a horizontal surface. The grouping of terms N x (A/A_w) describes the total skylight area as a fraction of the workplane area and is called the skylight to floor area ratio (SFR). The equation in the IESNA Handbook can now be regrouped and reorganized into the following:

$$E_i = \{ E_{xh\ sky}\ R_d\ EVT_{diffuse} + E_{db}\cos(\theta)\ EVT_{beam}(\theta)\}\ DF\ WE\ CU\ SFR$$

To compare flat and domed skylights purely on their shape we modeled both skylight glazings to have a visible transmittance of 50%. This is not much of a deviation from the tested glazing transmittances of 46.7% for the flat glass skylight and 50.5% for the double glazed dome. Thus a factor of 0.5 was multiplied by the curve fit equations listed in Table 14. Curve fit of EVT normalized to glazing transmittance. To minimize the error associated with extrapolation, the curves were truncated at incident angles less than 30° (for horizontal skylights solar altitude greater than 60°) and at incident angles greater than 80° (solar altitude less than 10°). Figure 47 plots the truncated curve fits

[10] Eq 8-35, p. 8-13 IESNA Handbook (Rea 2000).

against the measured source data. The actual EVT_{beam} is the product of the curve fit and the glazing transmittance. Thus for our two comparison skylights, the double dome and the flat glass have EVT_{beam} that are one half the normalized values shown in Figure 47.

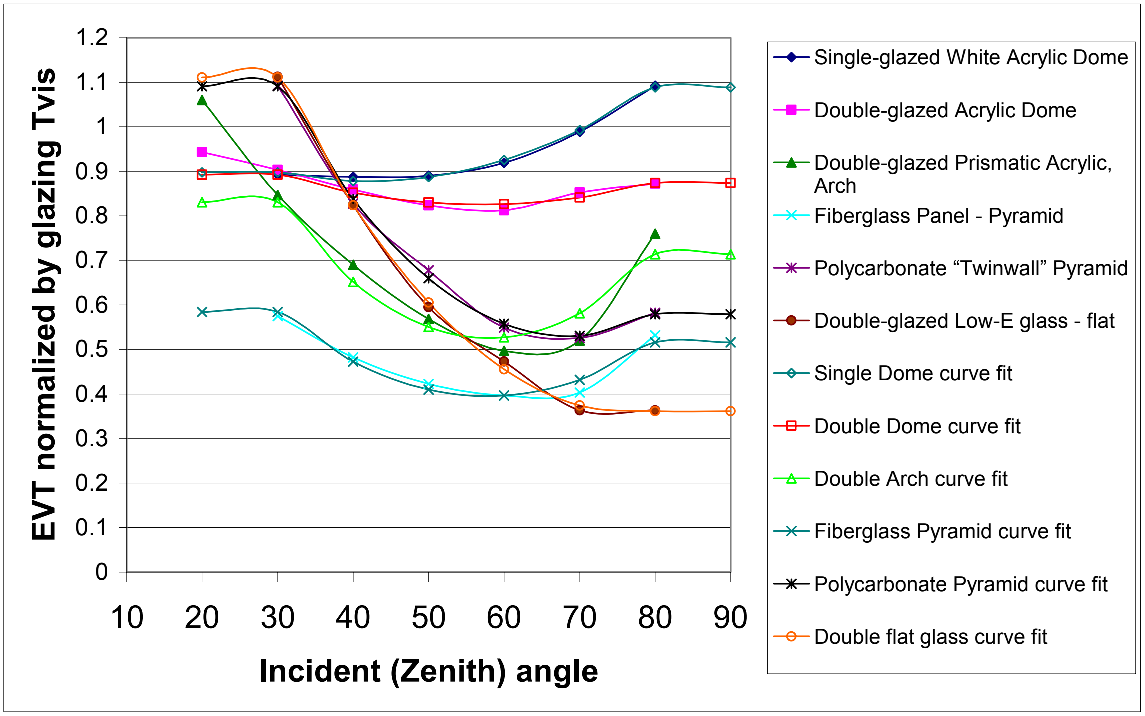


Figure 47: Measured and truncated curve fit normalized EVT

The EVT data collected was for clear skies where most of the light is direct beam from the sun rather than diffuse light. As described above, EVT is a function of sun angle. For this analysis an illuminance weighted EVT was developed for diffuse illuminance. This was achieved by applying the overcast sky luminance distribution to the integral used to calculate the illumination on a horizontal surface, and setting the limits of integration to 10 degree intervals of Zenith (incident) angle. This divides up the illumination on a horizontal plane into 10 degree increments of zenith angle of the overcast sky. These illuminance fractions are then multiplied by the angle dependent beam EVT for the Zenith angle that is at the midpoint of each interval.

The Moon-Spencer overcast sky luminance distribution, L(Z), is a function of Zenith angle, Z, only.

$$L(Z) = \frac{L_Z}{3}\left(1 + \mathrm{Cos}(Z)\right)$$

where,

L_z = overcast sky luminance at the Zenith

The illuminance on the horizontal surface, Eh, from the sky is given by the integral[11]:

$$E_h = \int\int L(Z,\alpha)\sin(Z)\cos(Z)\,dZ\,d\alpha$$

where

α = azimuthal angle of the sky position from the sun

Inserting the overcast sky luminance equation

$$E_h = \iint \frac{L_Z}{3}\left(1+2\cos(Z)\right)\sin(Z)\cos(Z)\,dZ\,d\alpha = \frac{L_Z}{3}\int_0^{2\pi}\int_0^{\frac{\pi}{2}} \cos(Z) + 2\cos^2(Z)\;(-d\cos(Z))\;d\alpha$$

Solving the integral for 10 degree increments of Zenith angle:

$$E_h = 2\pi\frac{L_Z}{3}\left[-\frac{\cos^2(Z)}{2} - \frac{2\cos^3(Z)}{3}\right]_{Z=10i}^{Z=10i+10}$$

where, interval i is from 0 to 8

When this is integrated from 0 to $\pi/2$, Lz = 0.4092 x E_h, thus to maintain dimensionless weighting factors, LZ is set equal to 0.4092. When the EVT_{beam} data is applied to this integral the diffuse weighted effective visible transmittance, $EVT_{diffuse}$, is 43% for the double dome and 39% for the flat double glazed glass skylight.

McHugh (1995) developed a numerical method for calculating R_d, the ratio of diffuse light on a tilted surface to that on a horizontal surface under overcast skies. [12] From this method a 4th order polynomial expression for Rd was developed as a function of tilt angle, Σ (in degrees).

Rd = $0.9477 + 0.00096926\Sigma - 0.00016105\Sigma^2 + 1.0033\times10^{-6}\,\Sigma^3 - 1.7137\times10^{-9}\Sigma^4$

The annual energy simulation compared the energy performance of six skylights, one horizontally mounted dome and a flat glass skylight at five different tilt angles: horizontal, 20° facing south, 30° south, 20° facing to the north and 30° north. The building simulated was a typical big box retail store with a 1.5 W/sf lighting power density, a 50 footcandle design illuminance, skylight to floor area ratios (SFR) were varied in increments of 1% from 1% to 6%. The well efficiency for this design with a 1 foot deep light well was 88%, the coefficient of utilization (CU) for this large open space was 76%, the dirt factor was 75%. The coefficient of utilization takes account of the space geometry including 7 foot high shelving.

[11] Eq 8-24b, p. 8-7, IESNA Handbook Rea(2000).

[12] Eq F-31 for Etilt/Ehoriz in McHugh (1995)

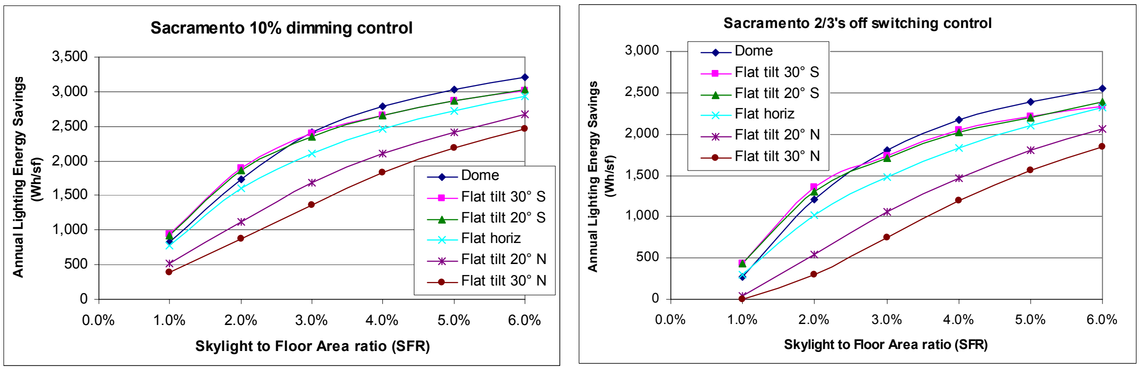


Figure 48. Lighting energy savings from flat and domed skylights - Sacramento

As shown in Figure 48and Figure 49, the overall trends hold for both dimming and switching systems in both Sacramento and San Diego. Lighting energy savings are highest for the horizontal domed skylight and the flat skylights facing south. Horizontal skylights with the same SFR saved about 10% less lighting energy than horizontal domes. Not surprisingly, flat skylights tilted to the north saved even less energy.

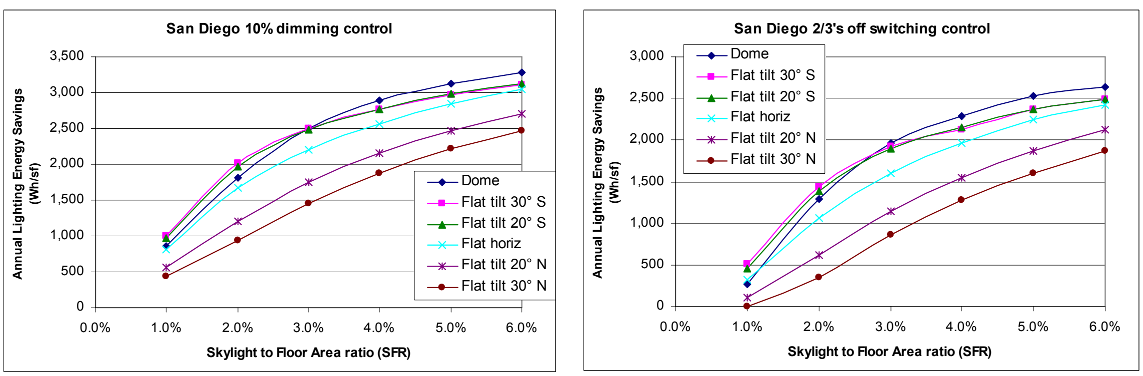


Figure 49. Lighting energy savings from flat and domed skylights – San Diego

Tabulated results in Table 15 and Table 16 quantify the energy results. Typical big box retail designs in California have SFR values around 4%. In Sacramento, one would have to install approximately 5% SFR or 25% more flat horizontal skylights to achieve the same lighting energy savings. If one specified south tilted flat skylights one would still need to install about 4.5% SFR or approximately 12% more skylight area to yield the same lighting energy savings. The results are fairly robust and hold for two different climates and two different multi-level lighting control strategies (dimming versus 2/3's off switching).

Table 15. Lighting energy savings by skylight and control type - Sacramento

Sacramento big box retail annual lighting energy savings Wh/sf

SFR	Dimming 10% minimum: Dome	Flat tilt 30° S	Flat tilt 20° S	Flat horiz	Flat tilt 20° N	Flat tilt 30° N	Switching 2/3's off: Dome	Flat tilt 30° S	Flat tilt 20° S	Flat horiz	Flat tilt 20° N	Flat tilt 30° N
1.0%	827	932	917	773	517	397	269	434	437	304	39	0
2.0%	1,739	1,894	1,858	1,602	1,124	881	1,202	1,352	1,309	1,019	548	302
3.0%	2,407	2,391	2,347	2,108	1,689	1,365	1,799	1,744	1,717	1,484	1,061	750
4.0%	2,781	2,665	2,652	2,464	2,106	1,825	2,177	2,054	2,026	1,828	1,466	1,194
5.0%	3,033	2,873	2,868	2,728	2,422	2,183	2,384	2,215	2,198	2,106	1,802	1,556
6.0%	3,202	3,020	3,030	2,937	2,672	2,460	2,554	2,337	2,385	2,321	2,058	1,852

Sacramento savings fraction relative to dome skylight

SFR	Dimming 10% minimum: Dome	Flat tilt 30° S	Flat tilt 20° S	Flat horiz	Flat tilt 20° N	Flat tilt 30° N	Switching 2/3's off: Dome	Flat tilt 30° S	Flat tilt 20° S	Flat horiz	Flat tilt 20° N	Flat tilt 30° N
1.0%	100%	113%	111%	93%	62%	48%	100%	162%	163%	113%	15%	0%
2.0%	100%	109%	107%	92%	65%	51%	100%	113%	109%	85%	46%	25%
3.0%	100%	99%	97%	88%	70%	57%	100%	97%	95%	83%	59%	42%
4.0%	100%	96%	95%	89%	76%	66%	100%	94%	93%	84%	67%	55%
5.0%	100%	95%	95%	90%	80%	72%	100%	93%	92%	88%	76%	65%
6.0%	100%	94%	95%	92%	83%	77%	100%	92%	93%	91%	81%	73%

From this analysis we conclude that energy analyses of dome skylights that treat them as having the same angular transmittance as horizontal flat glazing underestimates the lighting energy savings of dome skylights by at least 10%. Also noted is that the energy performance of flat tilted skylights is sensitive to orientation.

Table 16. Lighting energy savings by skylight and control type – San Diego

San Diego big box retail annual lighting energy savings Wh/sf

SFR	Dimming 10% minimum: Dome	Flat tilt 30° S	Flat tilt 20° S	Flat horiz	Flat tilt 20° N	Flat tilt 30° N	Switching 2/3's off: Dome	Flat tilt 30° S	Flat tilt 20° S	Flat horiz	Flat tilt 20° N	Flat tilt 30° N
1.0%	865	992	975	813	562	430	274	505	458	317	106	0
2.0%	1,814	2,014	1,965	1,668	1,208	945	1,291	1,444	1,389	1,065	625	354
3.0%	2,506	2,501	2,479	2,196	1,751	1,455	1,963	1,924	1,894	1,600	1,140	860
4.0%	2,897	2,772	2,767	2,560	2,152	1,878	2,290	2,126	2,158	1,963	1,545	1,283
5.0%	3,128	2,964	2,978	2,841	2,466	2,211	2,524	2,369	2,366	2,247	1,868	1,595
6.0%	3,274	3,113	3,126	3,043	2,710	2,474	2,642	2,493	2,487	2,416	2,125	1,869

San Diego savings fraction relative to dome skylight

SFR	Dimming 10% minimum: Dome	Flat tilt 30° S	Flat tilt 20° S	Flat horiz	Flat tilt 20° N	Flat tilt 30° N	Switching 2/3's off: Dome	Flat tilt 30° S	Flat tilt 20° S	Flat horiz	Flat tilt 20° N	Flat tilt 30° N
1.0%	100%	115%	113%	94%	65%	50%	100%	184%	167%	116%	39%	0%
2.0%	100%	111%	108%	92%	67%	52%	100%	112%	108%	82%	48%	27%
3.0%	100%	100%	99%	88%	70%	58%	100%	98%	97%	82%	58%	44%
4.0%	100%	96%	96%	88%	74%	65%	100%	93%	94%	86%	67%	56%
5.0%	100%	95%	95%	91%	79%	71%	100%	94%	94%	89%	74%	63%
6.0%	100%	95%	95%	93%	83%	76%	100%	94%	94%	91%	80%	71%

CONCLUSIONS AND RECOMMENDATIONS

The primary observation from this study is that the effective visible transmittance of projecting skylights behaves markedly differently than that of flat horizontal glazing. Thus predicting the luminous performance of skylights requires a different model than the flat glass model typically used by many lighting and energy simulation programs. The data collected here can be used to generate curve fits of skylight effective visible transmittance (EVT) with respect to sun angle. At the very least, an estimate of a constant EVT with respect to incident angle for dome skylights is better than angle dependent EVT's developed for flat glazing. The lighting energy savings from horizontal dome skylights with the same glazing visible transmittance and same skylight area were about 10% higher than the savings for skylights with horizontal flat glazing and about 5% higher than skylights tilted to the south..

Other conclusions from this study were:

- EVT's of skylights are reasonably proportional in most cases to the visible transmittance of the glazing *for the same skylight shape*.
- Rating of skylights and specular light wells for the US market should be based upon a 30º solar elevation as over the course of a year in most US locations, the sun is most frequently at solar elevations close to 30º.
- Current ratings based upon light perpendicular to the skylight (90º elevation) or based solely on glazing properties do not provide the information needed to compare between skylights.
- Skylighting system effective visible light transmittance is one of the most important metrics of skylighting system energy performance for mild climates such as in California.
- The EVT method of rating skylighting system overall transmittance is likely more robust than the photometric method as the EVT method can measure collimated light whereas the assumptions that underlie far field photometry are violated when the skylight is non-diffusing or light is otherwise collimated.
- This data can be used to generate better calculation tools for visible transmittance functions for projecting skylights. The SkyVision program from National Research Council Canada has made great progress in developing an analytical model for simulating the light transmittance of projecting skylights.
- This research has validated the statement made in the IESNA Handbook[13] that the visible transmittance of dome skylights can be treated as constant overall wide range of incident angles.

[13] p. 8-11 (IESNA 200)

- There is a clear demarcation of haze tested according to ASTM D1003 between glazing materials that are considered diffusing versus those that are not. Haze values above 90% describe glazing materials that are essentially diffusing.

The following statements about light well efficiency can also be made from the data collected

- The effective visible transmittances of skylighting systems diminish as skylight well depths increase.
- Specular light wells are more effective at transmitting light than diffusely reflecting light wells.
- The measured well efficiency of diffusing light wells matched closely the predicted light well efficiency nomograph contained in the IESNA Handbook. Well efficiency appeared to be insensitive to sun angle.

Recommendations

This study has identified that projecting skylights of the same glazing visible light transmittance as flat skylights can provide significantly more light than flat skylights at sun angles normally encountered most of the year. Predictive models and rating systems need to incorporate skylight shape as a key variable. Since effective visible transmittance of the skylighting system has such a large impact on system performance the following recommendations are offered to improve the quality of information available to building designers.

- The methodology of the skylight EVT test should be codified into an ASTM or NFRC test standard. Such a test method should be applicable to both diffusing and non-diffusing skylights as well as projecting and planar skylights. Such a test should yield results that can predict with high accuracy the transmittance of skylights at 30º solar elevation (60º incident angle).
- The EVT test described in this report was constrained by the necessity of measuring visible transmittance and solar heat gain coefficient simultaneously. Thus this EVT test method should be a starting point as accuracy is likely improved by some approximation of an integrating sphere or by sampling illuminances in more locations than the 16 point grid used in this test. Such a test could be used to calibrate a skylight effective transmittance model based upon glazing properties and skylight shape.
- The National Fenestration Rating Council (NFRC) should place high on their agenda a computer model to provide visible light transmittance ratings for projecting skylights and TDD's (tubular daylighting devices). The SkyVision program, created by National Research Council Canada, was identified as having the features that may well satisfy the criteria needed for rating skylights.

- The transmittance of specular light wells under clear glazing is highly dependent upon incident angle The sun positions encountered in most US locations over the course of a year are most frequently at solar elevations near 30º. The NFRC proposal for rating TDD's at a 60º solar elevation should be revised so that the rating is based on 30º solar elevation.
- Energy and lighting simulation tools should be updated to account for skylight shape on the angular transmittance of the skylighting system. In lieu of more detailed models, dome skylights should be modeled with constant visible transmittance instead of the angular transmittance models based upon the behavior of flat glass.
- Energy simulation tools should be updated to calculate the well efficiency of diffuse and specular light wells. This is usually left to the designer to calculate off-line.
- Glazing haze values greater than 90% when measured in accordance with ASTM D1003 (notwithstanding the scope of D1003) be used as a definition of a diffusing glazing in energy codes and product specification until a better metric is developed. This recommendation is being used in the recently adopted version of California's Title 24 Building Energy Efficiency Standards that will take effect in 2005.
- Further research should be conducted on metrics of diffusion. The current scope of ASTM D1003 limits haze measurements to materials that have haze values less than 30%. This limitation should be analyzed and potentially revised. Other methods of measuring diffusion of skylights and glazings should also be pursued. These other methods might include maximum luminous intensities per 1,000 lumens of light transmitted.
- In the United States, the key repository of light well efficiency information is the *IESNA Handbook*. This information is in the form of a nomograph of well efficiency with respect to well cavity ratio (WCR) for various reflectances. This nomograph is valid for light wells with diffusely reflecting surfaces. As specular light wells are increasingly being used, it is recommended that the *IESNA Handbook* be updated to include well efficiency nomographs for tubular and square specular light wells.
- We hypothesize that long term skylighting system performance is affected by UV degradation of materials and the effect of dirt and dust build-up. It may be that the performance of highly transmitting systems are especially affected by aging and depreciation issues. It is recommended that on site surveys be conducted and detailed measurements be taken on the maintained effective visible transmittance of skylighting systems.
- Research should also be initiated on the effect of exterior and interior reflectors on the effective visible transmittance of skylighting systems and their effect on the distribution of light from the skylighting system.

GLOSSARY

Angular Transmittance
Is the visible light transmittance as a function of incident angle on the glazing.

Clarity
A measure of light directly transmitted relative to the amount of light scattered 2.5°.

Effective Aperture
The fraction of light incident on a roof to that transmitted by the skylighting system. It is the product of the visible transmittance of the skylight, the transmittance of louvers, lenses or other elements in the light well, the well efficiency and the skylight area to floor area ratio (SFR).

Effective Visible Transmittance (EVT)
The ratio of the light transmitted through a skylighting system (skylight, light well diffusers etc.) to the light incident on the horizontal projection of the skylight opening.

Haze
Haze is ratio of diffusely transmitted light (scattered more than 2.5°) to the total transmitted light of a glazing. Haze is measured according to the procedures given in ASTM D1003-00.

Integrating Sphere
Hollow sphere with a diffusely reflecting inner surface used to measure total luminous flux from a source.

Solar Heat Gain Coefficient (SHGC)
The SHGC is the fraction of incident solar radiation admitted through a material, either by direct transmittance, or by absorption and release into the interior space.

Tubular Daylighting Devices (TDD)
Also referred to as tubular skylights. Typically a circular dome skylight mounted on top of a specular light well that is tube shaped. Usually there is a diffuser or lens at the base of the tubular light well.

Unit Skylight
A preassembled skylight – typically with dimensions no greater than 8 feet. Unit skylights are differentiated from architectural or monumental skylights that are site assembled.

Visible Light Transmittance (VLT)

Visible light transmittance refers to the fraction of light from the sun that passes through the product. Only light within the visible spectrum (between 360 and 800 nanometers) is considered in the measurement.

Well Efficiency (WE)
Well efficiency is the fraction of the light entering the top of the light well that exits the base of the light well.

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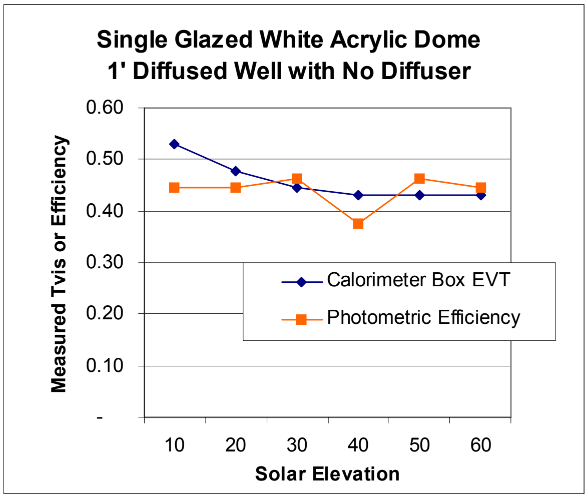
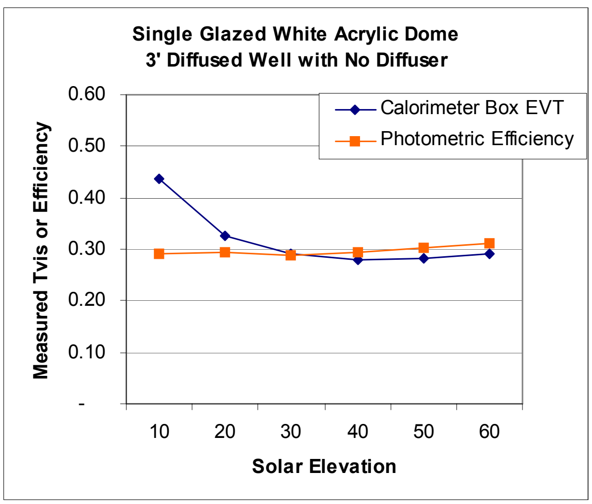
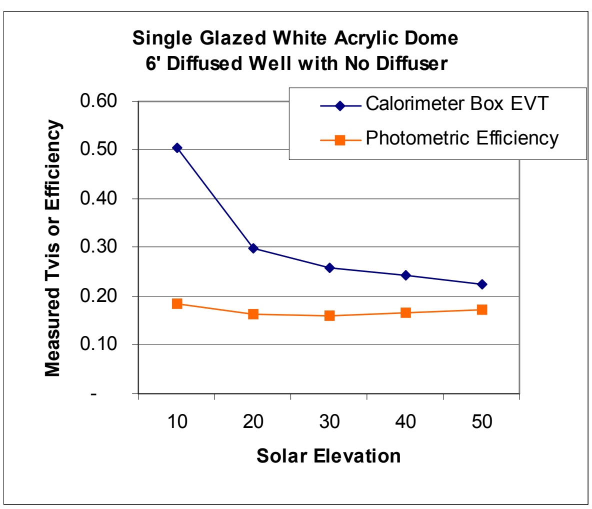
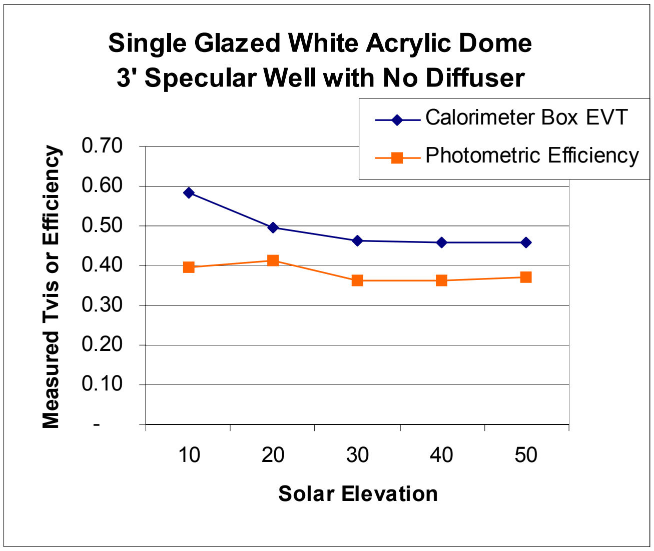
APPENDIX 1 – ANGULAR EVT VS ANGULAR PHOTOMETRIC EFFICIENCY

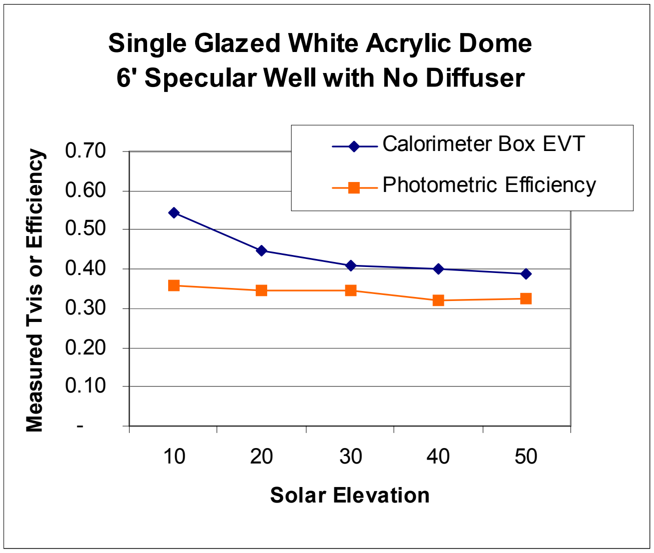
This appendix contains comparisons of the calorimeter box EVT (effective visible transmittance) from a grid of illuminance sensors and skylight photometric efficiency calculated from goniophotometric measurements for the range of solar elevations that were available. Comparison of these measurements may provide insight into when either method might be expected to confirm the other method and when one can expect deviations. For more discussion of the relative merits of these two methods, refer to the Section entitled *"EVT from Calorimeter Box vs. Photometric Efficiency."*

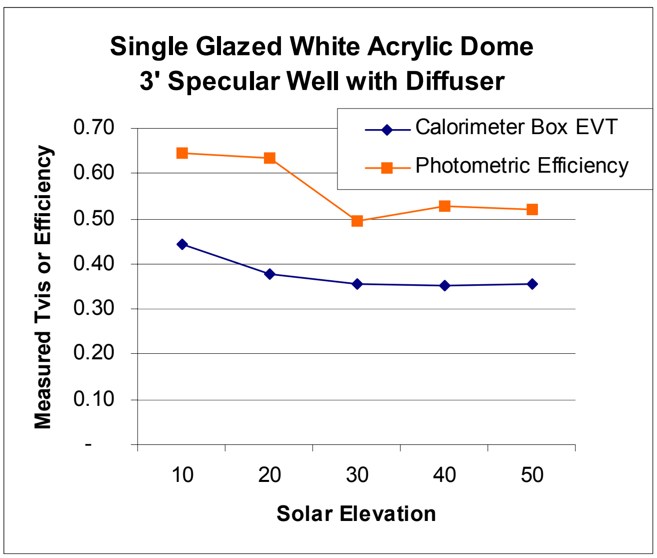


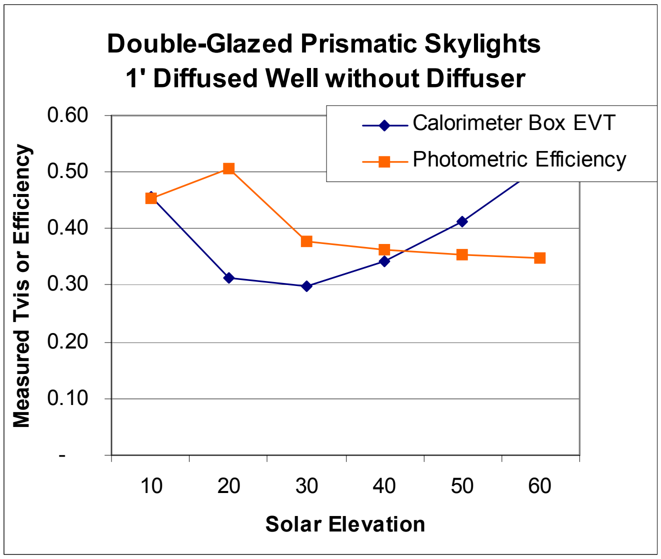


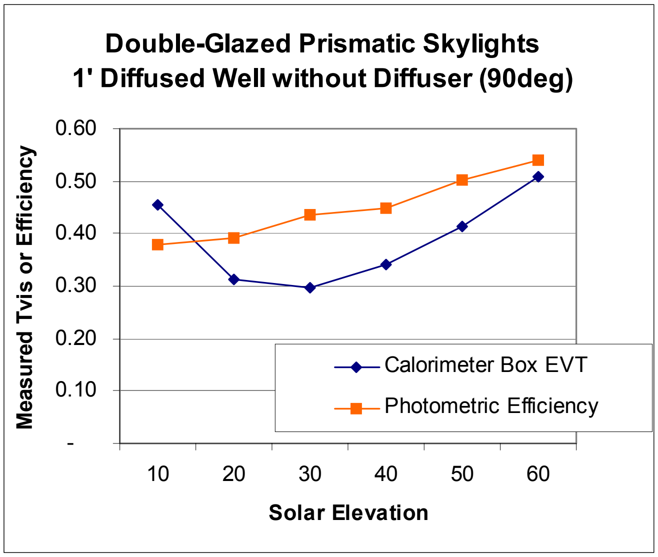


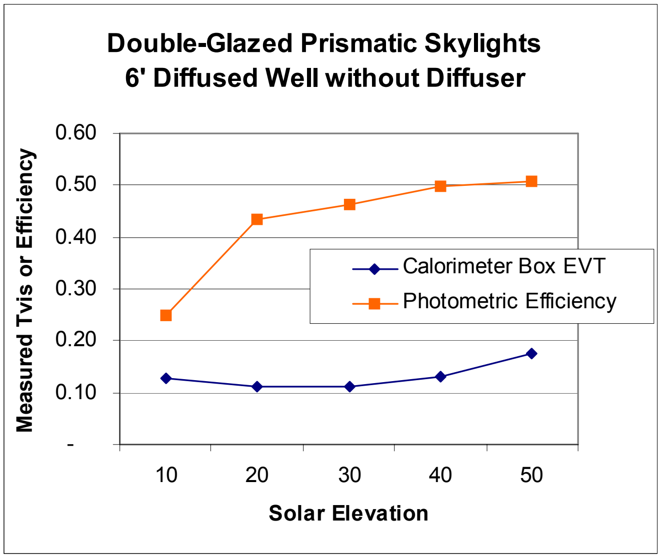

Single Glazed White Acrylic Dome
3' Specular Well with No Diffuser
Calorimeter Box EVT
Photometric Efficiency
Measured Tvis or Efficiency
0.70
0.60
0.50
0.40
0.30
0.20
0.10
-
10
20
30
40
50
Solar Elevation

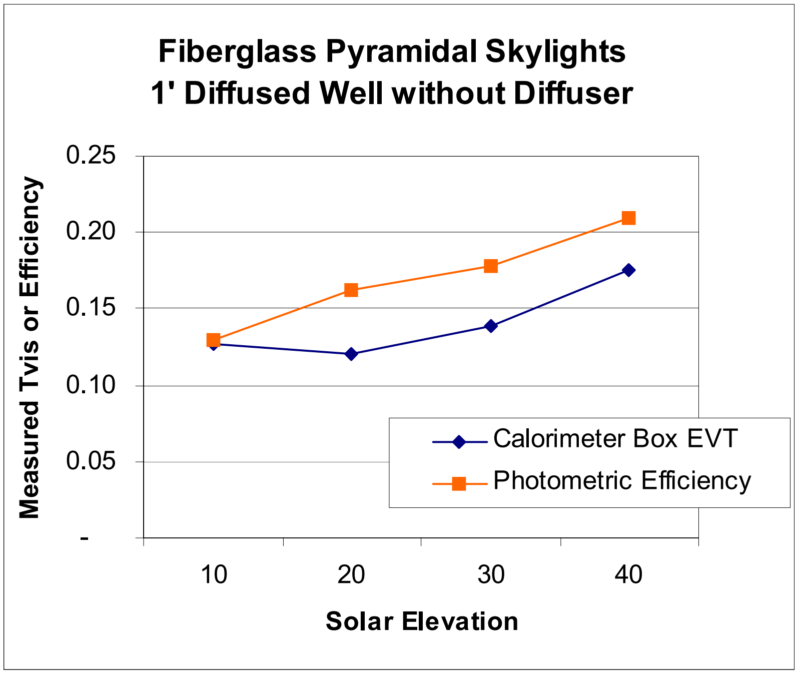

Single Glazed White Acrylic Dome
6' Specular Well with No Diffuser
Calorimeter Box EVT
Photometric Efficiency
Measured Tvis or Efficiency
0.70
0.60
0.50
0.40
0.30
0.20
0.10
-
10
20
30
40
50
Solar Elevation

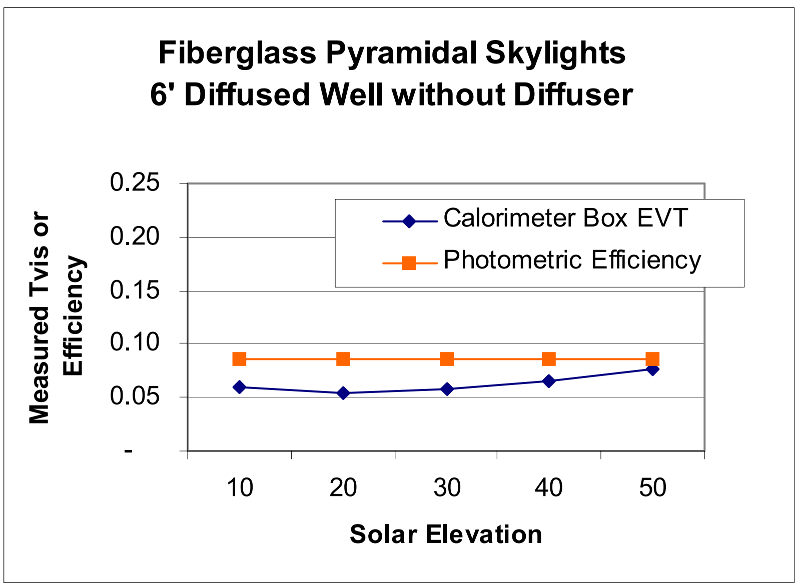

Single Glazed White Acrylic Dome
3' Specular Well with Diffuser
Calorimeter Box EVT
Photometric Efficiency
Measured Tvis or Efficiency
0.70
0.60
0.50
0.40
0.30
0.20
0.10
-
10
20
30
40
50
Solar Elevation


Double-Glazed Prismatic Skylights
1' Diffused Well without Diffuser
Measured Tvis or Efficiency
0.60
0.50
0.40
0.30
0.20
0.10
-
10
20
30
40
50
60
Solar Elevation
Calorimeter Box EVT
Photometric Efficiency


Double-Glazed Prismatic Skylights
1' Diffused Well without Diffuser (90deg)
Measured Tvis or Efficiency
0.60
0.50
0.40
0.30
0.20
0.10
-
10
20
30
40
50
60
Solar Elevation
Calorimeter Box EVT
Photometric Efficiency


Double-Glazed Prismatic Skylights
6' Diffused Well without Diffuser
Measured Tvis or Efficiency
0.60
0.50
0.40
0.30
0.20
0.10
-
10
20
30
40
50
Solar Elevation
Calorimeter Box EVT
Photometric Efficiency


Fiberglass Pyramidal Skylights
1' Diffused Well without Diffuser
Measured Tvis or Efficiency
0.25
0.20
0.15
0.10
0.05
-
10
20
30
40
Solar Elevation
Calorimeter Box EVT
Photometric Efficiency

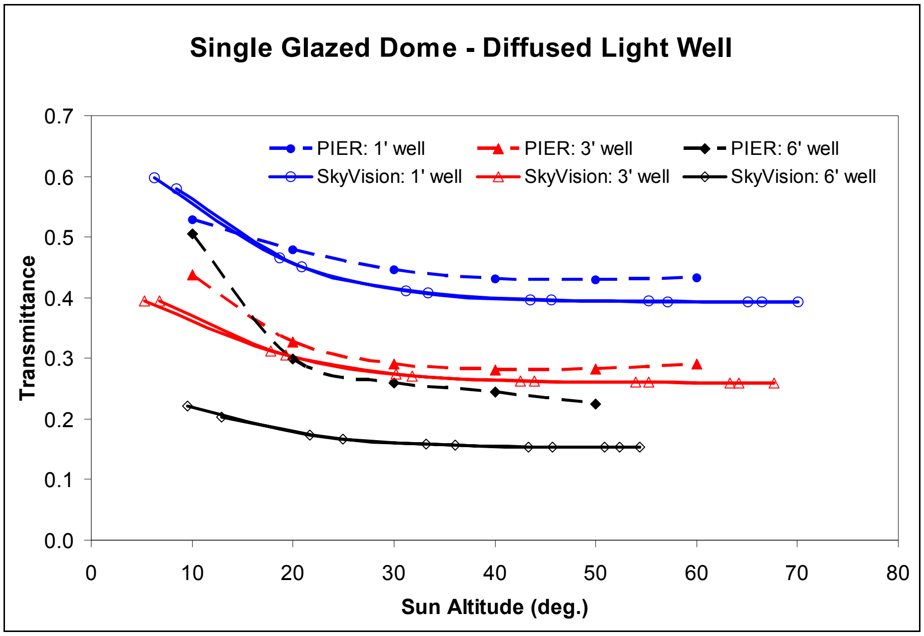

Fiberglass Pyramidal Skylights
6' Diffused Well without Diffuser
Measured Tvis or Efficiency
0.25
0.20
0.15
0.10
0.05
-
10
20
30
40
50
Solar Elevation
Calorimeter Box EVT
Photometric Efficiency

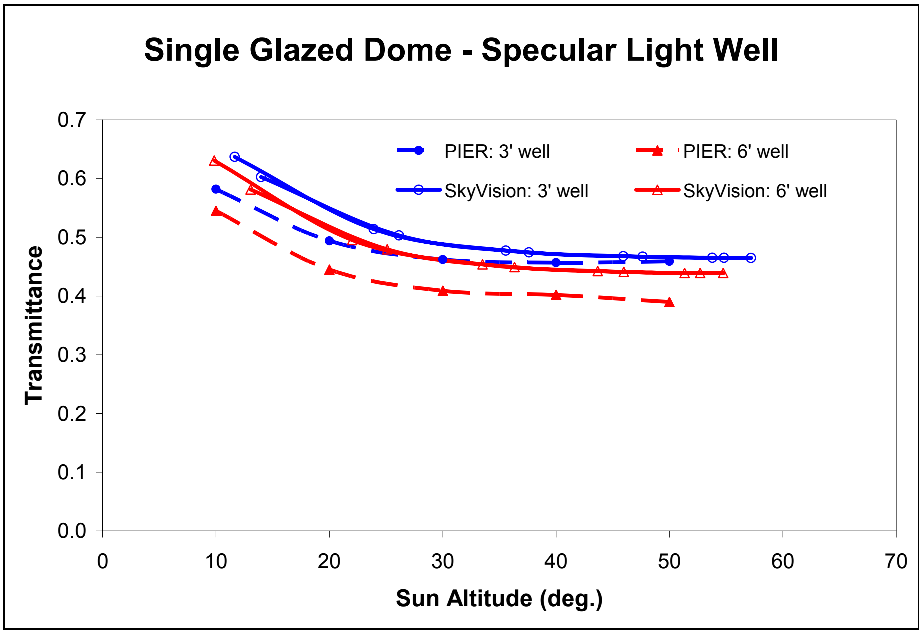
APPENDIX 2 – COMPARISON OF SKYVISION SIMULATIONS WITH PIER TEST RESULTS

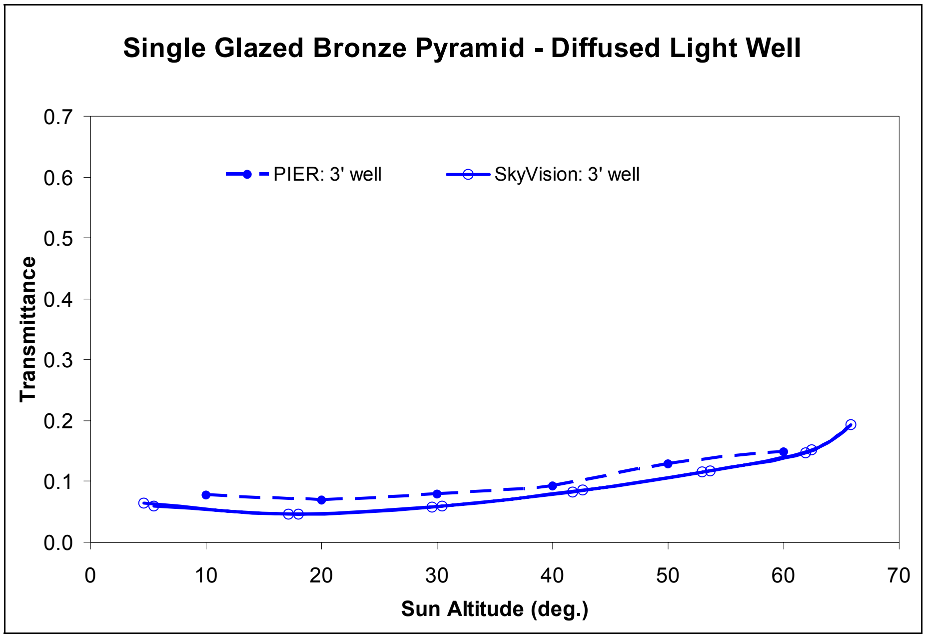
The following graphs are a comparison between the EVT (effective visible transmittance) test data from this study and SkyVision simulations based on skylight shape, glazing transmittance, light well shape and reflectivity of the light well material. The data is graphed as a plot of effective visible transmittance with respect to solar altitude.

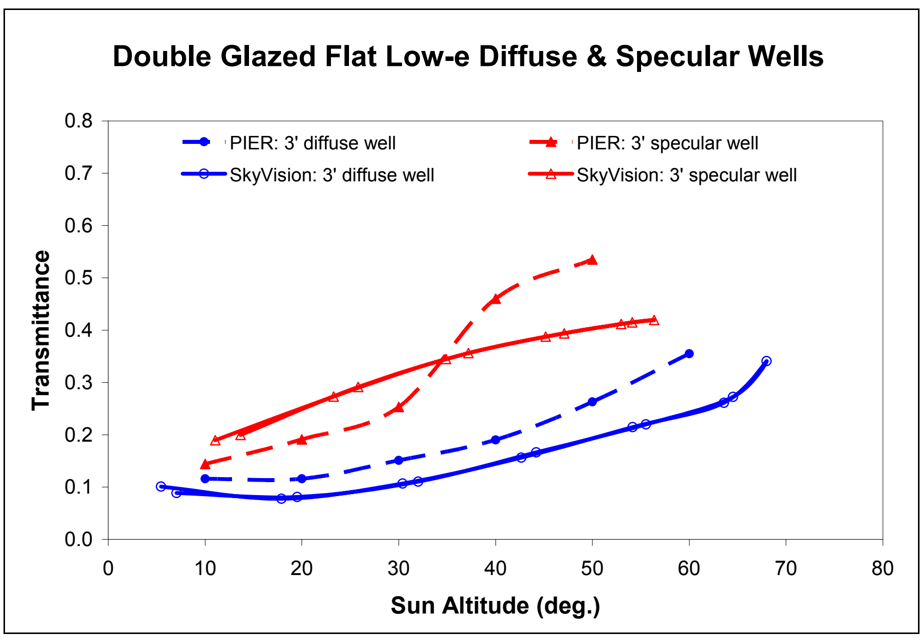
In general, the SkyVision simulations match closely the values and the shapes of the tested EVT curves. There are some notable differences:

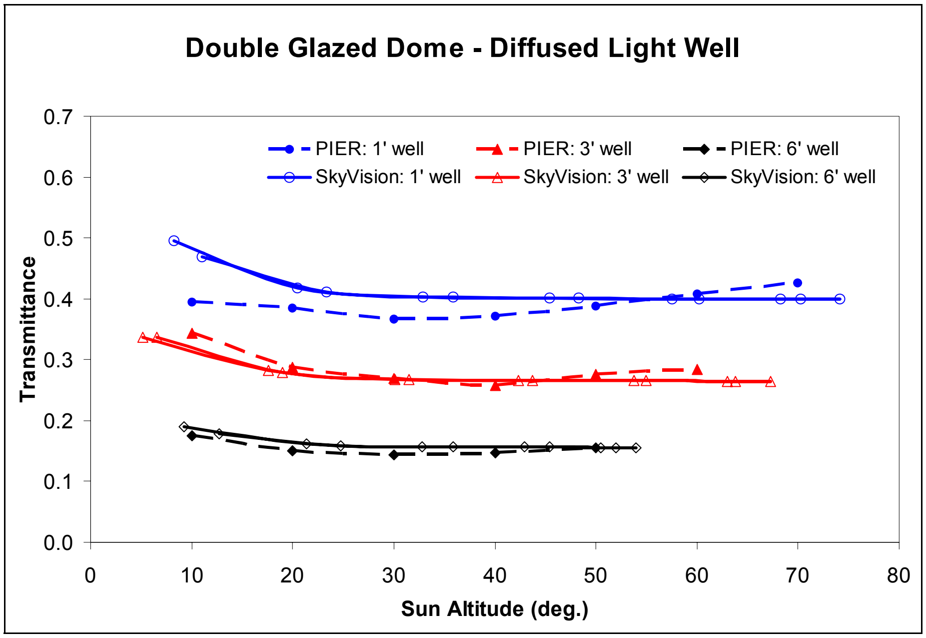
- In the *Single Glazed Dome – Diffused Light Well* graph, the EVT of the 6' tall light well is higher than that of the 3' light well. This result does not make sense and is most likely due to experimental error. The SkyVision result has a much lower EVT and is most likely correct. This comparison illustrated the value of simulations to identify experimental error.
- Another comparison that highlights experimental error is shown in the *Double Glazed Flat Low-e Diffuse & Specular Wells* graph. The EVT test results deviate above and below the simulated results depending upon sun angle. The error in the test results is due to the limited number (16) of light sensor locations in the grid beneath the light well. Depending upon sun angle, too many or too few sensors are receiving beam illumination directly or reflected from the mirror-like specular surface. There is less error with the diffuse light well as the reflected light is scattered across all of the light sensors. More sensors locations either from more sensors or by moving the sensors would decrease this error.
- In all of the graphs with specular light wells, the SkyVision calculated EVT's are higher than the measured EVT's. The reflectance used in these calculations makes use of the manufacturer's quoted reflectance of 95%. Actual reflectance of reflector material exposed to sunlight might be lower. This deviation highlights the validity of calibrating simulations with test results.

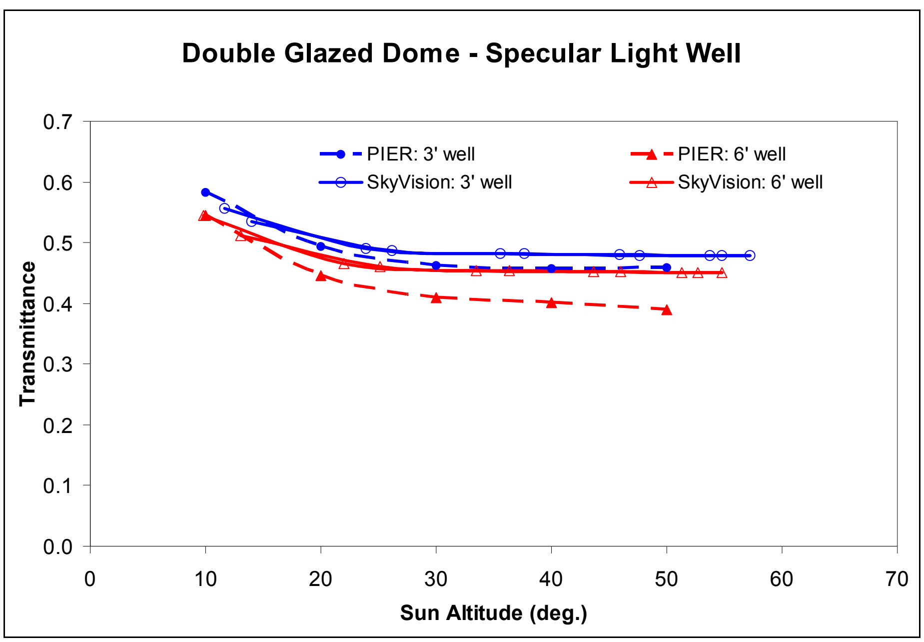

Single Glazed Dome - Diffused Light Well
Transmittance
0.7
0.6
0.5
0.4
0.3
0.2
0.1
0.0
0
10
20
30
40
50
60
70
80
Sun Altitude (deg.)
PIER: 1' well
PIER: 3' well
PIER: 6' well
SkyVision: 1' well
SkyVision: 3' well
SkyVision: 6' well


Single Glazed Dome - Specular Light Well
Transmittance
0.7
0.6
0.5
0.4
0.3
0.2
0.1
0.0
0
10
20
30
40
50
60
70
Sun Altitude (deg.)
PIER: 3' well
PIER: 6' well
SkyVision: 3' well
SkyVision: 6' well


Single Glazed Bronze Pyramid - Diffused Light Well
PIER: 3' well
SkyVision: 3' well
Transmittance
Sun Altitude (deg.)
0.0
0.1
0.2
0.3
0.4
0.5
0.6
0.7
0
10
20
30
40
50
60
70


Double Glazed Flat Low-e Diffuse & Specular Wells
PIER: 3' diffuse well
PIER: 3' specular well
SkyVision: 3' diffuse well
SkyVision: 3' specular well
Transmittance
Sun Altitude (deg.)
0.0
0.1
0.2
0.3
0.4
0.5
0.6
0.7
0.8
0
10
20
30
40
50
60
70
80


Double Glazed Dome - Diffused Light Well
PIER: 1' well
PIER: 3' well
PIER: 6' well
SkyVision: 1' well
SkyVision: 3' well
SkyVision: 6' well
Transmittance
Sun Altitude (deg.)
0.0
0.1
0.2
0.3
0.4
0.5
0.6
0.7
0
10
20
30
40
50
60
70
80


Double Glazed Dome - Specular Light Well
PIER: 3' well
PIER: 6' well
SkyVision: 3' well
SkyVision: 6' well
Transmittance
Sun Altitude (deg.)
0.0
0.1
0.2
0.3
0.4
0.5
0.6
0.7
0
10
20
30
40
50
60
70