Skylighting Design Guidelines

energydesignresources

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Chapter 1: Introduction

The use of skylights has grown in recent years, both because they enliven building interiors and because they can save energy and money through daylighting. Skylighting (skylights plus daylight controls) can be a solid asset for buildings, and help to satisfy human needs for building owners and occupants. Skylights can make a number of major contributions to the built environment:

- Skylights provide high quality lighting conditions to building interiors
- Skylights reduce the use of electric lighting, to save energy and reduce peak electric loads, when combined with effective photosensor control systems
- Skylights provide visual and thermal comfort for building occupants
- Skylights increase safety and security with highly reliable daytime lighting
- Skylights provide emergency smoke vents

These *Guidelines* were prepared to help designers optimize the use of skylights in commercial and industrial buildings. They describe opportunities for energy savings and high quality lighting design offered by skylights. They explain how to integrate skylights with the design of other building elements. They show how to estimate the potential energy savings and cost savings. Finally, they help designers avoid mistakes that could reduce the value of a skylight design.

These *Guidelines* apply primarily to skylight applications designed to provide uniform lighting for commercial or industrial buildings. They refer to manufactured, off-the-shelf skylight components used in commercial applications, commonly referred to as "unit skylights." These are typically simple, rectangular or linear skylights, although with creativity they can be applied to nearly any design situation. These *Guidelines* will also briefly discuss more specialized products such as Light Redirecting Skylights and Tubular Daylighting Devices (TDDs).

Many of the lighting principles covered here are also applicable to residential buildings, although the energy impacts are entirely different and should not be extrapolated from the information in this document. Similarly, atrium skylights and other large, custom designed skylights involve many other issues that are not addressed in this publication. The reader is referred to more specialized texts and tools for the analysis of custom applications.

While these *Guidelines* were created for a California audience, and make specific reference to California code requirements relating to skylights, the overall discussion applies to all audiences and geographical areas.

How Skylights Improve Buildings

Skylights use the most ancient and universal light sources, the sun and the sky, to bring natural light into buildings. Daylight can be beneficial for both buildings and building occupants.

At the most basic level, daylight can illuminate space, occupants and tasks in a building. Depending on the design of the skylight system, the daylight can be uniformly spread over a wide area, or it can be localized for particular tasks. For many types of buildings, skylighting is a very practical complement to electric lighting.

Beyond basic illumination, however, daylight can improve occupant comfort in buildings. Natural variations in daylight provide more visual interest than constant electrical lighting, and can help reinforce circadian rhythms in the human body. Daylight has also been shown to increase worker productivity, and can raise the value of real estate through higher rents and resale prices.

For example, surveys of occupants in skylit versus non-skylit retail spaces indicate that occupants found the skylit retail spaces to be more attractive than non-skylit spaces. The surveys also found that the skylit spaces were described as having better light quality, improved uniformity, and increased sales activity and customer satisfaction than the non-skylit spaces.[1]

All of these advantages and benefits of skylights have their exceptions, of course, but careful skylighting designs can avoid problems. Considerations to take into account when designing skylight systems for daylighting include:

- Visual and thermal comfort
- Seasonal and daily shifts in daylight availability
- Heat loss and heat gain
- Integration with electric lighting system

1 Pande, Abhijeet, Lisa Heschong, David Douglass. (Heschong Mahone Group, Inc.). 2012. Retail Revisioning. California Energy Commission. Publication Number: CEC-500-2013-006.

- Choice of daylighting control strategy
- Integration with roofing system
- Integration with HVAC design
- Utility costs and peak electric demand
- Structural and safety concerns

The following chapters provide the information and tools needed to design effective skylighting systems.

The primary role of skylights is to provide the best possible lighting conditions in the buildings they serve, and to enhance the visual environment so that the occupants of the building can be as productive and comfortable as possible. To that end, this *Skylighting Design Guidelines* document is structured to help designers and building owners understand how to apply skylighting in their buildings for maximum effect.

How Skylights Save Energy

Skylights save energy by providing adequate daylight illumination in buildings so that electric lights can be turned off when they are not needed. Daylight is free, and when utilized effectively, adds considerably less heat to a space than the equivalent amount of illumination from electric lights. By reducing the amount of heat contributed to a building by electric lighting, skylights can also significantly reduce the need for cooling.

However, if used ineffectively, skylights can also potentially increase heating loads by allowing more heat to escape through the roof, and increase cooling loads by allowing more of the sun's heat to enter a building. The optimum balance of lighting and cooling savings versus increased needs for heating or cooling is a function of the building design, the building operation and the local climatic conditions.

However, the potential energy savings from skylights are substantial. To provide a quick sense of the magnitude of these savings, the following calculations show the potential savings for a few typical buildings in the Los Angles, California area, using 2013 energy costs,[2] weather conditions from the San Fernando Valley, and many default assumptions. An average grocery store might save about $24,000 per year in operating costs, or $0.48/sf with the use of an appropriately sized skylighting system. A typical elementary school might save about $11,250 per year in operating costs, or $0.35/sf. An industrial processing and distribution center might save about $0.18/sf. These numbers vary considerably, based on building design, operation, climate location, and energy costs. Given these variables, the value of savings from skylighting might reasonably be expected to vary between a high of about $1.13/sf for air

2 Assumed a yearly average of $0.12/kWh for electric lights and cooling, and $.45/therm for gas heating.

conditioned buildings with intensive lighting use, and a low of $0.08/sf for unconditioned buildings with low lighting requirements (based on 2013 energy prices).

Skylighting as a lighting strategy is most obviously applicable to single story buildings which have large open areas. These generally include retail stores and shopping malls, grocery stores, schools, single story office buildings, manufacturing and agricultural buildings, and warehouses and distribution centers.

Since the vast majority of commercial and industrial buildings in California are single story buildings with flat roofs, most of them are appropriate for skylighting applications.[3] However, only a small percentage of these buildings have skylights, and an even smaller percentage of those use daylighting controls to save energy from the skylights.

The Commercial Building Energy Consumption Survey (CBECS) for 2003, prepared by the U.S. Energy Information Agency, revealed that less than 1% of all commercial buildings in the United States had any skylights. A recent analysis of lighting energy use in California[4] showed that the building types that are usually single story buildings and are best suited to skylighting also tend to dedicate large portions of their electricity use to lighting. The figures below show the average portion of each building type's electricity use that is dedicated to lighting:

Retail Buildings	43.0%
Grocery Stores	20.9%
Schools	38.5%
Small Offices	29.3%
Warehouses	49.6%
Average Commercial	**28.7%**

With the exception of grocery stores, all of these building types use more electricity on lighting than the statewide average. As a result, there is significant statewide energy savings potential from implementing skylighting in these building types.

How to Use These Guidelines

These *Skylighting Design Guidelines* focus on the use of skylights to provide uniform illumination in simple commercial and industrial buildings. They do not address residential buildings, or special, custom designed architectural spaces such as shopping mall arcades or grand hotel lobbies.

3 PG&E Codes and Standards Program. 2008. Draft Report – Updates to Skylighting Requirements. CEC Title 24 Building Energy Efficiency Standards. Prepared by the Heschong Mahone Group. http://www.energy.ca.gov/title24/2008standards/prerulemaking/documents/2006-07-12_workshop/reviewdocs/2006-07-11_SKYLIGHTS.PDF

4 California Energy Commission. California Commercial End-Use Survey, March 2006. Prepared by Itron. CEC-400-2006-005. http://www.energy.ca.gov/ceus/

The term "skylighting" is used throughout this text to refer to an illumination system that includes skylights, electric lighting controls, and a building designed to optimize the distribution of daylight.

The *Guidelines* start with the basics of skylighting, and become progressively more detailed. Initially, there is an introduction to the conceptual and qualitative aspects of daylighting from skylights, and the ways that they are used in buildings. Next, a number of important concepts are discussed that provide a better understanding of how skylighting works, and how to optimize its energy and cost benefits, using daylight-responsive controls to reduce electric lighting levels. The choice of the lighting control system has as much impact on energy savings as the choice of the skylights themselves.

This discussion of energy savings is then expanded to include the effects of skylighting on heating and cooling loads in buildings, peak electric demand, and other factors affecting skylight economics. A simplified analysis tool, *SkyCalc*, developed as an Excel® spreadsheet, estimates energy savings from skylighting based on various system parameter inputs. In combination with these *Guidelines*, *SkyCalc* assists designers in maximizing energy savings, while optimizing daylight illumination conditions using skylights.[5]

Newcomers to skylighting design should plan to spend enough time to cover the basics before using the more advanced material. Experienced designers may be able to skim the earlier sections and concepts, and proceed to the technical materials and the SkyCalc manual. For specific answers on a particular topic, refer to the Table of Contents to find the appropriate section.

The *SkyCalc* Spreadsheet Tool

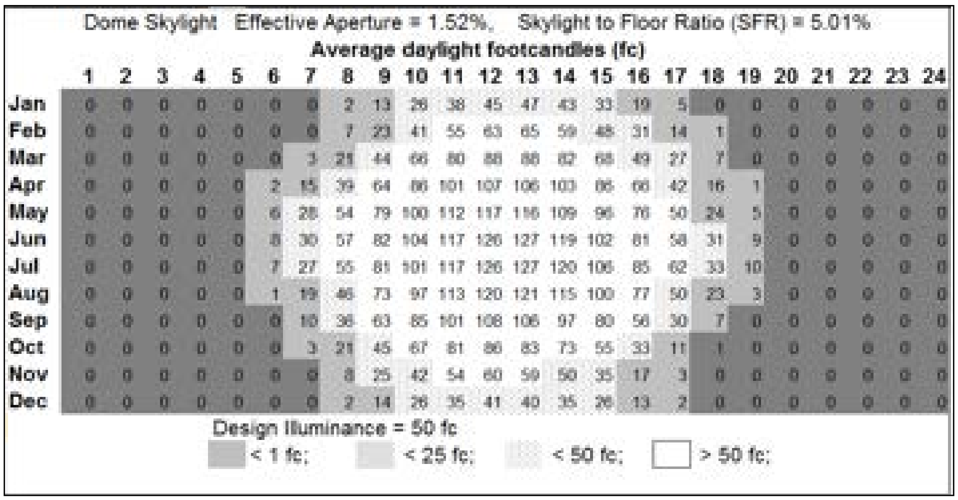
Correctly sized and with appropriate lighting controls, skylights can be a tremendous energy saver. An undersized skylighting system does not justify the cost of the electric lighting controls and never attains the desired effects of a well daylit space. An oversized skylighting system will over-light the space, admitting too much solar heat during the day and losing too much heat at night.

SkyCalc is a simple computer tool designed to help designers quickly determine the skylight strategy that will optimize lighting and HVAC energy savings. It is a spreadsheet application for Microsoft Excel®, and runs on any computer with Excel installed. The spreadsheet uses simple inputs to describe the building and the skylighting strategy and then calculates the lighting and energy impacts of the design. *SkyCalc* produces informative graphs and charts which describe the yearly energy use patterns. *SkyCalc* can be downloaded at http://www.energydesignresources.com/resources/software-tools/skycalc.aspx.

5 Note that several other software tools, including eQuest and Radiance, provide assistance in designing with skylights. For more information on skylighting in eQuest, see: http://energydesign-resources.com/training/tutorials/skylighting-in-equest-tutorial.aspx . For more information on Radiance, see: http://www.radiance-online.org/community/workshops/2013-golden-co/Rogers_RadianceDaylightDesign.pdf

The program can operate at three levels of detail. The first requires basic information about the design and uses extensive default settings to describe the skylighting system and the building operation. A second level allows the user to selectively change these defaults to more precisely describe the building. The third level of analysis allows the advanced user to create custom-defined products, building types and schedules. At this level users can enter performance data from specific products or detailed information about the actual operation of the building.

The program allows for analysis of a variety of typical climate conditions. Based on the climate data selected, *SkyCalc* calculates the level of illumination obtained from the skylights on an hourly basis throughout the year. The chart in Figure 1-2 illustrates the average hourly daylight illumination which would result from a given skylighting design for a particular climate. It is shaded to show which hours fall below the target footcandle setpoint of 50 fc.



Dome Skylight Effective Aperture = 1.52%, Skylight to Floor Ratio (SFR) = 5.01%

Average daylight footcandles (fc)

	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	17	18	19	20	21	22	23	24
Jan	0	0	0	0	0	0	0	2	13	26	38	45	47	43	33	19	5	0	0	0	0	0	0	0
Feb	0	0	0	0	0	0	0	7	23	41	55	63	65	59	48	31	14	1	0	0	0	0	0	0
Mar	0	0	0	0	0	0	3	21	44	66	80	88	88	82	68	49	27	7	0	0	0	0	0	0
Apr	0	0	0	0	0	2	15	39	64	86	101	107	106	103	86	66	42	16	1	0	0	0	0	0
May	0	0	0	0	0	6	28	54	79	100	112	117	116	109	96	76	50	24	5	0	0	0	0	0
Jun	0	0	0	0	0	8	30	57	82	104	117	126	127	119	102	81	58	31	9	0	0	0	0	0
Jul	0	0	0	0	0	7	27	55	81	101	117	126	127	120	106	85	62	33	10	0	0	0	0	0
Aug	0	0	0	0	0	1	19	46	73	97	113	120	121	115	100	77	50	23	3	0	0	0	0	0
Sep	0	0	0	0	0	0	10	36	63	85	101	108	106	97	80	56	30	7	0	0	0	0	0	0
Oct	0	0	0	0	0	0	3	21	45	67	81	86	83	73	55	33	11	1	0	0	0	0	0	0
Nov	0	0	0	0	0	0	0	8	25	42	54	60	59	50	35	17	3	0	0	0	0	0	0	0
Dec	0	0	0	0	0	0	0	2	14	26	35	41	40	35	26	13	2	0	0	0	0	0	0	0

Design Illuminance = 50 fc

< 1 fc; < 25 fc; < 50 fc; > 50 fc;

FIGURE 1-1:
SkyCalc Daylight Illumination Chart

An optimization feature graphically represents the energy performance of the skylights and lighting controls specified in the inputs, as illustrated in Figure 1-3. The graph shows performance over a wide range of possible skylight-to-floor areas and identifies where the current design lies. The graph below shows an optimization curve for a grocery store in Bakersfield, California with double glazed, acrylic skylights, and a dimming control system for the electric lighting. The design uses skylights that are 5% of the gross roof area of the building. It is apparent from this graph that this design will save significant energy, and that it is close to the optimum area for skylights in terms of overall building energy use, given the system described. A similar graph also calculates energy savings in terms of dollars saved.

Reports in *SkyCalc* are easily printed, just as from any other Excel file, and adjustments can be made to the basic spreadsheet by anyone familiar with the program. *SkyCalc* is installed as an Excel template, so that a new copy of the basic file can be saved for different building projects and/or climate zones. *SkyCalc* can be used in conjunction with these *Guidelines* to make it easier for designers to select the best skylighting system for a given building.

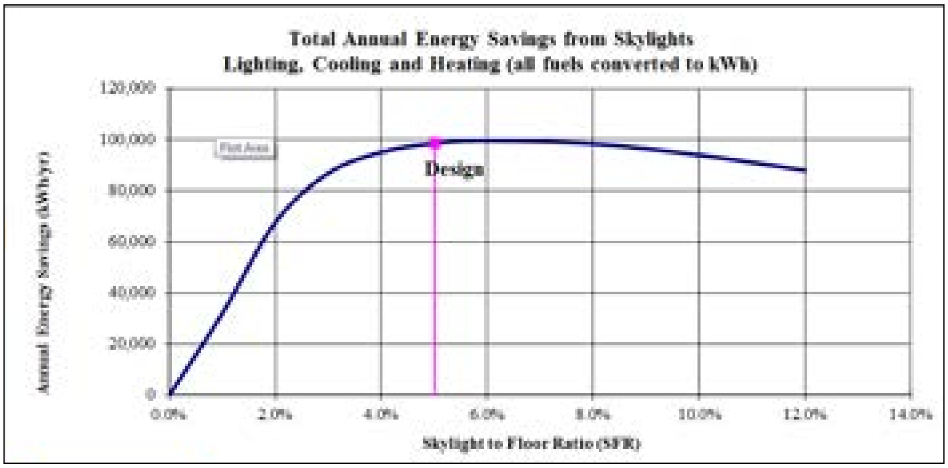


FIGURE 1-2:
SkyCalc Optimization Graph

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Chapter 2: Designing With Skylights

This chapter covers the more conceptual and qualitative aspects of skylights and daylighting controls that need to be understood by the architect and engineer as a building's design is being formulated. Later chapters provide numerical values useful in calculations, and more detailed information and advice useful to the specifier and building manager.

The discussion starts with how the sources of daylight outside interact with the building, then moves on to the skylight itself, and finally into the space below, addressing interior design and building operation issues. The basic parts of a skylight are show below in Figure 2-1.

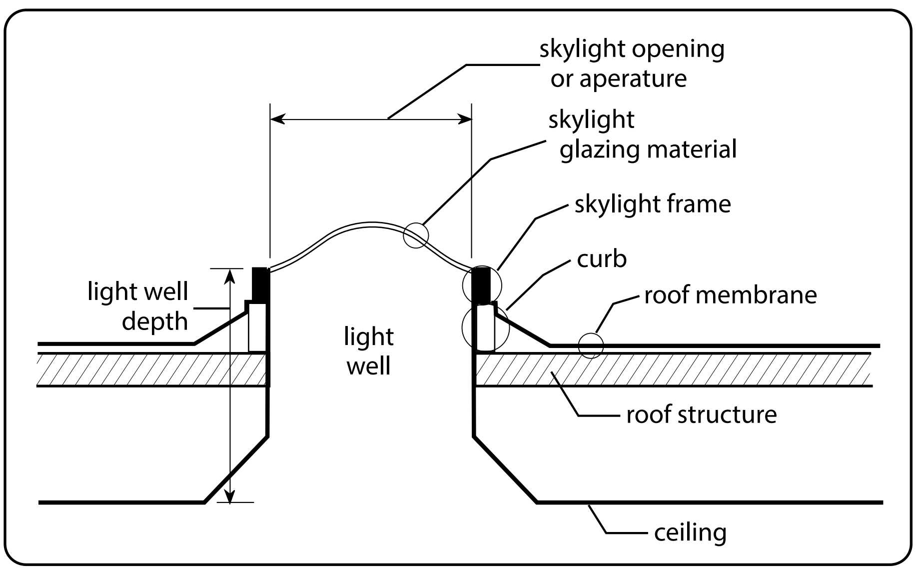


FIGURE 2-1: Components of a Typical Skylight

Characteristics of Daylight

The amount of light skylights can provide depends directly on how much daylight is available outside, which varies with climatic conditions, the time of day and the season of the year. The greatest amount of daylight is available on bright sunny days. On very dark, rainy days less daylight is available. In winter, days are short and the number of daylight hours may be 8 hours or less. In summer, days are long and daylight may last for 16 hours or more per day.

Since the light sources in skylighting are the sun and the sky, it is important to understand the different quantities and qualities of daylight from each source, and how they vary with climate and time of day. The specifics of the local climate will affect the optimum skylighting design for a given area.

Direct Sun Light versus Diffuse Sky Light

People often assume that "sun light" and "sky light" can be used synonymously. In reality, they have very different physical properties and different effects on skylighting design. The most important differences are intensity, color, and how much light is scattered, or diffused.

FIGURE 2-2:
"Sun light" versus "sky light"

"Sun light" is light that comes directly from the sun. The sun is considered a point source of light, often referred to as "direct" or "beam" sun light, because it is highly directional. Beam sun light casts sharp shadows. "Sky light," on the other hand, is the diffuse light that comes from the overall sky dome (for the sake of clarity, this document will use "sky light" to refer to diffuse sky conditions, and "skylight" to refer to the fenestration product). Light from the sky arrives from a large area and is diffuse, meaning scattered and arriving from all directions. Diffuse light does not cast a distinct shadow. On a bright cloudy day, some beam sun light makes it through the clouds casting an indistinct, fuzzy shadow. Depending on the proportion of beam to diffuse light delivered by local weather conditions, the performance of skylight products will vary.

Sun light generally provides 5,000 to 10,000 footcandles of illumination. The intensity of sun light varies with time of year and location on the planet. It is most intense at mid-day in the tropics when the sun is high overhead and at high altitudes in thin air, and least intense in the winter in the extreme latitudes, when the low angle sun light takes the longest path through the atmosphere.

Sun light also provides a warm to neutral color of light (which is characterized by its *correlated color temperature* - CCT - expressed in Kelvin), varying from a warm candlelight color at sunrise and sunset, about 2000K, to a more neutral daylight color at noon of about 5500K.

	Light Direction	Illumination (fc)	Brightness (cd/m2)	Color Temp.	Color Description
Sun at midday	beam	8,000 - 10,000	1,600,000,000	5,500K	neutral white
Sun at horizon	beam	3,000 - 8,000	6,000,000	2,000K	warm yellow-orange
Clear sky	diffuse	1,000 - 2,000	8,000	10,000K	bluish
Cloudy sky	diffuse & beam	500 - 5,000	2,000	7,500K	cool white
Incandescent	diffuse or beam	varies	varies	2,700K	warm white
Fluorescent	diffuse	vaires	varies	3,000 - 5,000K	warm to neutral white

FIGURE 2-3: Daylight characteristics

Sky light, as opposed to sun light, includes the light from both clear blue and cloudy skies. To the surprise of many, cloudy skies can be much brighter than clear blue skies. The brightness of cloudy skies depends largely on how thick the clouds are. A light ocean mist can be extremely bright, at 8,000 footcandles, while clouds on a stormy day can almost blacken the sky. The daylight on a day with complete cloud cover creates a very uniform lighting condition.

Sky light from clear blue skies, on the other hand, is surprisingly non-uniform. The blue sky is darkest at 90º opposite the sun's location, and brightest around the sun. Sky light also has a cool, blue cast to it, with color temperatures of up to 10,000K. Sky light from cloudy skies is warmer in color, a blend somewhere between sun light and clear blue skies, at about 7,500K.

In a given climate, the proportion of cloudy days to clear sky days, and of direct beam sun light to scattered sky light, will determine how much illumination is available for skylight daylighting in a building. This mix of climate conditions will influence design factors such as skylight glazing materials, light well design, and daylighting control strategies. For example, dimming controls on electric lighting systems may be more appropriate for areas with low daylight availability, while switching controls may be acceptable in areas with predictably sunny weather.

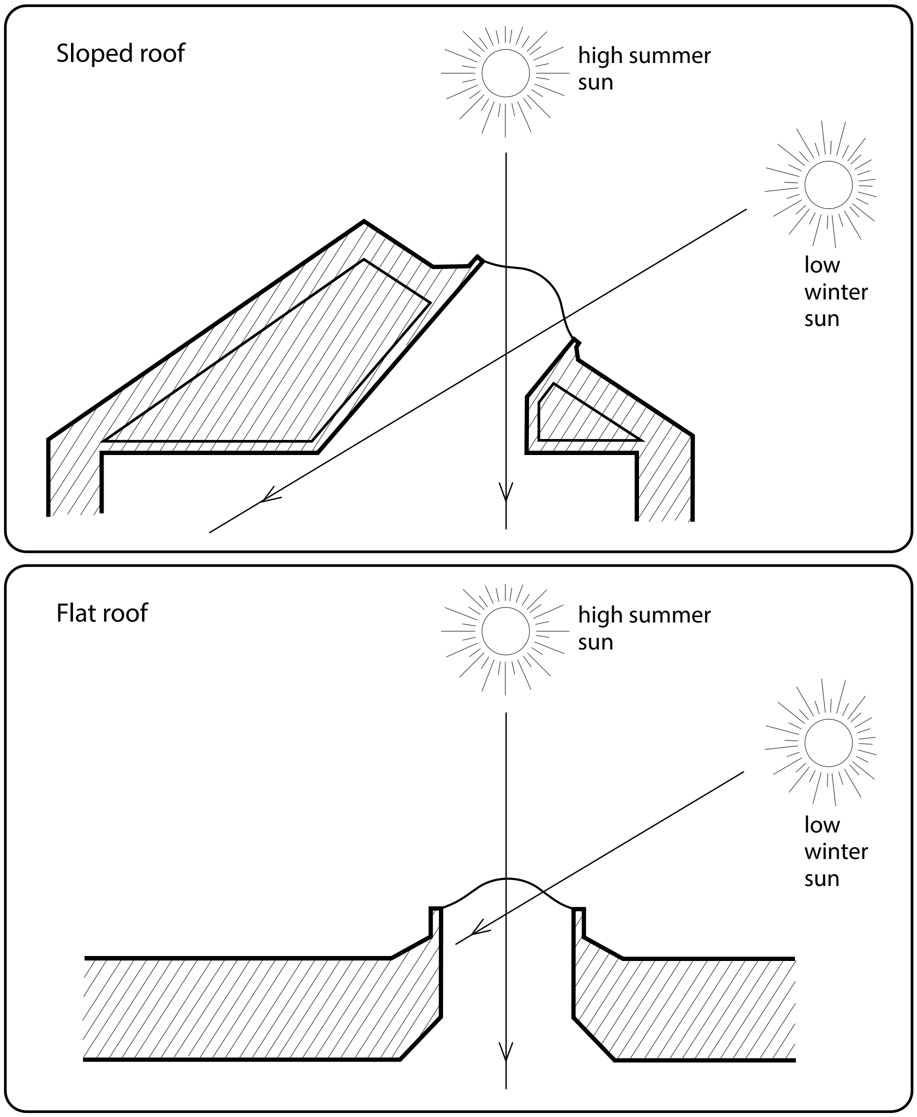
Solar Geometry

The majority of commercial and industrial skylights are installed on flat roofs, where the skylight has access the full hemisphere of the sky. Typically, there are few obstructions to block sun light from reaching the skylight, although the location of rooftop HVAC or other equipment can significantly affect daylight access at an individual skylight. In urban settings, adjacent multistory buildings can also have an impact.

A skylight on a sloped roof has access to only a portion of the sky hemisphere, determined by the slope of the roof. Furthermore, depending upon the angle and orientation of the sloped roof, the direct sun light may not reach the skylight during certain times of the day or year. For example, a skylight on an east facing roof with a 45º slope will only receive direct sun during the morning and midday hours. In the afternoon it will receive sky light, but only from ¾ of the sky. As a result, in the afternoon it will be able to deliver substantially less light to the space below than an identical skylight located on a flat roof.

FIGURE 2-4: Sun Penetration on Flat versus Sloped Roofs

The slope and orientation of the roof and the light well have a major impact on how much direct sun light penetrates into the interior of the building.



The shape of a skylight also affects the quantity of sun light entering into a building's interior at different times of the day, although the effects tend to be much more subtle than changing the building's roof slope or orientation. For example, a flat glazed skylight on a flat roof will receive very little sun light when the sun is low in the early morning and at the end of the day. However, a skylight with angled sides, whether a bubble, pyramid, or other raised shape, will receive substantially more sun light at these critical low angles, increasing the illumination delivered below by 5% to 10% at the start and end of the daylight hours.

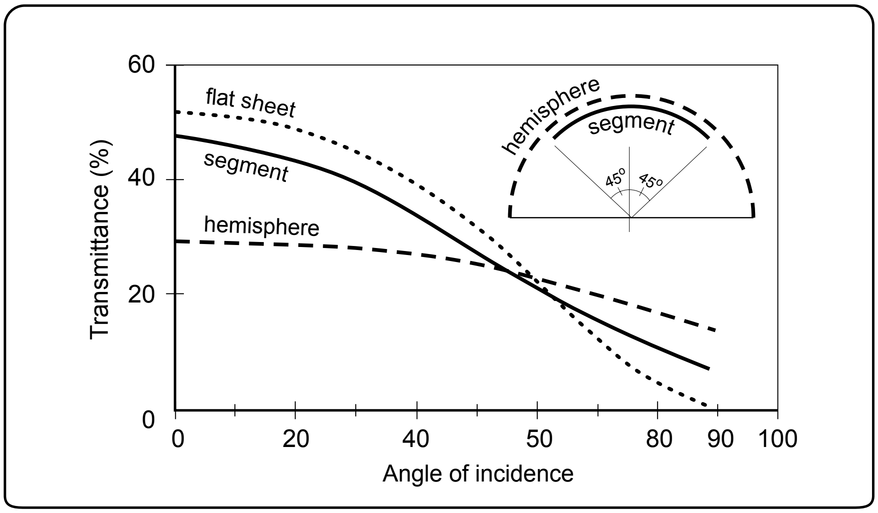


FIGURE 2-5:
Transmission of Light in Domed Skylights

A domed or pyramid skylight shape on a flat roof will transmit slightly more sun light than a flat skylight at low sun angles and less sunlight at high sun angles.

Figure 2-5[1] illustrates the difference in transmission of solar energy (light and heat) for a 50% translucent glazing material as a function of the angle of incidence for three different shapes—a flat skylight, a hemispherical skylight, and a segment of a sphere (which most closely models the typical bubble skylight). It shows for very low sun angles (60° - 90° angle of incidence) that the rounded shapes will collect noticeably more light. Note that they also admit less light at midday.[2]

Skylight Types and Placement

The size, shape, number and location of skylights on a roof are among the most basic decisions affecting performance of a skylighting system.

Sizes and Shapes

Skylights are available in a wide variety of shapes, from simple rectangles to complex polygons. Sizes vary as well. Individual skylights can be small enough to fit between rafters. Individual units can be grouped to run the length of a building or cover large spaces. Glazing comes in several configurations as well. Flat glazing can be used in a single plane or in a faceted framing system that assumes various pyramid shapes. Plastic glazing is also available in molded dome or pyramid shapes for greater stiffness. Figure 2-6 shows a variety of standard skylight shapes.

The challenge for the designer is to integrate the form and light admitting properties of the skylight with the design concept for the building. This is usually achieved by selecting skylights that complement the

1 L. Schutrum and N. Ozisik, "Solar Heat Gains through Domed Skylights," ASHRAE Journal, August 1961

2 *SkyCalc* does not currently account for this difference in transmission as a function of angle of incidence and shape of skylight.

ceiling grid and room proportions. Examples can be found in manufacturer's literature and by visiting buildings with skylights.

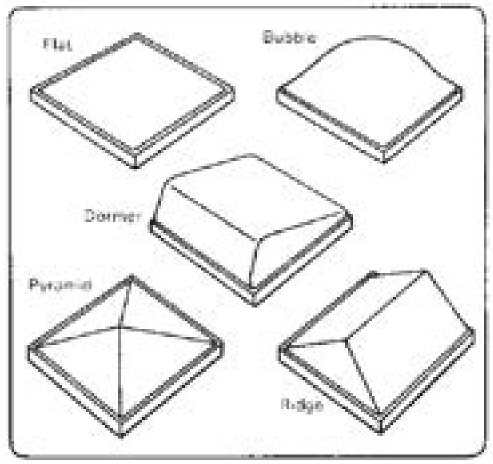


FIGURE 2-6:
Basic Skylight Shapes

Skylights are available in a wide range of standard shapes and sizes. In addition, custom skylights can be fabricated to meet nearly any requirement.

For complete information on the skylight size and shape options available, consult specific manufacturer's data.

Layout and Spacing

The layout and spacing of skylights in a roof are important determinants in the light distribution characteristics of the skylight system. Given a fixed percentage of the roof area devoted to skylights, a designer could select anything from a single large skylight to many small skylights distributed uniformly across the roof. For special applications, such as entry lobbies or small rooms, the skylight layout will probably be dictated primarily by the design concept for the space. However, when skylights are provided in order to create uniform lighting in large open spaces, careful attention to spacing is important.

For the same total skylight area, the tradeoff is typically between large skylights far apart versus smaller skylights spaced closely together. Large, widely spaced skylights are usually the most economical to install, but may produce bright conditions under the skylights, and relatively dark conditions in between. This results in uneven light distribution, reduced energy savings, and possible glare problems. Small closely spaced skylights, on the other hand, will provide more uniform lighting conditions and greater energy savings, but will be more costly to install.

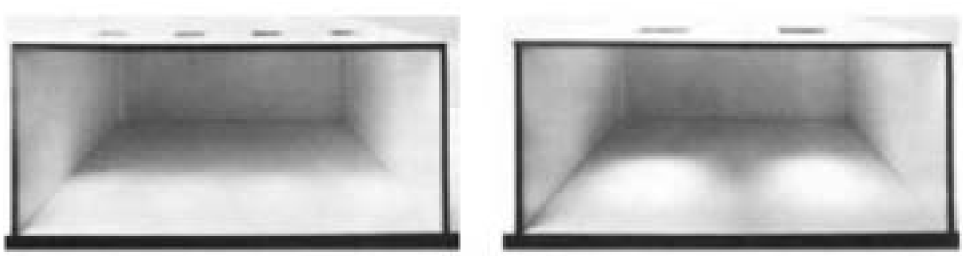


FIGURE 2-7:
Effect of Skylight Spacing

Skylighting spacing affects the uniformity of light distribution.

The differences in illuminance level between locations directly under the skylight, compared to locations between skylights, will be greater as skylight spacing becomes wider. The left photo shows close skylight spacing, with relatively even illuminance at the work plane; the right photo shows a wider range of light and dark areas. The total skylight area is the same for both.

The general rule-of-thumb is to space skylights at 1.0 to 1.5 times ceiling height (center-to-center in both directions). This assumes a highly diffusing glazing and a modest depth for light wells. Actual designs can vary considerably from this rule of thumb for spacing. For example, if the light well is widely splayed (see the "Light Wells" section, below), the vertical dimension to the bottom of the skylight can be used instead of the ceiling height. Skylight placement must be coordinated with the structural, mechanical and lighting systems; and other variables also come into consideration, such as glazing type, light well design, controls, and the other factors discussed below. SkyCalc includes a simple "Spacing Calculator" to help designers choose an optimum spacing.

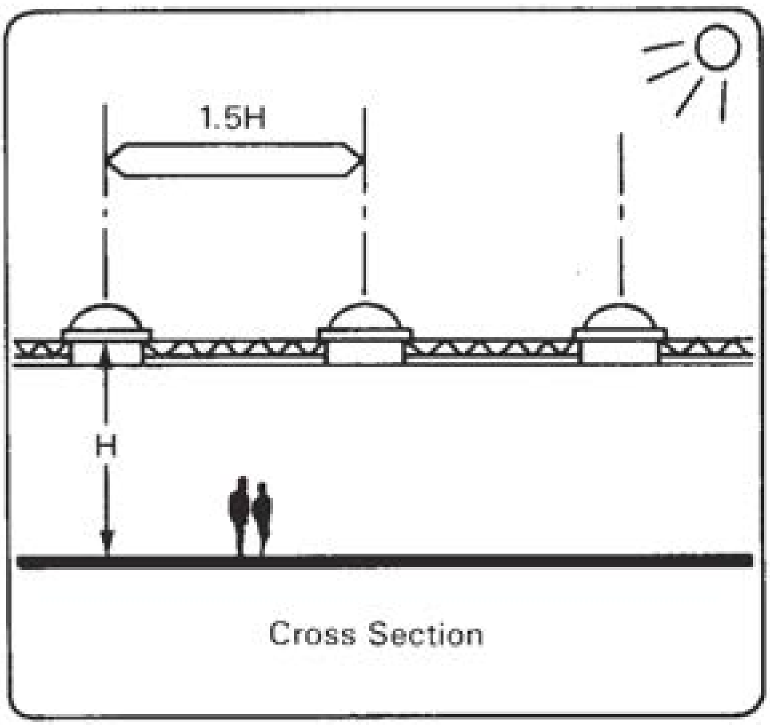


FIGURE 2-8:
Spacing Rule-of-Thumb

Skylights should be spaced between 1.0 and 1.5 times the ceiling height. This generally produces acceptable uniformity in illuminance levels.

Skylight Glazing

The common glazing materials for skylights include a variety of plastics and glass. The common plastic materials include acrylics, polycarbonates, and fiberglass. These materials come in a variety of colors—from clear, to translucent white, to bronze and gray colors. They also come in a variety of thicknesses, and number of layers. All these variables affect the performance of the skylight.

The choice of the glazing material for a skylight can have significant effects on the quality of the light provided and the energy efficiency of the design. Factors to consider include:

- How much light is transmitted through the glazing—measured by the visible transmittance (VT)
- How much direct beam sunlight is diffused—measured by the transparency of the material[3] or the haze rating
- How much of the sun's radiant heat is transmitted through the glazing—measured by the solar heat gain coefficient (SHGC).
- How much heat from the air will pass through the glazing—measured by the U-factor of the skylight unit assembly

There are other properties to glazing that are also important in selection, such as the strength of the material and the resistance to breaking or cracking, and how the material will age over time. These, and other technical issues related to glazing, are discussed in greater detail in Chapter 3 - Specification Choices.

Transmission of Light

In terms of the lighting performance of a skylight, the two most important properties are how much light is allowed to pass through, and how much the light striking the skylight is diffused. It is a common assumption that the more transparent a piece of glazing is, whether glass or plastic, the more light will pass through it. However, the two properties—transmittance and transparency—are not directly related.

For example, it is possible to have a material which scatters all of the light that strikes it, while still allowing a very high percentage of light to pass through. A common example is frosted or patterned glass. Although a clear image cannot be seen through the glass, just as much light can pass through the glass as through clear window glass. Another example is the plastic lens commonly found in a florescent lighting fixture. The prismatic pattern in the plastic prevents a clear view of the fluorescent lamp inside the fixture, but allows almost all of the light to pass through, scattering it in the process.

The converse is also possible, with a transparent material obstructing most of the visible light that strikes it. All tinted glasses do this to some extent, with some transmitting less than 10% of the visible light.

In general, the higher the visible transmittance of the material, the more efficiently the skylight can provide light to the room below. Diffusion of beam sunlight is important to avoid "hot spots" below, where sunlight is more concentrated and can create areas that are both too bright and less comfortable due to the radiant heat of the sun. Highly diffusing skylights are important to achieve uniform illumination,

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3 Transparency is not typically reported for skylight glazing materials. However, there is an ANSI Standard Practice for Goniophotometry, E-167-96, which reports on the geometrical distribution of light transmitted through a glazing material.

allowing the overall lighting system and controls to be more efficient. When skylights are prescriptively required by California's Title 24 Energy Standards, they must have a haze rating of at least 90%.

Transmission of Heat

The choice of glazing materials also affects the amount of heat that passes both in and out of the skylight. The two key characteristics to consider in relation to heat transmission are the relative proportion of the sun's radiant heat that is blocked by the glazing material, measured by solar heat gain coefficient (SHGC), and the overall resistance of the skylight unit to all types of heat flow, measured by U-factor.

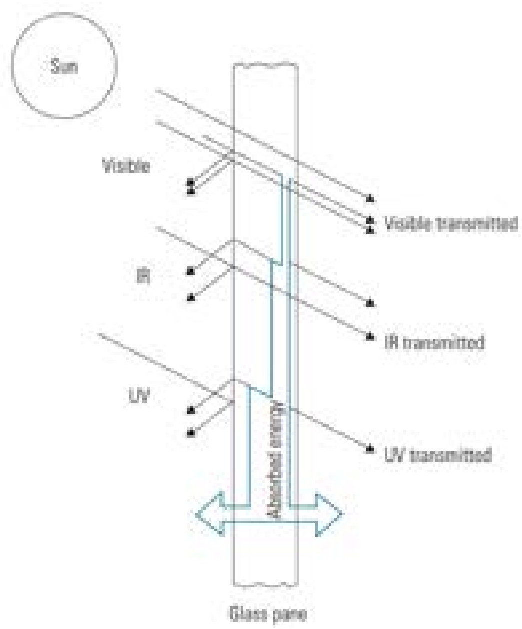


FIGURE 2-9: Light and Heat Transmission through Glass

Glass or other skylighting materials allow some solar energy to pass through, while reflecting and absorbing the remaining portion of the solar energy. In addition to visible light, skylighting materials transmit, absorb or reflect infrared (IR) and ultraviolet (UV) solar energy.

All wavelengths of solar radiation transmit heat, but only about 50% of solar wavelengths are perceived by humans as visible light. Different glazing materials will transmit, absorb, or reflect different portions of the sun's spectrum. If the glazing material is highly transmissive to visible light, as well as to wavelengths in the infrared and ultraviolet portions of the solar spectrum, a high percentage of the sun's radiant energy will pass through to the space below, and the skylight will have a high solar heat gain coefficient. If more of the radiant energy is reflected, then the material will have a lower solar heat gain coefficient.

If the non-visible components of solar radiation are absorbed, rather than reflected or transmitted, then the glazing material itself will heat up. Part of the heat will be conducted downward into the space, raising the solar heat gain coefficient. The rise in temperature of the glazing material may also cause it to expand and deform, which is very undesirable.

For skylighting, the most efficient glazing material will allow the maximum amount of light to pass through, while rejecting the non-visible wavelengths of solar radiation. Such a material maximizes useful light while minimizing unnecessary heat gain in the space below. This concept of an efficient, spectrally-selective glazing material for daylighting is based on a relatively high visible transmittance in conjunction with a comparatively low SHGC, and is described by a term skylight efficacy (SE). Skylight efficacy is described in greater detail in Chapter 5.

There are many more spectrally-selective products available for window glass than for plastic skylights. Plastics are more limited in their chemical formulations by structural and forming considerations. Also, special coatings that help increase the daylighting efficacy of glass are difficult to use with the plastic materials suitable for making skylights. Plastic skylight manufacturers have instead focused on improving the light transmission and insulation value of their products.

The heat flow through the entire skylight assembly, frame and glazing, is indicated by the unit's U-factor. U-factor considers heat transfer by conduction, convection, and radiation. Because U-factor describes the rate of heat flow, lower is better. Adding additional layers of glazing to create dead, insulating air spaces is one way to improve a skylight's resistance to heat flow. Just as double or triple glazed windows decrease heat loss, so do double or triple glazed skylights.

Bubble skylights can be manufactured with two layers of formed plastic. Plastic skylights can also be made with one shaped glazing layer, and one or more flat layers below. Some skylight manufacturers use inner layers of transparent mylar to add additional insulating layers to their units.

Since each glazing layer inevitably represents additional cost, and loss of light, there is obviously a balance point at which the benefits of an additional insulating value is not cost effective. This balance point is highly dependent upon the local climate conditions, the design and operation of the building, and the relative costs of electricity versus heating fuels. The SkyCalc tool is specifically designed to help determine this balance point for the designated climate.

Another factor in determining a skylight unit's U-factor is the material used in the frame. Aluminum is highly conductive. Some aluminum frames are designed with internal thermal breaks, non-metal components that reduce conductive heat flow through the frame. Specification of a thermally-broken, double-glazed skylight should be the starting point for good practice.

Daylight Distribution

Once daylight has passed through the skylight glazing, it can be controlled and diffused by the shape and reflective properties of light wells, shading devices, and the surfaces of the room itself. Well balanced lighting conditions are essential to the visual comfort of the building occupants.

Light Wells

Light wells are an essential component of skylights. They bring the light through the roof and ceiling structure, and they simultaneously provide a means for controlling the incoming daylight before it enters the main space. The light well is similar to the housing of an electric light fixture. It is designed to distribute the light, and to shield the viewer from an overly bright light source.

Light wells can be designed in a wide variety of shapes. At the simplest, they are vertical-sided shafts, the same size as the skylight opening. More elaborate wells have splayed or sloping sides that spread the light more broadly through the space. Figure 2-10 shows some common well shapes.

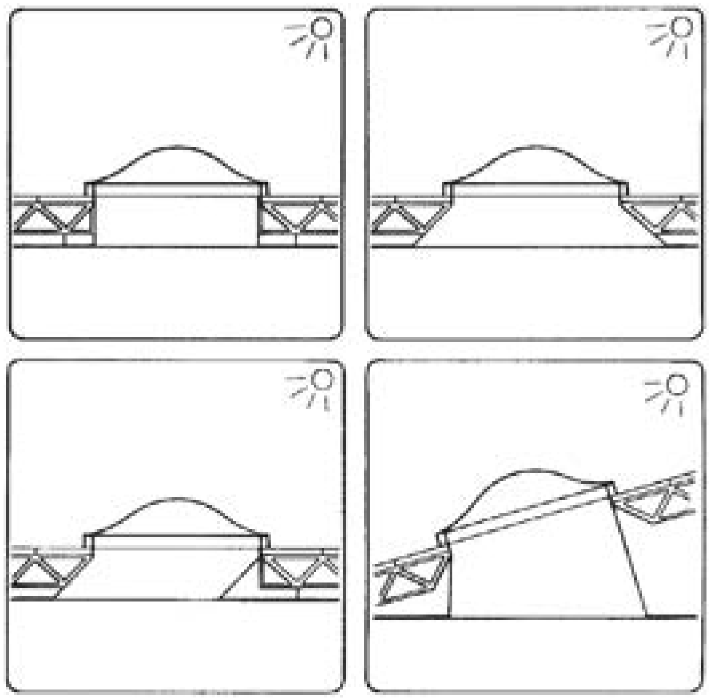


FIGURE 2-10:
Types of Light Wells

The shape and size of the light well is often determined by the roof and ceiling structure. Wells can be made from wood, gypsum board, ceiling tiles, other common construction materials, or proprietary light well products can be used.

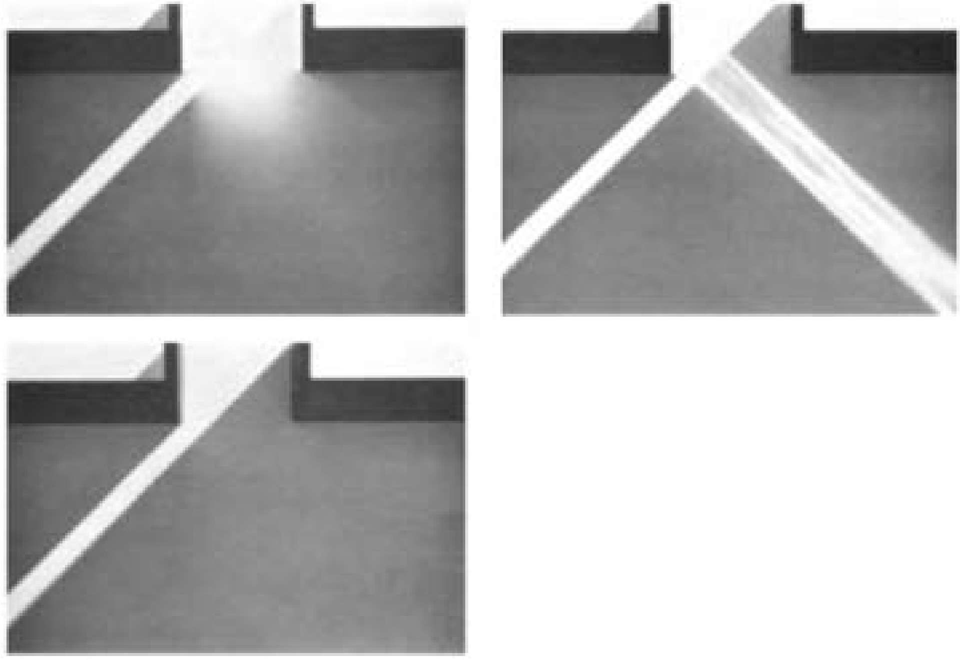
In some buildings, light wells consist only of the depth of the curb and the thickness of the roof structure, but in buildings with hung or dropped ceilings, the skylight well can become several feet deep. Deep wells are an opportunity for greater control of the distribution of the daylight from skylights.

In designing wells for skylights, there are a number of factors that must be considered:

- *Surface reflectance.* Light wells reflect and diffuse sunlight as it bounces from the skylight to the task surface. A highly reflective, diffusing surface (such as flat white paint) will help to provide a diffuse, broadly distributed light pattern below the skylight. A specular reflective surface, such as reflective foil, will not diffuse the light, but will reflect an image of the sun and sky onto a limited area below the skylight. Colored surfaces will distribute the light evenly, but will reduce its intensity and can dramatically shift the appearance of colors in the room below. For applications where uniform light distribution is desired, a matte white surface is best.

FIGURE 2-11:
Reflective Properties of Well Surfaces

Diffuse walls (e.g., flat or matte paints) reflect incident light in all directions, spreading the brightness (top-left). Specular walls (e.g., mirror surfaces) reflect a direct image of the sun or skylight to the space below (top-right). Semi-specular walls (e.g., gloss paints) exhibit qualities of both diffuse and specular reflection (not shown). Deeply colored well surfaces reduce nearly all light scattering, and tend to admit only direct sunlight (left).



- *Wall Slope.* The slope of light well walls helps to determine the distribution of light in the space. The broader the base of the well, the larger the task area in the space having a direct view of the skylight. This is an advantage under overcast sky conditions or with a diffusing skylight, but it can be a serious disadvantage with a transparent skylight when direct sunlight is present. Deep wells with vertical walls prevent direct view of the skylight and block low angle beam sunlight, but tend to keep the light concentrated in a smaller area and provide less uniform light distribution.

- *Solar geometry.* The height and orientation of the sun change both daily and seasonally. The direct sun light that enters a transparent skylight can be prevented from penetrating down to the task surface by light wells; conversely, the wells can reflect the sun light to a particular destination. Blocking the sun at higher angles above the horizon requires a deeper light well than blocking the sun at low sun angles. Sun path studies are used to design for direct sun control. With diffusing skylights, the angle of the sun is less of a concern, but the amount of light and heat entering the space will still be affected by solar geometry.

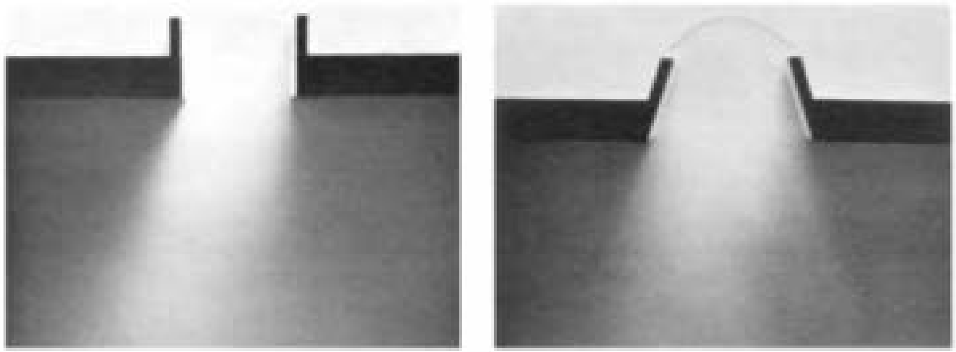


FIGURE 2-12:
Splayed Wall Effect

Splayed light well walls (right photo) allow a larger area of the space to view the skylight surface. With diffusing glazings, this helps provide uniform illumination.

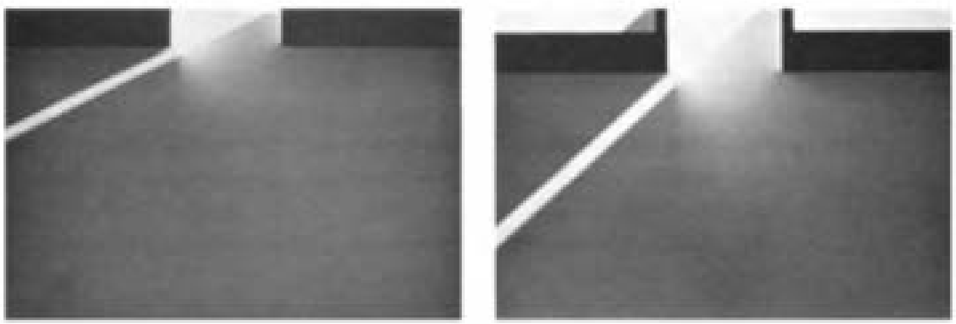


FIGURE 2-13:
Shading of Direct Sun by Light Well

If transparent glazings are used, the design of the light well must carefully consider sun angles. Light wells can provide a means of cutting off direct sun penetration. The photo on the left shows a shallow well. The deeper well on the right cuts off higher angle sunlight.

In addition to the surfaces of the light well, daylight can also be controlled and diffused with the use of additional vertical surfaces like banners or structural elements, or horizontal shading devices located under the skylight in the light well. Operable shading devices, whether manual or automatic, can also allow the amount of light reaching the room to be controlled, from full brightness to dim. (Shading options are discussed in Chapter 3)

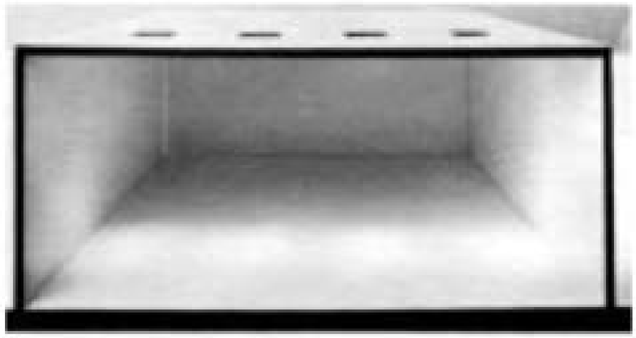
Room Surfaces

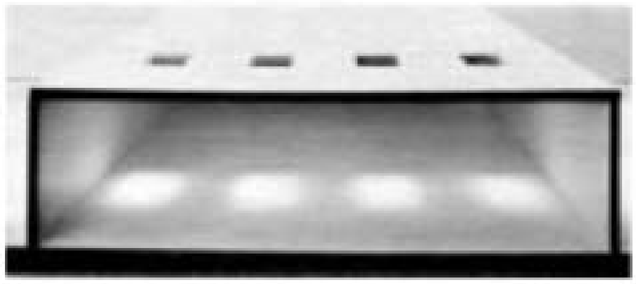
Once the daylight has penetrated past the glazing, the light well and the shading devices, it interacts with the interior of the building. There, it can be absorbed and contained, or bounced and blended, depending on the building design and the intended use of daylight.

With skylights, ceiling height strongly influences daylight distribution within the space. Depending on skylight size, spacing and light well design, varying the ceiling height may increase or decrease the uniformity of the daylight distribution. Keeping all the other parameters constant, as ceiling height is increased, the light transmitted by skylights is distributed over a larger floor area and working plane. This generally results in more uniform skylighting. Lower ceiling heights result in less uniformity, with brighter areas under the skylights and darker areas in between. As a rule-of-thumb, skylight spacing should be 1.0 to 1.5 times the ceiling height. (See the "Layout and Spacing" section, above)

FIGURE 2-14:
Effect of Ceiling Height on Light Distribution

For the same skylight spacing, a higher ceiling height will result in more uniform illuminance levels at the work plane (top photo). Lower ceiling heights exhibit darker areas between and brighter areas under the skylights (bottom photo).

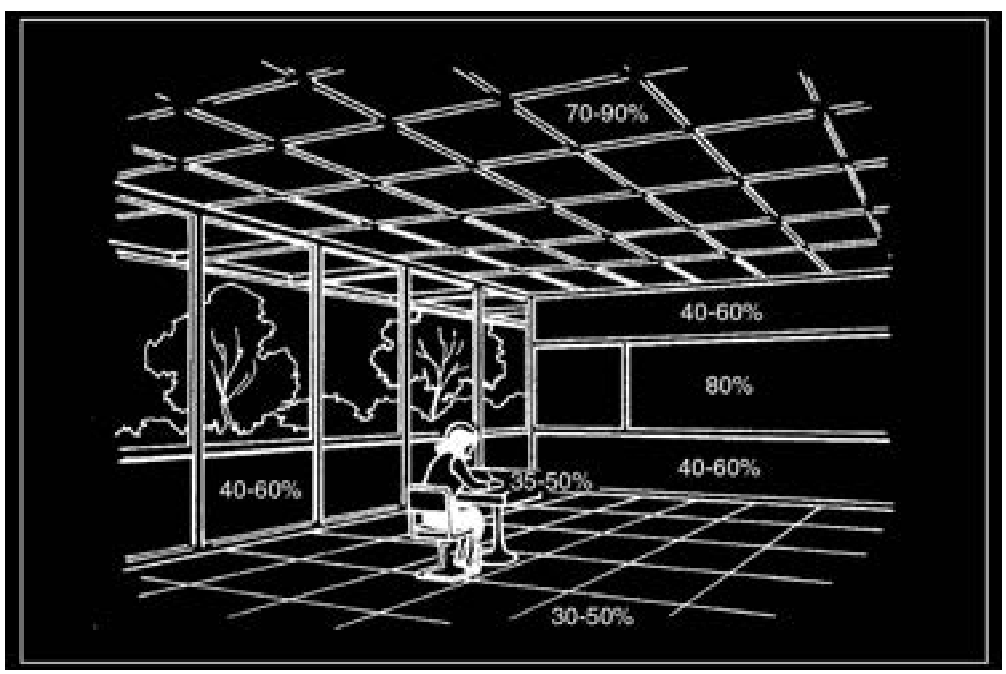




The surface reflectances of walls, floors, ceilings, and furnishings also have an impact on light distribution. Light colored surfaces, which have high reflectances, will help to distribute brightness around the space, and this, in turn, will reduce the brightness contrasts that cause visual discomfort. It is especially important for ceilings to be light colored, so that they are as bright as possible. This reduces the glare potential from having bright skylights next to darker ceiling areas. High reflectance floors and furnishings will also help in this regard, because they help to brighten the ceiling. (See Chapter 5 for specific values of reflectances of various colors and surface materials)

FIGURE 2-15:
Room Surface Reflectances

As a rule, primary surfaces should be white or very light colors to reflect as much light as possible. More saturated colors can be used on smaller and secondary surfaces where light distribution is not as important.



It is important to use matte textures on major surfaces to further diffuse the light. Shiny or specular surfaces tend to reflect bright images of the skylights, which can be visually uncomfortable. For example, a highly-polished dark-colored floor will reflect an image of the skylights (and electric lights) above, which can cause glare and visual discomfort.

Visual Comfort

A primary objective in the design of any lighting system (daylight or electric light) is to provide the illuminance levels required for visual performance at the task, using a system that enhances visual comfort in the work environment. Both ceiling-mounted electric lights and skylights have the potential to cause visual discomfort, and the techniques for avoiding this are the same:

- Avoid excessively bright sources within the occupants' field of view
- Avoid reflections from bright sources on the work surface.

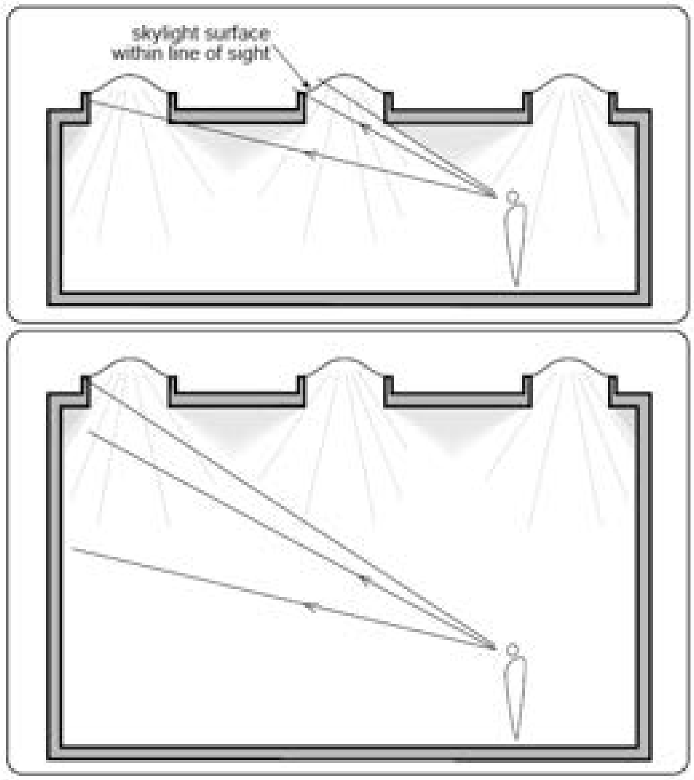
Bright light sources in the field of view can cause discomfort glare. This is the result of a strong contrast between the light source and the illumination levels surrounding field of view, such as looking out a bright window past silhouetted objects. The eye has difficulty accommodating to the contrast differences.

The surface of diffusing skylights can become very bright in sunlight, and is a potential source of glare to people working in the space. If the skylight is directly in an occupant's line of vision, it may cause visual discomfort, as their eyes try to adjust between the extremely bright skylight and less bright room surfaces.

The height of the ceiling in relation to the proportions of the room affects the probability that the skylight may cause glare. If a room has a very low, or very large ceiling, it is more likely that the skylights will be within the occupants' field of view. The higher the ceiling, the less likely this is to be a problem. Using a section drawing of the building to understand the angles of sight within the room is the best way to determine if there may be a potential problem.

FIGURE 2-16:
Visual Comfort Effect of High versus Low Ceilings

A high ceiling keeps skylights out of the line of view, reducing the need for other glare control efforts.



Careful design of the light well can prevent direct view of the skylight, while still allowing wide distribution of the light. This is best understood in relation to the "cut-off" angle created by the light well. "Cut-off angle" is a term frequently used in relation to light fixtures. It describes the angle of a line of sight, such that a viewer cannot directly see the bright light source in a lighting fixture. For lighting fixtures in offices with computers, the IESNA recommends a minimum 55º cut-off angle from vertical. A similar principle is involved with skylights, where a proper cut-off angle for the light well prevents a viewer from seeing the bright surface of the skylight. In skylit buildings with less critical visual tasks, such as warehouses and some retail situations, a less stringent cut off angle of 45° to 50° will usually be sufficient. However, in skylit offices and classrooms, a sufficient cut off angle to block direct views of the skylight surface is necessary to maintain visual comfort.

Some manufacturers and designers have created light wells that include a diffuser at the bottom to further spread the light. If the diffuser is dropped below the ceiling plane, it will contribute some daylight to brighten up the ceiling. However, it is also more likely to come into the field of view of the occupants. Since the diffuser will be the brightest object in the room, the probability of glare is very high. If the dropped diffuser is kept above the ceiling plane, it will be more removed from the occupants' field of view. With a splayed well, a recessed diffuser can still spread the light widely. The splayed well will tend to reduce ceiling contrasts, as will light reflected from the floor below.

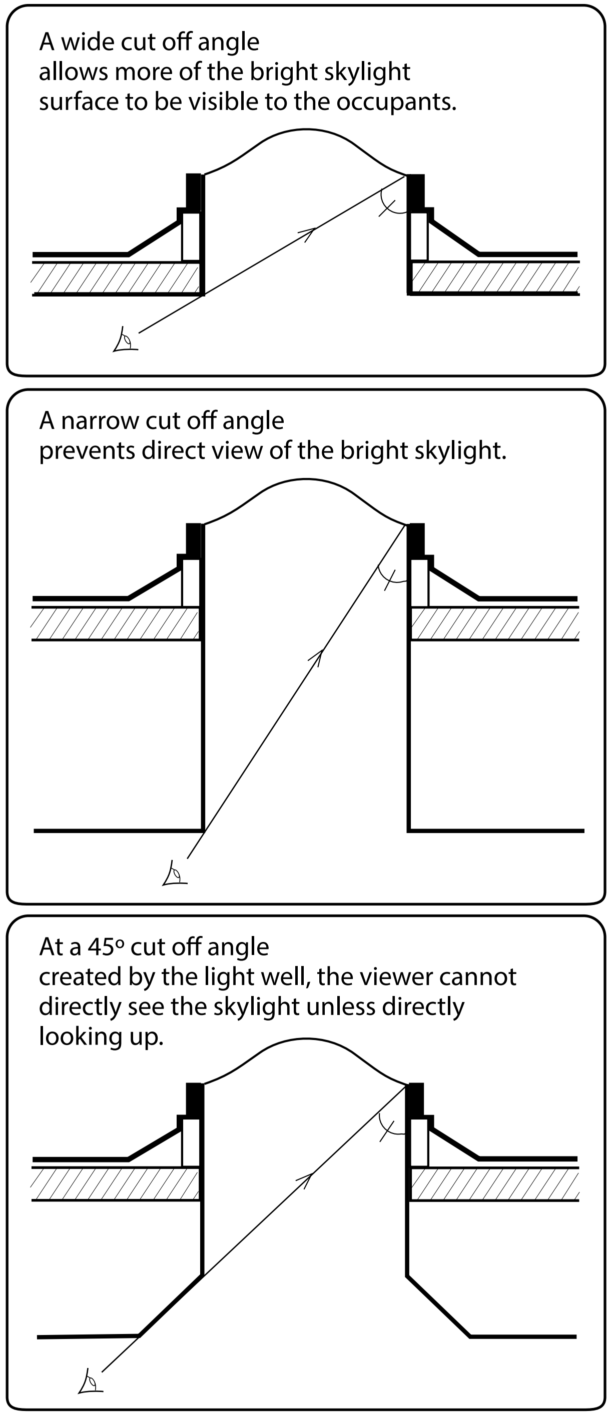
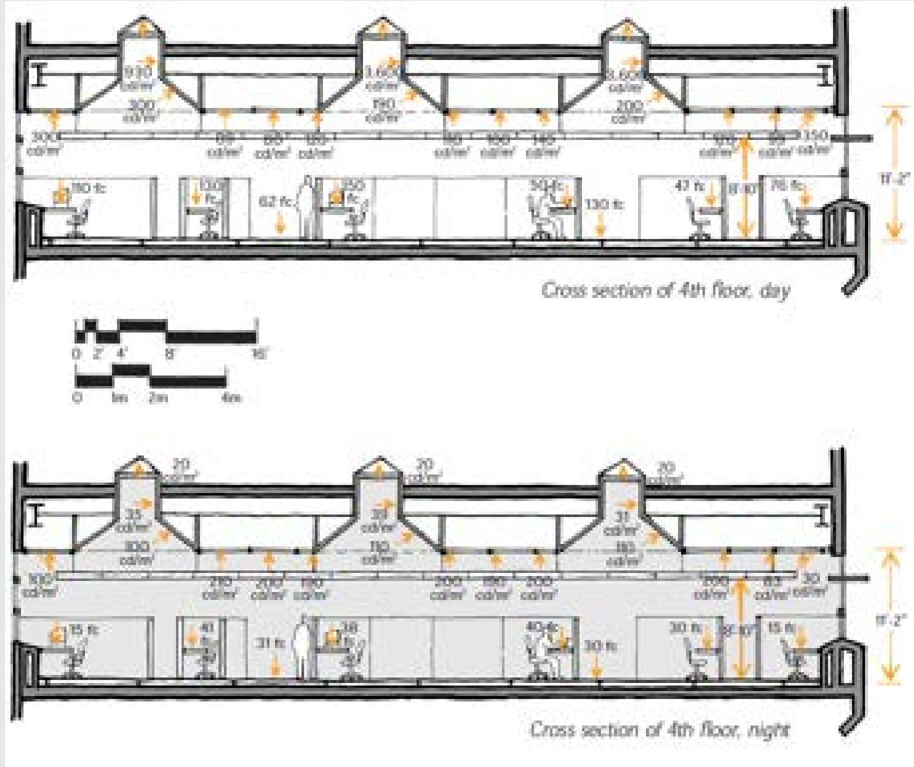


FIGURE 2-17: Cut-off Angle for Light Wells

A light well with a wide cut-off angle will allow the widest distribution of light, but will not prevent occupant's view of the skylight. A light well with a very narrow cut-off angle will prevent direct view of the skylight; however, it will also concentrate the light into a small area. A compromise between these two conflicting needs can be reached with a light well that has straight walls at the top and splayed walls at the bottom.

FIGURE 2-18:
Light Well Design at Sacramento Municipal Utility District Offices



Graphic courtesy of the Lighting Research Center

A light well design utilizing a vertical shaft at the top and a 45º splayed walls at the base was used very successfully in the skylit floors for the Sacramento Municipal Utility District's daylit office building. The well design distributes light evenly with no glare to the occupants below. Indeed, employees who work on the skylight floors gave the highest rating to the lighting quality in their work spaces, according to the Lighting Research Center, Delta Report on Sacramento Municipal Utility District's office building, 1997. Workers on the skylit floors rated their lighting system higher (96% satisfaction) than those working on floors with daylighting provided only from windows (67% satisfaction).

Light well design also affects illumination levels, and so is an important factor in optimizing energy savings. See Chapter 5 for a more complete discussion of the quantitative effects of well design.

Daylight Metrics

In order to optimize a design for visual comfort, metrics are needed for visual comfort for daylight in buildings, as well as to establish thresholds of acceptable conditions using these metrics. Until recently, the only metric for daylighting was a crude ratio of indoor to outdoor illuminance called the Daylight Factor. Daylight factor is calculated under a fully overcast sky condition, limiting its application in areas of California and North America with predominantly sunny skies.

In an effort to develop better and more nuanced, climate-based metrics for assessing and describing various dimensions of daylight conditions in a space, the Illuminating Engineering Society of North America (IESNA) published "IES LM-83-12,[4] Approved Method: IES Spatial Daylight Autonomy (sDA) and Annual Sunlight Exposure (ASE)," in 2012. As the title implies, the document describes two new metrics, Spatial Daylight Autonomy (sDA) and Annual Sunlight Exposure (ASE), which evaluate daylight conditions in a space over a typical year, based on climate conditions.

Spatial Daylight Autonomy (sDA) is a measure of "daylight sufficiency" in a space. The metric reports "a percentage of floor area that exceeds a specified illuminance level, e.g. 300 lux, or approximately 30 footcandles, for a specified amount of annual hours, e.g. 50% of the hours from 8am-6pm." (sDA300/50%)

Annual Sunlight Exposure (ASE) evaluates the potential source of visual discomfort from direct sunlight. The ASE reports the percentage of area that exceeds a specified direct sunlight illuminance level, e.g. 1000 lux, for more than a specified number of annual hours, e.g. 250 hrs. (ASE1000,250h)

Both of these metrics should be reported together as an initial assessment of daylight quality in a space. As the IESNA document states, "When used together, these two metrics proved a meaningful first-level understanding of how a space/design is expected to perform, and can help inform the daylighting design evaluation process as design solutions are developed and refined." These metrics were designed to be referenced by building codes or design rating systems such as LEED to describe acceptable daylight conditions for a space.

The IESNA document also provides recommended performance criteria for the two metrics in order to provide guidance to designers.

For sDA, the IESNA recommends:

sDA300/50% ≥ 75% of analysis area as the 'Preferred' threshold

sDA300/50% ≥ 55% of analysis area as the 'Nominally Acceptable' threshold

The IESNA recommends that ASE should be considered a relative value. The thresholds provided below are guidelines based on only the dataset in the supporting research.

ASE1000,250h <3% of analysis area as the 'Preferred' threshold

ASE1000,250h <7% of analysis area as the 'Nominally Acceptable' threshold

These metrics enable comparing various design strategies, spaces or climates, which now make it possible to design skylit spaces that are more likely to produce well lit and visually comfortable environments. For more information on these metrics and approved methods for calculating them, reference IES LM-83-12.

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4 IES LM-83-12, "Approved Method: IES Spatial Daylight Autonomy (sDA) and Annual Sunlight Exposure (ASE)" ISBN # 978-0-87995-272-3

Integration with the Electric Lighting System

Even the most aggressively designed skylighting system will require a full electric lighting system—for occasional cloudy days and most especially for use of the space at night. In general, the electric lighting system should be designed to supplement the skylight system, and not vice versa. If the skylighting system is treated as the primary light source, it should be designed to optimize lighting conditions throughout the daylit spaces. The corresponding electric lighting system should be designed to complement the skylighting.

A common approach is to provide the basic ambient light for the building from skylights, along with a back-up electric ambient system on photosensor controls, while using electric lights to provide higher levels of task lighting in critical locations. This design approach is referred to as "task-ambient" lighting. Special task lighting can be provided at work counters, in shelving aisles, or critical equipment, as show in Figure 2-19.

FIGURE 2-19:
Task-Ambient Lighting with Skylights

An example from a manufacturing plant provides ambient light with a uniform grid of skylights and metal halide fixtures on photosensor controls. Strip fluorescent fixtures provide higher light levels at critical task areas and active shelving areas.

Another aspect to consider is the color temperature of the light sources. Daylight is generally a cooler color than interior electric lighting (although it varies considerably throughout the day). Many designers have chosen light sources with cooler color temperatures, such as fluorescent lamps at 4100k, to blend better with daylight. However, when a lamp is a different color temperature than its ambient surroundings, it draws attention to itself. This may be an aesthetic choice. For example, daylighting can be used as a complement to a light source with poor color rendition, such as certain types of LEDs and Metal Halide lamps. In such a case the presence of daylight greatly enhances the ability to see colors accurately.

There are three primary considerations for the design of electric lighting systems that successfully integrate with skylights:

- Supplementing the daylight provided from the skylights
- Providing sufficient light at night, or when there is insufficient light from the skylights
- Integrating with automatic daylighting controls

Lighting the Room Surfaces

Skylights, and their associated light wells, can be quite bright. If the ceiling is not lit, the contrast between the bright well and darker ceiling can be uncomfortable. Splayed light well walls can help reduce this effect by creating a surface with intermediate brightness.

Often designers choose to supplement reflected daylight with an indirect component in the electric lighting fixtures, which directs some portion of the light upwards to brighten the ceiling plane. Pendant mounted direct/indirect fixtures are especially appropriate for high value spaces with lower ceilings, such as offices or retail stores. (Note the direct/indirect fixture choice in Figure 2-18: Light Well Design at Sacramento Municipal Utility District Offices). These fixtures can also brighten both the ceiling plane and the light well walls at night.

Another issue in an electric fixture layout is achieving proper levels of illumination on the walls of a space. Well illuminated vertical surfaces can improve the visual quality of a space. Some researchers have found that, all other things being equal, people judge a space to be brighter and better lit overall if the walls are brightly and uniformly illuminated. This makes a strong argument for directing light to the wall surfaces, which can be achieved with either the skylights or the electric lights.

If the daylight is concentrated in the center of the room or building, an effort should be made to direct additional electric light to the walls. This can be achieved by some combination of standard pendant fixtures placed close to the walls, using lensed fixtures with a wide light distribution (such as a "bat wing" lens), and/or selecting special "wall wash" fixtures that are designed to provide even illumination on vertical surfaces.

An example of this approach is seen in the classroom design for Capistrano School District in Figure 2-20. There, a perimeter ring of lensed, recessed fluorescent fixtures provides even illumination to the walls of the classroom, while a central skylight illuminates the center of the room. The electric lights can be switched between full power, ½ power and off depending on the classroom needs. Even though there are no fixtures in the center of the room, nighttime illumination tends to be quite even due to reflections from the brightly lit walls.

FIGURE 2-20: Classroom design for Capistrano School District

Perimeter fluorescent lighting provides even illumination to the walls of the classroom, while the skylight illuminates the center of the room with daylight.

Alternatively, if the skylights can be located near the perimeter of the room such that daylight is fairly evenly distributed across the walls, then the electric lighting system can be designed to fill in the middle during the day. However, nighttime appearance should also be considered. It may be also appropriate to include a special nighttime wall washing system.

Skylights at Night

The skylight well can become a dark hole in the ceiling at night if no light is directed up into it. When buildings are used extensively at night this can be disconcerting. Some designers have addressed this issue by providing coved fixtures in the light well which directly light the well at night. However, there can be a conflict between the placement of fixtures to light the well at night, which then block some of the daylight during the day. Other solutions include providing light in the well with a narrow linear fluorescent or LED strip running around the perimeter of the well, or placing a direct/indirect lighting fixture directly under the well for nighttime illumination. There is an efficiency tradeoff for all of these choices, in allowing light to escape out the skylight and providing illumination to a well that is not part of the general room task area versus creating a comfortable and pleasant visual environment at night.

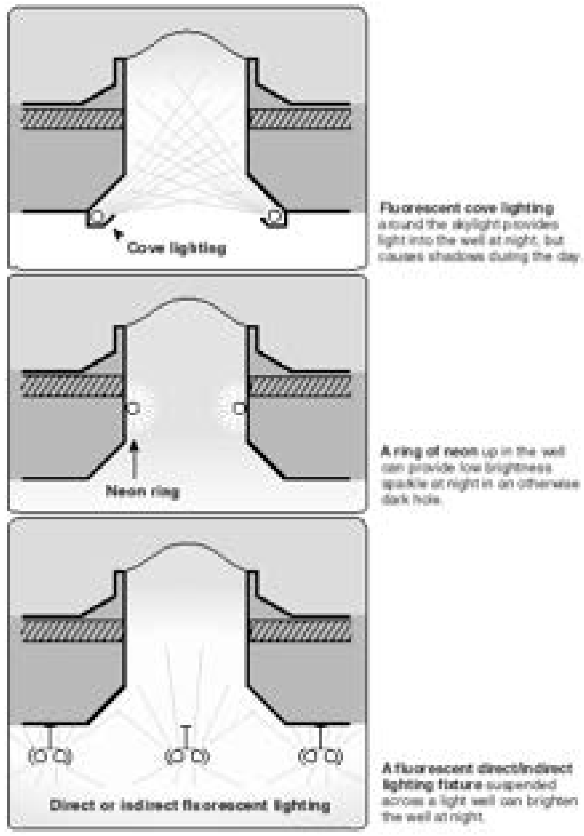


FIGURE 2-21:
Three Approaches to Bright Light Wells at Night

It is important to remember that, at night, transparent glazing will allow all light from below to pass through, and thus will appear dark. Diffusing glazing, on the other hand, will reflect some of the light downwards. So a diffusing skylight that is illuminated at night will appear brighter.

Another factor to consider when dealing with skylights at night is the impact on the night sky and the surrounding environment. Building owners have noted that in the evening, transparent skylights that are brightly lit from below can attract birds, who attempt to fly through the skylight. Reducing the transparency of the view seems to prevent the problem. However, light escaping from skylights at night can also contribute to nighttime light pollution. Designers and specifiers should consult any nighttime lighting or dark-sky ordinances before deciding on lighting strategies for skylight wells at night.

Spacing Criteria

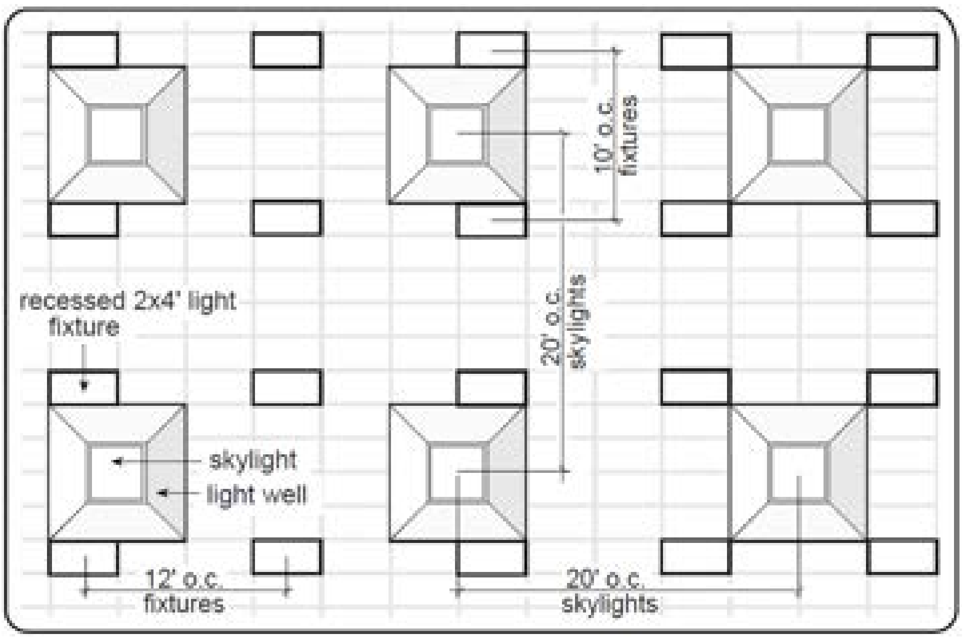
For large open areas with high ceilings (20+ feet), the relationship of the skylights to the electric lights is usually not critical. Electric lights are typically pendant fixtures hung from the structural grid with wide distribution of their light. The two can be laid out fairly independently of each other with acceptable results.

Even with lower ceilings (12-20 feet) the use of pendant mounted direct/indirect fixtures allows the skylight grid and electric light grid to be somewhat independent of each other. Pendant direct/indirect fixtures can be mounted directly under a skylight without interfering very much with daylight distribution.

Electric lighting systems that are recessed into the ceiling, however, present more of a challenge. A good rule of thumb is that the skylights should be located on a direct multiple of the fixture spacing dimension, or vice versa. Also, the skylight well should not have greater dimension than the maximum spacing of electric lights, which is a function of the fixture type and the fixture mounting height. For example, if the maximum spacing for the lighting fixtures is 10 feet on center, then the skylights could be spaced at 20 feet on center, with a 10 foot square well around each skylight.

FIGURE 2-22:
Integrating a Lighting and Skylighting Grid

The maximum spacing criteria for recessed lighting fixtures should set the maximum width of light wells. Also, skylights should be laid out on a grid which is some multiple of the lighting spacing.



While these two factors are relatively straightforward, layouts can be further complicated by other requirements, including the structural grid, the maximum spacing between the skylights for uniform lighting (rule of thumb =1.5 x the ceiling height), the ceiling grid, and requirements for HVAC duct runs. In general, the lower the ceiling, the more critical it is to coordinate all of the grids affecting the skylight location.

Laying Out Circuits and Control Zones

Selecting a rational circuit design for the electric lights is also very important to the success of any photosensor controls. It is assumed throughout these Guidelines that skylights will be laid out to create uniform lighting conditions. However, sometimes it is inevitable that there will be some form of daylighting gradient. Perhaps the building also has daylighting from windows, or the skylights are on an unequal grid. When this is the case, the lighting circuits should also be laid out along the same gradient so that the photosensor controls can differentiate between regions of different brightness.

An important consideration for lighting layout is the presence of shelving aisles or storage racks. The spacing of the shelves and the skylights are rarely coordinated, resulting in some aisles that get less daylight than others. There are two schools of thought on how to respond to this. If the aisle heights are relatively low compared to the ceiling height, then laying out the lighting system perpendicular to the shelves has a number of advantages. First, any shadowing from the skylights is negated by the perpendicular lights, and secondly, the aisles can be reconfigured without changing the locations of any lights.

If the shelves are relatively high, locating fixtures down the center of the aisles is more efficient. In this case, it is also important that the lighting circuits run parallel to the aisles, rather than on a grid. This way, each aisle can be controlled separately depending on daylight availability.

Requirements for special emergency circuits or controls that set lower light levels for stocking or maintenance are additional factors that must be considered. These issues may impact the control patterns.

In addition to these considerations, the 2013 California Building Energy Efficiency Standards require fixtures located within the Skylit Daylit Zone to be controlled by automatic daylighting controls. These requirements are discussed in more detail in Chapter 3.

Integration with the HVAC System

The mechanical system design for a building with skylighting requires a few special considerations. None of these are difficult for the mechanical designer, but they may be different from the designer's standard practice. If the mechanical design does not recognize some of the special characteristics of the skylighting system, then some of the benefits may be lost to the building owner. The mechanical system considerations fall into several categories, which will be discussed in the following sections:

- Equipment sizing to reflect different loads
- Placement of rooftop equipment
- Location of ductwork
- Placement of supply and return registers

Equipment Sizing

Skylights affect the design loads on the mechanical system in four ways:

- Reduced cooling loads due to lights turned off during daylit hours
- Increased cooling loads due to increased conduction and solar heat gains
- Increased heating loads due to loss of roof insulation levels

- Increased heating system loads due to reduced internal heat gains from lights

These are listed in approximate order of significance, with the cooling load effects being most significant, although in a cold climate the heating load effects may increase in importance.

The primary HVAC system energy benefit of skylighting comes from turning off electric lighting, especially in climates with substantial air conditioning requirements. Skylit buildings should include automatic lighting controls with photosensors that measure the available daylight, and dim or turn off the unneeded electric lighting (lighting controls are discussed in Section 4). While this leaves plenty of light for the occupants, it substantially reduces the electric lighting power in the space, with a concurrent reduction in the internal heat gains and loads on the cooling system. There are also increases in solar heat gains and heat conduction through the skylights, compared with the opaque roof that they replace. If the architect or building designer has sized the skylights properly, the reduction in the lighting component of the cooling load will be substantially greater than the increase in solar heat gains and conduction loads. The skylighting reduction in electric lighting usually coincides with the building's peak cooling load, which typically occurs under conditions of strong sunshine. It also occurs during the period of peak electric demand charges, when reductions in electric load are most beneficial to both building owner and electric utility.

This rule of thumb will be less true in very humid climates, where the magnitude of latent cooling loads far outweigh the magnitude of cooling loads created by the lighting system, and where peak loads are associated with the most humid summer days. In very humid climates, any changes to the cooling loads due to skylights tend to be trivial in comparison to the magnitude of loads due to the general humidity.

It is clear that skylights in combination with photosensor lighting controls can often reduce peak cooling loads. This potential should be considered in the mechanical design in order to determine whether the peak capacity of the air conditioning system can be reduced, thereby reducing first costs on the HVAC system. In order for these savings to become reality, the mechanical designer must have confidence that:

1. The skylights are not oversized, resulting in excessive heat gains (which can be verified with *SkyCalc*), and

2. The daylighting controls are correctly designed and will reliably turn off lights during peak cooling conditions (per Chapter 4).

The first requires coordination with the architect or building designer, and the second requires coordination with the lighting controls designer. These collaborations are essential to successful skylighting design.

In terms of heating loads, the largest impact from skylights is the increase in heat conduction out through the roof. The opaque roof is typically insulated to values of R-30 or greater, while most skylights have an overall R-value between R-1 to R-5. This obviously increases the heat loss of the building, an effect that goes on day and night during the heating season. The heat losses can be mitigated with additional ceiling insulation and/or with more insulating skylight designs using double or triple glazing, insulated curbs, thermal breaks, etc. Skylights produce some offsetting solar heat gains during daylight hours by allowing the sun's heat to penetrate through the roof. There is also a secondary increase in the heating loads because of electric lighting turned off by the photosensor control system during daylit hours. This is not significant, however, because the heat of lights is replaced by heat from the building's heating system, which is more efficient and less expensive. The skylighting system may require a modest increase in the size of the heating system because of these effects.

Placement of Rooftop Equipment

Many skylit buildings also have rooftop mounted mechanical equipment. The placement of both skylights and rooftop units require coordination with the structural system. Skylights should be located between structural members as penetrations of the roof membrane, while rooftop units must be located over structural supports sized to carry their relatively concentrated loads. In a rationalized structural system layout, the coordination of these placements is relatively straightforward. The skylights must be placed to provide uniform illumination and to avoid blockage of light by structural members. The rooftop HVAC units must be spaced to provide coverage to the spaces below (larger units will be placed farther apart than smaller units), and they must be positioned to allow the ductwork to be efficiently laid out.

Centralized HVAC systems can have cooling towers or equipment rooms that shade large areas of the roof. The effect of these shadows on the performance of the skylights should be considered during the design process. These considerations require coordination between the architect, the structural designer and the mechanical designer.

Location of Ductwork

The layout of ductwork in a skylit building is probably a greater challenge than the placement of rooftop units, because ducts have the potential to block daylight if they are too close to the skylights. In a building without ceilings or light wells, ductwork should be located between the skylights so as to obstruct as little daylight as possible.

Buildings with dropped ceilings and light wells can create additional challenges for duct runs. In many single story skylit buildings, there is ample vertical dimension to run the ducts below the structure and above the suspended ceiling, but the light wells can become quite large if their walls are splayed, creating greater obstacles for duct runs. A common solution is to run the primary supply ducts around the perimeter of the building, with smaller branch ducts between the light wells.

In buildings with less vertical dimension between structure and ceiling, the ductwork must often run through the structural system. Here, the light wells are also smaller because they are shorter, but there may be more constraints on the duct locations.

An alternative approach was used in the Sacramento Municipal Utility District's skylit office building. A raised floor allowed duct runs and HVAC registers to serve the space from below. This system allowed very flexible wiring to all workstations, and kept the ducts from interfering with the direct/indirect lighting system and the daylighting from windows and skylights.

As with the placement of the rooftop units, the location of ductwork requires coordination between designers, general contractor, and trades. In general, the skylights and their light wells should be positioned first, then the duct runs worked out between them. In a new project, it is usually not difficult to work out a rational arrangement for the systems. In a retrofit project, the coordination may be more difficult because of existing locations of rooftop curbs and internal ductwork.

Placement of Registers

The final element of coordination between skylighting and mechanical systems is the placement of supply and return air registers. In most skylit buildings, both supply and return ducts are typically located in the ceilings. In a well-designed system, the placement of the registers is coordinated with the skylight placement as well.

Cooling registers are usually concentrated near windows with substantial solar heat gains. The remainder are then spread uniformly throughout interior spaces. With a skylighting system, there are potential warm spots below the skylights (although this will be minimized with effective diffusing glazing materials). In buildings with light wells under the skylights, there is an opportunity to create a zone of stratified air in the well. As solar gains enter the skylight, the heat is typically absorbed by the surfaces of the light well, which in turn heat the surrounding air. This warmed air will tend to rise and collect at the top of the light well. It is best to leave it undisturbed, and to direct both supply and return air flows down below the ceiling plane rather than up into the well. Placing return registers high up inside the light wells would pick up the solar heated air and return it to occupied space, increasing the need for air conditioning.

Heating registers near skylights are different. In cold climates, skylights tend to create cold downdrafts as heat escapes through the relatively uninsulated glazing. By placing heating supply registers at the base of the light well, downdrafts mix with the heating supply air stream, and the cold drafts can be eliminated. An alternative strategy is to place heating return registers at the base of the light wells, drawing the cold downdrafts into the return system and mixing them with the warm return air from the ceiling.

In a mixed heating and cooling system, it is usually best to apply the latter strategy. By placing return registers near the bottom of light wells, in the cooling season stratification leaves unwanted heat gains at the top of the well, and during the heating season cold air falling from the skylights is drawn into the system return air ducts before it can establish a pattern of cold air drafts on the occupants below. Under this scheme, the supply registers are distributed between the light wells, where the duct work would typically be run.

An alternative approach is to add an additional glazing layer at the bottom of the skylight well to prevent mixing of the room air with the air in the well. This additional glazing layer can also function as a diffuser for the skylight.

As this discussion illustrates, the architect, mechanical engineer, and electrical engineer or lighting designer must coordinate their work on the ceiling system design. The contractor must also be involved in this coordination to ensure successful construction results. This will maximize occupant comfort, as well as the performance and savings potential of the mechanical system.

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Chapter 3: Specification Choices

The following sections cover the specification issues and technical concepts that should be considered in the selection of skylight products.

Glazing Materials

Glazing is one of the most important factors in good skylight design. There are many alternatives and choices to consider, and careful selection is important to a successful design. The optical properties of glazing materials influence both daylighting quality and potential energy savings. The thermal properties affect heating and cooling loads. Thermal properties are discussed more fully in "Skylight Efficacy" section, below.

First it is necessary to introduce two important concepts—glazing efficacy and skylight efficacy—which should guide selection of other properties of skylights.

Glazing Efficacy is the measure of how much light gets through all the layers of glazing in relation to how much solar heat gets through. It is more specifically referred to as the "light to solar gain ratio" or LSG. It is a ratio of the visible transmittance (Tvis) to the solar heat gain coefficient (SHGC) of the glazing. It is important to understand that it is not just one property or the other that is important, but the relationship between the two of them that determines how efficiently the glazing material will perform. Values for light to solar gain ratio (LSG) for various products are shown below in Figure 3-1.

Skylight Efficacy combines light to solar gain ratio with the effects of the light well. The well factor (WF) describes how much of the light that enters the well is actually transmitted down to the room, after reflectances and absorption. The well factor is explained in greater detail below, in the "Well Factor" section, below. Thus, skylight efficacy is a measure of how efficiently the overall skylight assembly can deliver light to the room below without delivering an undue burden of additional heat.

Visible Transmittance

The visible transmittance of a glazing material is the essential measurement for judging how much light will get through. It is reported as a ratio, and either labeled T_{vis} or VT for visible transmittance.

It is best if the manufacturer can provide test results for the skylight unit which account for multiple layers and obstruction by any intermediate framing members. The NFRC 300 test procedure was developed to measure or calculate overall visible transmittance of windows.

If these results are not available, the manufacturer should at least be able to provide the visible transmittances of the individual sheets of glazing material. It should be noted whether these are values for the flat material before it has been formed, or tested values after the material has been formed. For example, an acrylic bubble skylight made from sheet material which is nominally ¼ inch thick will stretch in the center and have higher visible transmission in its thinner areas.

An appropriate test method is ASTM Standard E972. When the overall transmittance for a multiple layer glazing is not available, a reasonable approximation is to multiply the visible transmittance of the glazing layers together.

Very often the only T_{vis} values that are available are generic values for the product material, such as those published in the ASHRAE or IESNA Handbooks. When this is the case, specifiers should include a test procedure to verify that the product delivered has the specified light transmittance. At the very least, using a light meter to take reading of light levels immediately above and below a product will give a rough indication of the visible transmittance. Be sure that the light meter is taking an average reading for the product, and that there is no light leakage from other sources. Placing the skylight unit over an opaque box and using a light meter that will take a remote reading will increase accuracy.

Another issue with visible transmittance is performance over time. Some products may degrade over time, and have lower transmittance as they age. Fiberglass is especially suspect in this area, as the thermo-setting resins used in manufacture can change their properties under extended exposure to heat or UV light. Skylights are often subject to a great deal of heat and UV light on the top of a building roof. For this reason, specifiers should check with manufacturers on the long term performance of their products.

Solar Heat Gain Coefficient

Visible transmittance indicates the percentage of the solar energy in the visible spectrum that will pass through a material. The solar heat gain coefficient (SHGC) indicates the percentage of the solar energy in the full solar spectrum that will pass though the material. Solar radiation contains a wide spectrum of wavelengths including ultraviolet, visible light and infrared radiation. All of this energy eventually degrades to heat within the building.

The SHGC accurately accounts for variations in reflectance and absorption for different wavelengths and can describe a wide range of materials. The SHGC also measures solar heat gain through multiple layers of glazing, materials with low-e coatings, or plastic materials that interact differently with different wavelengths of the solar spectrum.

Coatings that reflect the visible spectrum are sometimes applied to window glass to lower the SHGC. These optically reflective coatings are not available on plastics formed for skylights. Such coatings are not recommended for skylights because they can create blinding reflections for occupants of nearby buildings or hillsides, and also can be disorienting for aircraft pilots and birds.

There are other coatings which are highly transmissive of the visible solar wavelengths while primarily reflecting the infrared portion. These coatings are called "selective surfaces" or "spectrally-selective" and lower SHGC while admitting high levels of daylight. They are typically combined with low-emissivity or low-e coatings when applied to glazing surfaces. Low-e coatings reduce radiant heat transfer from window or skylight glazing, reducing u-factor. However, not all low-e coatings are also spectrally selective. Such products have low u-factor but high SHGC. For skylights, low SHGC is preferable. Do not select glazing simply because it is described as 'low-e'. Check product information to select glazing with both low u-factor and low SHGC.

Spectrally-selective low-e coatings can be applied to the surface of glass or polyester film. They are not currently applied to other plastic materials which are subsequently heated for forming. Because these coatings are susceptible to scratching and atmospheric damage, they are usually applied to an inner surface of multiple layer glazing.[1] They are not commonly found on unit skylights.

Spectrally-selective, low-e coatings are available in some residential glass skylights, where heat loss and occupant comfort at night are important concerns. They are not widely available for commercial applications, although some manufacturers offer a coated polyester film in some products with multiple glazing layers.

Glazing Efficacy

The following table in Figure 3-1illustrates how the visible transmittance, the solar heat gain coefficient and the resulting light to solar gain ratio[2] (LSG) vary depending on the glazing material, color and number and type of layers. These are some of the generic values used in *SkyCalc*. Product specific values should be obtained whenever possible.

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1 See *Residential Windows: A Guide to New Technologies and Energy Performance*, listed in the bibliography, for a more thorough discussion of low-e coatings.

2 Light to solar gain ratio (LSG) is the ratio of visible transmittance to solar heat gain factor, and is used later to calculate overall skylight efficacy.

FIGURE 3-1:
Solar-Optical Properties of Skylight Glazings

Type	Layers	Color	Tvis	SHGC	LSG
Acrylic/ Fiberglass	Single glazed	Clear	0.92	0.77	1.19
		Med White	0.42	0.33	1.27
		Bronze	0.27	0.46	0.59
	Double glazed	Clear	0.86	0.77	1.10
		Med White	0.39	0.30	1.28
		Bronze	0.25	0.37	0.67
Fiberglass	Insulated translucent U-0.24	Crystal	0.30	0.30	1.01
		White	0.20	0.23	0.85
		Bronze	0.10	0.16	0.64
Polycarbonate	Single glazed	Clear	0.85	0.89	0.96
		Bronze	0.50	0.69	0.73
		Med White	0.37	0.50	0.73
	Double glazed	Clear	0.73	0.75	0.97
		Bronze	0.43	0.58	0.73
		Med White	0.32	0.43	0.74
Glass	Single glazed	Clear	0.89	0.82	1.09
		Bronze	0.55	0.64	0.87
		Green	0.74	0.59	1.25
	Double glazed	Clear	0.78	0.70	1.11
		Bronze	0.48	0.51	0.94
		Green	0.66	0.47	1.40
	Double glazed low-e	Clear	0.72	0.57	1.25
		Bronze	0.45	0.39	1.15
		Green	0.61	0.39	1.56
	Triple glazed low-e	Clear	0.70	0.53	1.32
		Bronze	0.42	0.37	1.14
		Green	0.61	0.38	1.61

Diffusion

Merely specifying the visible transmittance and solar heat gain coefficient is not a sufficient description of a glazing product for skylights. Any specification should also include a description of diffusing properties. *SkyCalc* assumes that the skylights used in the calculations are perfectly diffusing, an ideal case. The more diffusing the material, the more uniform the distribution of light. However, there is a wide range of diffusion among the various skylight materials commonly used.

In California, the Building Energy Efficiency Standards require nonresidential skylights to have a glazing material or diffuser that has a measured haze value greater than 90 percent when tested according to ASTM D1003. However, there are also a number of visual inspection procedures a designer can use to understand the diffusion properties of various skylight products.

A quick first judgment can be made by looking through a translucent material. If any image can be seen through the material, some portion of light must be passing directly through, and thus the material will not be highly diffusing. However, even a product that passes this test could have poor diffusion, since such a visual test does not evaluate how widely light is scattered.

Currently, most acrylic and polycarbonate glazings use pigments in their “white” products to diffuse light. Since these pigments also absorb visible light, generally the higher the visible transmission of the material, the less it is diffusing. Thus, "high white" acrylic, with a high visible transmission is less diffusing than a "medium white" with lower transmission. Bronze or gray acrylics do not follow this pattern, and usually have poor diffusion even at lower transmission values.

There are clear plastic products that are formed with a "prismatic" surface. These are both highly diffusing and have very high visible transmittance. This is similar to the prismatic lenses used on light fixtures.

Fiberglass materials have a different relationship of visible transmittance to diffusion. In fiberglass, the glass fibers act as a diffusing element. However, fiberglass is a highly variable material, since it depends upon the mix of resins and glass fibers used in the manufacture. Also, most fiberglass skylights are not made from pre-manufactured uniform sheet material, but from a mixture applied to a form. Thus, exact thickness and composition of the material can vary between manufacturers, and even between individual units.

Glass skylights can increase diffusion with the use of frosted glass, fritted glass, or etched or fritted patterns on the surface. While many advanced glass products are available for use in windows , they are not common in commercially available unit skylights.

It should be noted that the diffusion from skylights can also be enhanced through other design options, such as the light well design, or inclusion of other diffusing elements. See Chapter 2 for more discussion on designing for light diffusion.

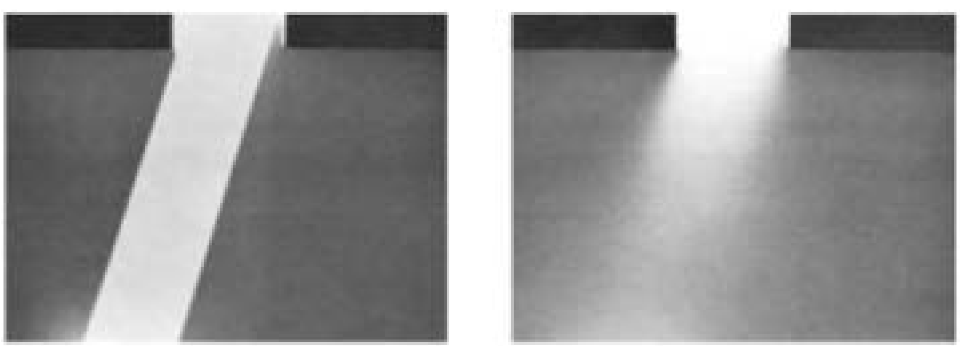


FIGURE 3-2:
Effect of Skylight Glazing on Light Transmission

Transparent glazing materials (left photo) admit beam sunlight to the building, which can result in either harsh shadows or pleasant bright spots, depending upon the design intent. Diffusing glazing (right photo) provides a more uniform light distribution and avoids the creation of "hot spots" that can raise the perceived temperature in a particular area.

Glazing U-Factor

The U-factor of a skylight measures its heat transfer capabilities when placed between two spaces of different temperatures. The U-factor is simply the inverse of the R-factor, which measures the material's resistance to heat transfer. The overall U-factor of a skylight is a function of its glazing materials and its frame. This is often referred to as the "unit U-factor" and is discussed further, below. This section will address the U-factor of the glazing assembly.

Most skylight manufacturers offer units with double, and even triple, glazing. Increasing the number of glazing layers produces higher insulating qualities (lower U-factors), but will also lower the SHGC and visible light transmittance of the skylight. Thus, for diffusing skylights, generally one layer is of a diffusing material and other layers are of a clear, highly transparent material. Inner layers of glazing can be constructed of less resilient material, since they do not need to resist the weather or physical impacts. Some manufacturers use a very thin polyester film layer to provide additional insulating value with little loss in visible transmission.

Another alternative to increasing the insulating value of skylights is to add fiberglass insulation between layers of glazing. This is typically done in units with two flat layers of fiberglass or glass stretched between a rigid frame. A range of U-factor options are available, some extremely low (highly insulating). Generally in these products, the better the U-factor, the worse the visible transmission.

There are also skylights made with extruded glazing materials that have hollow chambers cast between two outer layers of plastic. These integral air spaces lower the U-factor, and the multiple surfaces of the extruded material serves to diffuse some of the light.

The incorporation of low-e and spectrally-selective glazing materials into a skylight assembly can also lower the U-factor (and SHGC) while preserving high visible transmission. Glass skylights can include a selective coating on an inside surface. Plastic skylights can include a layer of low-e coated polyester film. Because the polyester film is fragile, and easily punctured or torn, it is generally protected between an upper and lower glazing layer, to create a triple glazed assembly.

See Figure 3-6 below for a sample unit U-factors for various glazing materials combined with frame types.

Other Properties

The physical properties of glazing materials that should be considered include:

- Impact resistance. The ability to resist breakage from impacts such as hail, rocks, or roofing ballast from adjacent buildings.
- Breaking characteristics. Whether the material shatters into dangerous shards, or fails in less dangerous fashion.
- Strength. The ability to withstand applied forces, such as wind, snow, and gravity.

- Thermal expansion. The length of expansion per degree temperature difference. This determines the amount of movement that must be accommodated by the frame.

- Weatherability. The ability of the material to resist surface erosion due to dust and other airborne abrasives, and ultraviolet or thermal degradation resulting in yellowing or hazing, which would reduce light transmission and desired performance.

- Flammability. The amount of heat, smoke, and/or toxic fumes generated by the material in a fire.

Plastic materials vary considerably in their performance on these various issues. The glazing material or skylight manufacturer should be consulted for information about the particular properties of their glazing materials. Some of these properties are discussed more thoroughly in the sections below.

Tubular Daylight Devices (TDDs) and Other Advanced Skylights

In addition to the domed or flat unit skylights described above, there are a set of products that use more advanced strategies to bring daylight into a space. Tubular daylighting devices (TDDs) combine a skylight aperture at the roof, a highly reflective light well, and a diffuser at the finish ceiling plane, to convey daylight through deep or crowded plenum spaces without requiring large openings at the roof and the ceiling and without losing much of the daylight in the lightwell. They are well suited for retrofit applications as well as certain new construction applications with the need to traverse long distances with light wells. Their smaller roof aperture usually works to reduce heat exchange compared to traditional skylights. However, because they are smaller in dimension, their placement needs to be carefully considered to ensure uniformity.

Other advanced skylights like light redirecting skylights use specialty lenses, advanced optics molded into the outer lens, reflectors, or solar tracking mirrors to better utilize low angle sun to extend the effectiveness of the skylight to morning and evening hours when the angle of the sun is too low to be usefully admitted into a space with a traditional skylight. These skylights also reject some higher angle sunlight to help prevent excessive solar heat gain.

Because of the unique characteristics of these types of advanced products, they are not subject to the same considerations as the typical unit skylights discussed in these Guidelines. Designers should consider the unique characteristics of these advanced product types when specifying them on a project.

Shading Devices

Manufacturers have experimented with various external shading devices for skylights over the years, including static overhead shades that block the direct sun at certain sun angles and operable "hatches" that can be moved to alternately shade a skylight, focus additional sun into the skylight, and/or insulate it at night. While these devices can be designed to improve the long term energy performance of a skylight, they can add considerably to the expense. They are also subject to all the nuisances of weather, dirt and debris, which combined with rarity of roof-top maintenance, tends to result in eventual failure.

Interior shading devices include horizontal louvers, roller shades, screens, and shutters. They are usually manufactured products, but they can also be custom assembled from fabrics, panels, screens, or other architectural components. Interior shades are typically located within or at the bottom of skylight wells. Because they are inside the building, they are not subjected to the rigors of wind and weather that beset exterior shading devices.

Shading devices should be included in any calculations of skylight efficacy and solar heat gain coefficient. *SkyCalc* can account for static shading devices in the Optional Inputs tab. However, manual or automatic operable devices cannot be modeled easily. Since correct operation would lead to lower solar heat gains when there is ample daylight, and perhaps also lower heat losses when there is no daylight, the *SkyCalc* should be assumed to represent a worst case scenario. Consult the ASHRAE Handbook of Fundamentals for more detailed guidance on determining the lighting and heating effects of various shading devices.

Horizontal Blinds

Some of the most flexible interior shading devices are adjustable horizontal blinds. These are available for mounting in a horizontal or tilted plane. Orienting the blinds on an east-west axis across the light well enables the best response to changes in the sun's elevation both during the day and seasonally. By changing the tilt of the blinds, the amount of light (and heat) entering the space can be reduced, and partially reflected back to the sky.

The materials used should be highly reflective to bounce much of the unwanted direct solar radiation back to the exterior. The reflective materials could become glare sources themselves if they are not kept out of the viewing cut-off angle.

Horizontal blinds need strength to span the width of the skylight while permitting angular adjustment without sagging. Thus, blinds are typically made just for this purpose. Given the limited market, there are currently only a few national manufacturers of such blinds.

The adjustment of the blinds can be manual or automatic, and can change hourly or seasonally.

Horizontal blinds can be operated manually, using a removable turn-wand or an electrically-powered wall switch, or automatically with photosensor control. A powered system requires the addition of a small motor to open or close the blinds plus wiring to a wall switch or dial, and adds considerably to the expense. Photosensor control of the automatic motor adds yet another expense. However, if the photosensor control can control multiple blinds, and thus provide for reliable control of a large space, it may be an appropriate choice.

Screens, Roller Shades, and Shutters

Horizontally mounted shades, screens or shutters can also be pulled across a skylight well. Typically these are mounted on a track to keep them from sagging across the opening. They can be operated with a pull cord, a crank, or an electric motor and switch.

Shades can vary from opaque to translucent, or a mesh allowing through 5% to 20% of the light. The color of the shade should be carefully considered so it does not become a glare source if it is within the viewing cut off angle. The amount of daylight can be adjusted by how far the shade is pulled closed, although uniform light distribution may also be somewhat affected.

A horizontal blind or shade, if it is sufficiently sealed at the edges, can provide a small additional layer of insulation at night and/or help to keep hot air stratified in the upper light well on hot days.

Shutters are often rigid opaque devices that can be swung open or closed from a horizontal hinge. If the shutter fits neatly into the light well, it can be fairly unobtrusive when open.

While a shutter offers less light control options, it does offer the ability to add considerable additional insulation during cold or very hot weather. One inch of foam can provide an R-3 to R-5 layer at a light well. One school in Colorado uses a system of insulated shutters that automatically close every night and automatically open every morning. The teachers have the option using an override switch to close the shutters during the day to darken the room for video presentations or prevent unwanted heat gain during hot months.

Maintenance

The operating mechanisms of any shading device should always be easily accessible to maintenance personnel, and replacement parts easily obtained. Anything that moves will eventually break if it cannot be cleaned, oiled and/or repaired on occasion.

The Elk Grove School District in California used horizontal louvers in skylights in one of their high schools to provide teachers the ability to darken classrooms. However, over the years the louvers became increasing difficult to operate with the accumulation of dust and grime. The maintenance staff tried to replace some louvers, but decided the expense and time involved was unacceptable. So instead, each time a louver failed they gave the teacher the option of leaving the louvers permanently open or closed.

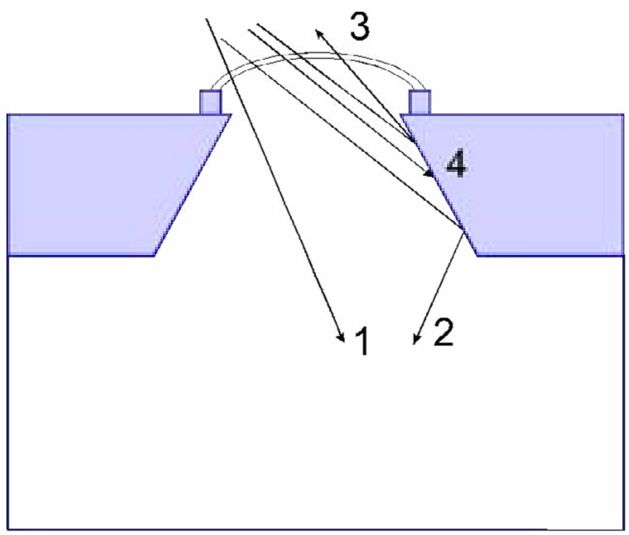
"So far, all of the teachers have chosen to leave them permanently open," explained the director of maintenance.

Light Wells

The light well is as important to the efficiency of the skylight as is the glazing material. There is not much point in specifying the most efficient glazing material if the light well is inefficient. As explained below, white paint on the light well is a basic first step to skylight efficiency. Paying attention to the details of light well configuration and surface finishes, such as the selection of paint color, can be a much less expensive step to efficiency than specifying high tech glazing materials.

Understanding how light well shape and reflectance affects the efficiency of the skylight leads to some simple guidelines on how to maximize the efficiency of skylight wells. Daylight passing through the light well can 1) pass directly though unhindered, 2) be reflected and exit the light well into the building, 3) be reflected and exit backwards through the skylight or 4) be absorbed by the sides of the light well.

FIGURE 3-3:
Light Transfer though a Light Well



A couple of basic observations can be made about light wells:

- The deeper a light well is relative to its width, the less light transmitted.
- Splaying the light well, so the bottom of the light well is wider than the top as illustrated in Figure 3-3, transmits more light than a light well with vertical sides.
- For a given geometry, a light well which is painted white will have the highest efficiency.

The Well Factor

The well factor (WF) describes the fraction of the light entering the light well that reaches the room below. This factor is determined by the geometry of the light well and the reflectance of the surfaces of the light well. To calculate well factor, determine the well cavity ratio and the reflectances of the well surfaces.

The well cavity ratio (WCR) is a single value that describes the proportions of the light well. It is the ratio of wall area to opening area, similar to the room cavity ratio used in electric lighting calculations. The well widths and lengths used are those at the bottom of the light well.

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

A cube shape has a well cavity ratio of ten. An extremely narrow tall well might have a WCR of twenty, and a very shallow well might have a WCR of 2 or 3.

Figure 3-4 provides guidance on typical reflectances of various materials. Some paint manufacturers can provide tested reflectance values for all their paint colors. In the absence of tested information, a rough approximation of the reflectance of a material can be made by using a light meter to compare the amount of light incident on a surface to the amount of light one foot away that is reflected by that surface.

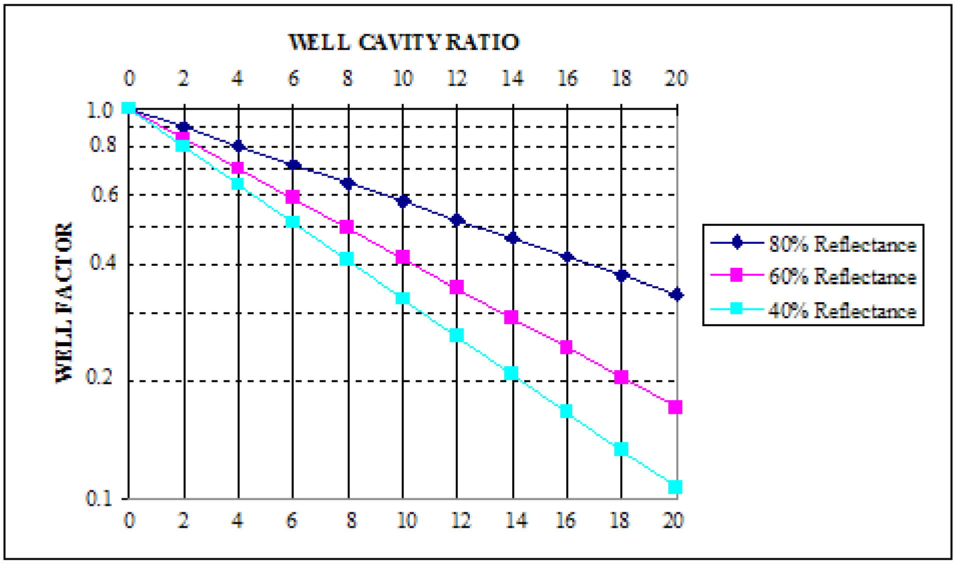
Material	Reflectance
White Plaster	0.93
Aluminum Foil	0.85
White Paint	0.80 - 0.90
Lightly Tinted Paints	0.60 - 0.80
White Enamel	0.65
Pastel Paints	0.40 - 0.60
Red Brick	0.45
Granite	0.45
Concrete	0.40
Bright Colors	0.20 - 0.40
Galvanized Steel	0.35
Saturated Colors	0.10 - 0.30
Medium Grey Paint	0.25
Dark Colors	0.05 - 0.10
Flat Black Paint	0.04

Figure 3-4: Typical Surface Reflectances

Reflectance is the fraction of incident light reflected from a wall surface. The rest of the light is absorbed by the surface.

A graph plotting the well factor is shown in Figure 3-5 for three wall reflectances over a range of well cavity ratios. Notice that the less reflective the surfaces of the well, the lower the well factor. The deeper the well, the more important surface reflectance is to the overall light transmittance of the skylight.

FIGURE 3-5:
Well Factor Graph



Skylight Efficacy

The efficiency of a skylight design is measured as the skylight efficacy (SE), which is a ratio of the light transmitted to the solar heat gains of the entire skylight assembly. It is defined as a function of the light to solar gain ratio of the glazing material times a well factor.

Skylight efficacy[3], SE, can be expressed by the following equation:

$$SE = LSG \times WF = \frac{T_{vis} \times WF}{SHGC}$$

It can be seen from this simple equation that doubling the well factor will double skylight efficacy. For a cube shaped light well, cutting the reflectance of the surfaces in half by changing the paint color from white to goldenrod (80% to 40%), will also reduce the skylight efficacy by half. Thus, designers should communicate assumed interior finish reflectance of skylight wells, room walls, and ceilings to those responsible for interior design.

Frames and Unit U-Factor

The most basic function of any skylight frame is to provide a rigid frame for the glazing material and a secure method of attachment to the roof. However, there are many possible secondary functions that can add complexity to the design of a frame, such as:

3 The concept of Skylight Efficacy (SE) was introduced in the original Skylighting Handbook as a function of the shading coefficient, not the solar heat gain coefficient. In order to use the more accurate SHGC, the term has been redefined as above.

- raising the skylight above any ponding water on the roof
- venting the building
- dispersing internal condensation
- securing multiple layers of glazing
- resisting heat flow
- resisting vandalism
- supporting internal shading devices
- supporting internal screens or safety grills
- automatic venting of smoke

Unit skylights are typically fabricated with glazing material and frame bonded together with a gasketing material and all sealants at the factory, and shipped as a unit ready to install. The attachment of glazing material to frame needs to accommodate expected expansion and contraction of the materials, natural building flex and vibrations, and aging due to exposure to weather and ultraviolet light. The method of attachment of glazing material to frame may largely determine its long term weather-resistance and resistance to vandalism.

Skylight frames can be made out of a variety of materials. Most common are metal (typically aluminum), wood or vinyl. There are also variations, such as metal clad wood, metal reinforced vinyl, and insulated metal frames.

Thus, the design of the skylight frame is a very important criterion in the selection of a skylight product. Energy performance of the skylight is heavily influenced by thermal performance of the frame. The U-factor of a unit skylight is a function of both its glazing material and the thermal resistance of the frame.

Frame Thermal Performance

Metal is highly conductive of heat, thus a metal skylight can contribute a lot of heat to the light well on hot days, and allow even more heat to conduct to the outside at night and during cold weather. The larger the surface area of metal exposed to the weather, the greater the magnitude of this heat flow.. A very cold frame will also cause moisture from the interior of the building to condense on its surface. This condensed moisture is likely to drip down the light well and potentially cause water stains on the ceiling, giving the appearance of a leaking skylight. There are a number of solutions to these problems.

The most energy efficient solution is the use of a “thermalized” frame that may include either a “thermal break,” an insulating layer, or both. A thermal break is a rubber or plastic insert into a metal frame that prevents any continuous thermal path of metal from inside to outside. Metal frames with thermal breaks have become a standard in the window industry in order to improve the thermal performance of windows. They are less common in the skylight industry, where heat loss has been less of a concern.

A frame can also be insulated to reduce heat flow. This can be either a factory applied foam insulation or a site installed insulating material on the inside of the frame. Wood frames are naturally much more insulating than metal. Hollow vinyl performs similar to wood. A vinyl frame with injected insulating foam will be the most insulating of all. A frame can be rated with its own R-factor or U-factor. An even better indication is an overall unit U-factor that integrates the performance of both glazing material and frame.

Condensation

In addition to thermal breaks or insulation, condensation problems can be reduced in two other ways. Many unit skylights will have condensation gutters that capture the condensed water that drains off of the glazing. This water is vented to the outside via weep holes. In a non-critical application, this is usually sufficient. However, weep holes do allow a potential path for both infiltration and wind driven rain to enter the building. An alternative is to size the condensation gutters with enough capacity so that the condensed water will be stored until it can re-evaporate. Typically, this is a daily cycle, with condensation forming at night and evaporating during the day. Select a skylight that meets or exceeds the requirements of the applicable energy code while also incorporating a condensation gutter.

Mounting Types

There are three major mounting types for skylight frames:

- Curb mounted frames - the frame attaches to the top of a separate curb. The curb is the structural connection to the roof, most commonly site built of wood 2x10s or 2x12s. The curb also creates the transition from roofing material to skylight flashing to ensure a water tight seal around the skylight opening.

- Integral curb - the curb is pre-manufactured as part of the skylight frame, typically of the same materials as the frame.

- Flush mount - the skylight is flush with the surface of the roof. This is appropriate for a tilted roof surface.

An integral curb skylight, if it is not insulated, will lose more heat than a similar curb mounted skylight, because there is a larger surface area of frame exposed to the outdoors. Flush mounted skylights, on the other hand, will usually have less heat loss than a comparable curb mounted or integral skylight, because they do not project from the surface of the roof and have less area to lose heat.

Operable and Venting Frames

Operable skylights are designed to open to provide natural ventilation, and occasionally even egress. This type is fairly common in residential applications but is rarely seen on larger commercial buildings.

More common are venting skylights which have louvers in the frames designed to allow air to escape from the building while preventing rain from entering. Venting frames are used on unconditioned buildings, such as warehouses, agricultural and industrial buildings, to increase the flow of air through the space, and especially allow heat build-up at the roof to escape. They are more common in hot climates, where cooling is more of an issue than heating. Venting skylights do, however, have the potential to allow wind driven rain to penetrate into the building.

Smoke vent skylights are designed to pop open automatically in case of fire, releasing fumes and hot air at the ceiling plane, and thus reducing the spread of the fire in the building. They usually have a fusible link which breaks at high temperatures, and a spring action hinge that then is free to pop open. An alternate design allows the glazing material to drop out when overheated. Smoke vent skylights are a fire-code requirement for some building types (see the "Fire Codes" section). Often these buildings will have a mixture of smoke vent frames for the code required area and standard frame skylights for additional daylighting.

Unit U-factor

The heat losses or gains due to temperature differences between the outside and inside air results from the product of the U-factor (thermal transmittance) skylight area, and the temperature difference. An accepted way of describing U-factor is in terms of Btu per hour of heat loss per square foot of skylight opening, per degree Fahrenheit of temperature difference between the outside and inside air temperatures. The heat losses through the glazing, frame, and curb all contribute to the overall unit U-factor.

When specifying a product unit U-factor, be sure to compare similarly defined values. U-factors can be made to look "better" (lower) by considering the loss only through the glazing or by defining the area as the total surface area of the skylight, including sides, instead of the skylight opening. There is room for confusion here since for a window, the rough opening is larger than the nominal size of the window, whereas with skylights, the rough opening is smaller than the nominal size. Ultimately, heat loss calculations are concerned with the heat loss through the opening in the insulated wall or roof.

Current standards for skylight U-factor testing are included in the NFRC 100 document. Representative U-factors are shown in Figure 3-6 for low profile skylights (either flat skylights or low rise dome skylights). Barrel vaulted or pyramidal skylights have larger surface areas to lose heat. The resulting increased "effective U-factor" per horizontal area covered by skylights can be found by multiplying by the relative area increase relative to a flat skylight.

FIGURE 3-6:
Skylight Unit U-factors in Btu/h ºF sf

Note: these factors are calculated assuming a flat glazing material. They are reasonably representative for low profile skylights. Use tested factors whenever possible.

	Curb Type	Integral Frame			Flush/Site Assembled		
Glazing Type	Glazing layers	Metal w/ thermal break	Metal clad wood	Wood or vinyl	Metal	Metal w/ thermal break	Structural Glazing
Plastic	Single glazed	1.730	1.600	1.310	1.210	1.100	1.100
	Double glazed	1.100	1.040	0.840	0.810	0.690	0.650
	Triple glazed	0.870	0.810	0.610	0.620	0.510	0.450
Fiberglass	Ins. panel U-0.24	0.483	0.494	0.368	0.460	0.363	0.295
Glass	Single glazed	1.890	1.750	1.470	1.360	1.250	1.250
	Double glazed	1.100	1.040	0.840	0.810	0.690	0.650
	Double low-e	0.990	0.920	0.720	0.700	0.580	0.540
	Triple glazed	0.870	0.810	0.610	0.620	0.510	0.450
	Triple low-e	0.760	0.710	0.510	0.520	0.410	0.360
	4 layer low-e	0.710	0.660	0.460	0.470	0.360	0.300

When talking about U-factor, we are mainly concerned with heat loss in winter because for most of the country, the difference between indoor and outdoor temperature in winter is much greater than in summer. Considering U-factor only to estimate summer thermal transmittance will overestimate this component of heat gain because in the summer, the stratified air rises and is trapped in the light well. This stratified air acts like a blanket, insulating somewhat against heat transfer.

The U-factor of skylights is primarily a function of the number of glazing layers, the emissivity and selectivity of the glazing itself or applied coating, thermally insulating gasses injected between the layers of glazing such as argon, the material used in the spacers which hold the glazings apart, and the materials used in the frame.

Structural and Safety Issues

There are three basic structural and safety issues that need to be addressed in skylight design:

- maintaining the integrity of the roof structure
- the resistance of the skylight itself to weather loads and abuse
- prevention of accidental breakage or entry

Roof Structure

The roof of a building is often a structural "diaphragm," or plane, that is designed to stiffen the building and resist forces that might tend to twist the structural frame. This diaphragm can have a certain number and size of holes in it and still continue to function. However, at some point, additional holes will weaken its strength. Thus, the structural engineer for a building may calculate that there are limits on the number, size, and location of holes in the roof that can be made for skylights, or any other penetrations, such as mechanical ducts, vents or access hatches.

There are ways to strengthen the diaphragm to allow additional penetrations. If more skylights than the initial structural limit are desired, redesigning the roof structure may be an option. In wood construction, thicker plywood and additional nailing can strengthen the diaphragm. In steel construction, added framing members around openings can strengthen the roof. In concrete construction, additional reinforcing or formed concrete curbs can be used. Thus, while structural considerations can be a limiting factor on skylight design, there are always alternatives that can be considered.

Structural Loads

Skylight units (frames and glazing) must also be able to resist a variety of potential loads. These include:

- Snow loads
- Wind (uplift) loads
- The weight of the skylight assembly
- Loads transferred from the building to the skylight (flexing and vibrations)
- Weight of people
- Forcible entry and vandalism
- Flying objects (wind driven gravel, debris, and errant birds)

It is important to remember that structural and safety concerns do not begin and end with the glazing only – the attachment of the glazing to the frame, the frame itself, and the attachment of the frame to the roof are also concerns.

The magnitude of potential snow loads are usually addressed in local building codes that specify a maximum loading expected for a given area. This is normally specified in terms of withstanding a particular "live," or changeable, load of a given PSF (pounds per square foot). Testing for this requirement is typically done by evenly placing enough sandbags on the skylight so that the loading exceeds the requirement. The requirement should exceed the worst case predicted snow load by a healthy safety margin.

Wind can create uplift pressures on the roof and skylights. Most local building codes specify a wind load that must be resisted. This loading, however, is more commonly calculated for vertical surfaces resisting a horizontal force, than for horizontal surfaces resisting suction uplift. Very strong storms, such as hurricanes, can cause sudden pressure differentials that can blow a skylight off from the inside, especially if there is an opening elsewhere in the building. The manufacturer should be able to detail suitable attachment methods in shop drawings and warranty the skylight and attachment method for a given set of wind conditions.

Small unit skylights do not usually have a problem supporting their own weight, but large site assembled skylights have to be carefully designed to prevent failure. Skylights are not designed to support structural loads transferred from the roof. The structural engineer should ensure that all structural forces are diverted around the skylight openings.

Refer to AAMA published guidelines for structural criteria in skylights listed in the bibliography for further guidance on the design, selection and installation of skylights.

Safety Grates

Few skylights can withstand the impact of people, whether inadvertently falling on them, intentionally jumping on them or trying to break them with a heavy object. These should be labeled as not resistant to standing or falling people. There are, however, some skylight products that can resist these abuses. Underwriters Lab (UL) Standard 972 covers the strength of the glazing resisting the efforts of burglars, while American Society of Testing Methods (ASTM) Standard F588 tests how well the frame will hold up to "forced entry." To meet these standards products may be limited to specialty glazing materials and a heavy-duty frame. These types of skylights are particularly popular with school districts.

Another way of addressing security and safety issues is to install a safety grate above or below the skylight. A metal grate will effectively resist the weight of a person and stop a fall. The most common safety grate is a steel grid mounted inside of the frame or curb. This protects people from accidental falls and prevents break–in by thieves. Some manufacturers provide a safety grate as a factory built option for their units. Conversely, a building owner may include it as a standard site-built specification item.

A safety grate will, of course, also reduce the amount of light transmitted through the skylight, and should be accounted for in any calculations (SkyCalc has a safety grate option). A white painted grate will reflect more light, but sometimes is more visible from below, especially at night. Depending on visual conditions, a black grate can sometimes be less apparent.

Roofing and Insulation Decisions

The integration of the skylight with the roofing system is another important consideration. A roof membrane is usually selected independent of the choice of skylights. Skylights can be successfully flashed and waterproofed with any roofing system. The flashing design is no different than for mechanical curbs, roof parapets, or other interruptions of the roof surface. (See the AAMA Skylight Installation Manual).

The vast majority of commercial skylights are installed with a hot-mop, multi-ply asphalt roofing system. Properly installed, the skylight junction will last as long as the rest of the roof. Single ply roofing systems are also amenable to skylights. The biggest concern is likely to be the added cost of additional penetrations, which can raise the installed cost significantly.

The most important roofing choices occur in specification language. Many specifiers require skylight installers to have a minimum number of years of experience. Others mandate a team meeting of the roofing contractor, structural engineer, skylight installer and distributor, and general contractor to resolve all timing and detailing issues. It is an excellent idea to require a warranty of roof performance from the contractor (10 year and 15 years are standard) that specifically includes the skylight penetrations, and a guarantee that any leaks which are identified will be addressed immediately (within a fixed time period of hours or days). Inclusion of a water pressure test on the roof after skylight installation and before occupancy is also advisable for specifications. With these provisions, skylights and the rest of the roof are more likely to remain leak free for the roof's expected service life.

Roof Insulation

Selecting a roofing system also includes the choice of roof insulation. In an "up-side-down" roof, the insulation, commonly rigid board, is installed above the roof deck and roof membrane and held down with stone ballasts. Gravel on the roof is a potential source of abrasion or puncture of skylights. Thus these systems are rarely used with skylights. Locating foam insulation under the roof membrane, but above the deck typically does not involve the same ballasting problem. It does, however, raise the height of the skylight curb that must reach from structure to above the insulation. There may be more flex at the membrane-to-curb joint, creating a potential source of failure.

By far the most common insulation approach is to locate fiberglass batt or board insulation below the roof deck. For buildings without a finished ceiling, this offers the potential to use a reflective-surfaced insulation material, which will reflect more light down into the space. Alternatively, the surface of the insulation material can be painted white, which will actually reflect even more light.

Finally, thought should be given to insulating the light well and skylight curb. As discussed above, this will reduce heat loss and reduce the potential of condensation forming on the cold surface of the skylight frame.

Building Codes and Standards

Skylights are regulated by a variety of building codes to assure that their application does not compromise the energy efficiency, structural integrity or safety of a building. Building codes as they apply to skylights may vary by jurisdiction. Therefore, the applicable codes for the local jurisdiction should be reviewed prior to design.

In spite of the variations, however, some general comments can be made about the more widely applicable codes. These apply primarily to energy efficiency, the load bearing capacity of the skylight, and the area and spacing for combustible skylight materials (principally plastic glazing).

Energy Codes

Many of the key energy codes enforced in the United States recognize that appropriately sized skylights, when used with daylighting controls, save energy. The California Standards and the national ANSI/ASHRAE/IESNA 90.1 Code are reviewed below.

California Building Energy Efficiency Standards

The 2013 California Building Energy Efficiency Standards (also referred to as "Title 24") include requirements for skylights and lighting controls in daylit areas, as described below.

The prescriptive path of the California Nonresidential Building Energy Efficiency Standards (Title 24) sets an area limit for skylights of 5% of the gross exterior roof area, or up to 10% for an atrium over 55 feet high. Skylight area of unit skylights is the area of the rough opening of a skylight.

Along with limitations on skylight area, the Standards have a maximum U-factor and SHGC for skylight areas, as well as a minimum VT. These requirements vary depending on product type and installation methods. Starting with 2013 Standards, there is no variation by climate zone. Maximum U-factors range from 0.46 for glass, deck-mounted skylights, to 0.88 for plastic, curb-mounted skylights. In addition, all glass skylight types must have a maximum SHGC of 0.25. Glass skylights must have a minimum VT of 0.49, while plastic skylights must have a minimum VT of 0.64.

California has another, highly flexible compliance approach, called the "performance approach" which uses whole building energy budgets. The designer can use whatever skylights (and other building features) desired, as long as an approved building simulation program demonstrates that the proposed design uses less energy than a similar building that meets the prescriptive energy standards.

In addition to these performance requirements, certain space types are required to include skylights. Any space over 5,000 square feet, with a ceiling height greater than 15 feet, and directly under a roof must have a combined total of 75% of its floor area within a skylit daylit zone, or a primary sidelit daylit zone.

The California Standards define the "skylit daylit zone" as an area within 0.7-times the ceiling height of the bottom of the skylight well. Thus for a rectangular skylight, the skylit daylit zone becomes a rectangular area with dimensions that are 1.4-times the ceiling height, plus the length or width of the well. Figure 3-7 shows an example of space that has 75% of its area within the skylit daylit zone.

Starting with the 2013 Standards, any light fixtures fully or partially within the skylit daylit zone or the primary sidelit daylit zone are required to be controlled by automatic daylight controls, when the total combined installed wattage in the daylit zone is greater than 120 Watts. To determine which lighting fixtures are required to be controlled and which ones are excluded, a simple rule has been developed. Area beyond a permanently installed obstruction greater than one-half of the ceiling height is considered to have insufficient daylight availability, and fixtures in that area are not required to be controlled. Figure 3-8 shows an example of the determination of the daylit area and fixtures in skylit

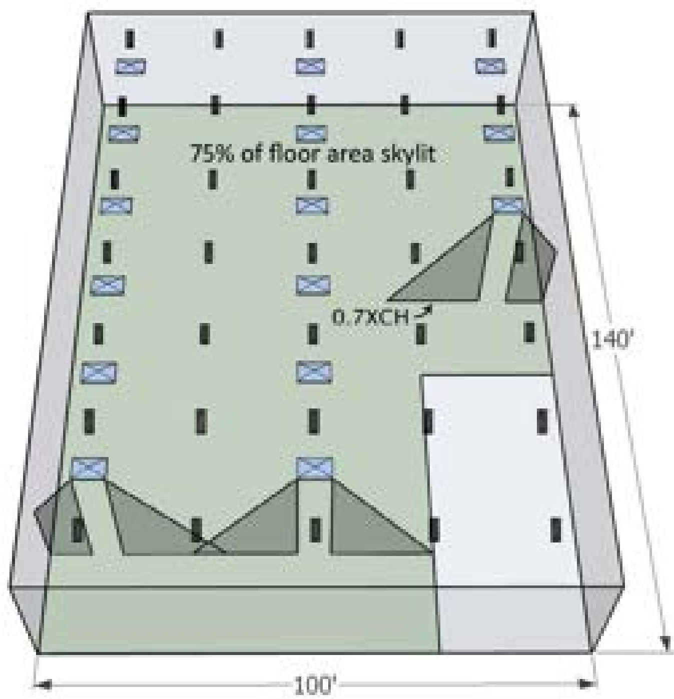


FIGURE 3-7:
Skylit daylit zone

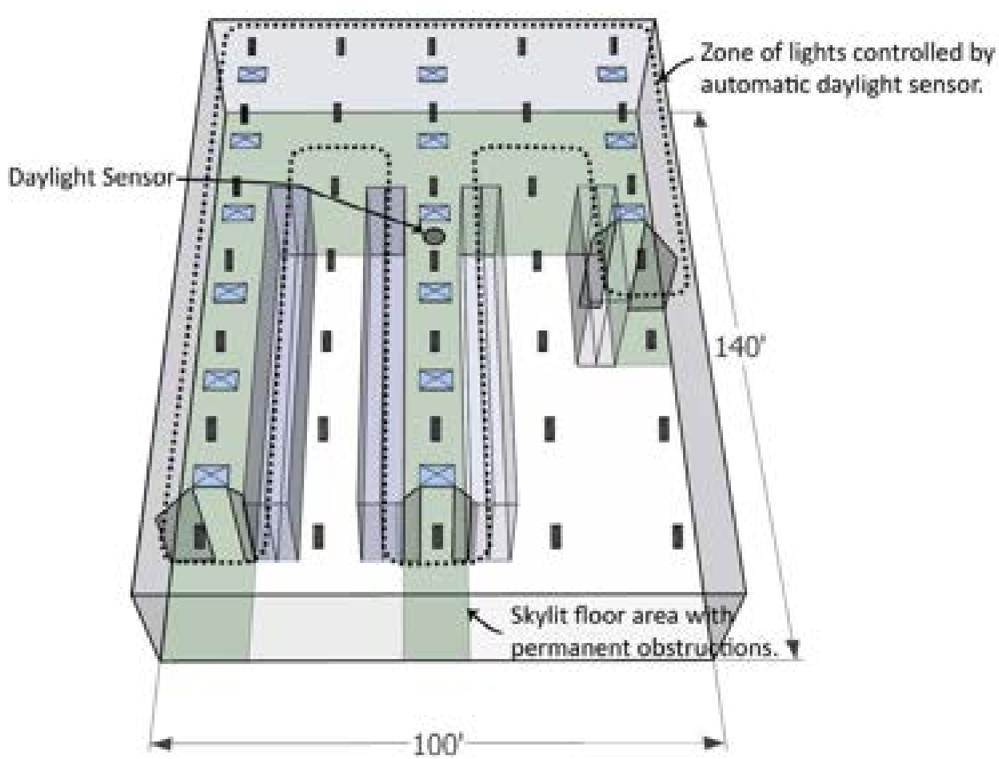


FIGURE 3-8:
Skylit daylit zone with permanent obstructions

daylit zones, in a space with permanent obstructions. This is the same space shown in Figure 3-7, only this time, with permanently installed tall storage racks that block the daylight coming from the skylights in the space. Because these storage racks are taller than one-half the ceiling height, only the fixtures indicated within the dotted black line are required to be controlled by automatic daylighting controls.

The Standards require that all fixtures must meet the appropriate multi-level controls requirement. The 2013 Standards establish a minimum level of controllability for all lighting installations, based on the type of light source. The multi-level control requirement specifies that all LED fixtures must have continuous dimming control from 10-100 percent; fluorescent fixtures must have a minimum of four control steps (one each between 20-40%, 50-70%, 80-85%, and 100%) plus off; and HID fixtures must have at least one control step between 50-70% plus full output and off. The new standard also requires any step switching to occur within each luminaire, using either a multi-step ballast, or by separately switching lamps within each fixture. The Standards no longer allow controlling entire fixtures separately to meet the multi-level controls requirement. Therefore a fluorescent fixture must have at least four lamps to meet the multi-level control requirement by separately switching individual lamps.

Current requirements of the Title 24 Building Energy Standards are available from the California Energy Commission. See the Title 24 home page at http://www.energy.ca.gov/title24/.

National Energy Codes

Similar to California, more recent versions of national model codes such as IECC and ANSI/ASHRAE/IESNA Standard 90.1 are starting to require skylights in certain applications. However, standards vary across the country. Most states that have energy codes use the Standard 90.1 model as the basis for the code, with about 35 states using codes that are comparable to 90.1-2007 at the time of this writing. Three states had codes comparable or better in energy efficiency to 90.1-2010. Four states have energy codes comparable in energy efficiency to 90.1-2004, and 10 states have no statewide codes. A number of states are 'home rule' states, where the adoption of energy codes falls to the local jurisdictions. This results in a large variation in the level of energy efficiency within the state as well.

Designers and specifiers working outside of California should familiarize themselves with the energy code requirements related to skylights for their local jurisdiction.

Fire Codes

Plastic glazing materials are combustible and their use is allowed with area limitations and spacing requirements. The use of automated fire suppression equipment (sprinklers) affects these parameters, as does the type of plastic used. Approved plastics are separated into two types, based on a small scale flammability test: CC-1 (or C-1) and CC-2 (or C 2). The Uniform Building Code places the following limitations on plastic skylights:

- The plastic glazing must be mounted at least 4” above the plane of the roof.
- Skylights with CC-1 glazing may be no larger than 200 sf per skylight
- Skylights with CC-2 glazing may be no larger than 100 sf per skylight
- The total area of skylights containing CC-1 materials is limited to maximum of one third of the roof area (SFR = 33%)
- The total area of skylights containing CC-2 materials is limited to maximum of one quarter of the roof area (SFR = 25%)

The use of sprinklers may relax some of these limitations.

The Uniform Building Code (UBC) requires smoke vents for 1% of the roof area in Business, Factory, Mercantile and Storage occupancy single story buildings with over 50,000 sf of undivided space. Office and retail spaces are exempted from this smoke vent requirement if storage height does not exceed 12 ft. The UBC also requires that Hazardous occupancy buildings with over 15,000 sf per floor have 2% of the roof area in smoke vents.

These smoke vents typically have a metal or plastic cover and many manufacturers have developed clear covers so that the smoke vent doubles as a skylight. Though the skylight-to floor ratio (SFR) of 1% or 2% required for smoke vents is less than what is usually needed for an effective skylighting system, the smoke vents can be interspersed with non-opening skylights and help keep the incremental cost of the skylighting system down. Smoke vents are usually Factory Mutual rated. The fusible links on mechanical opening smoke vents are also typically UL or FM listed.

ANSI and other standards

The following is a list of organizations and their publications that may be referred to when specifying skylights.

AAMA - American Architectural Manufacturers Association

- AAMA 501.2: Field Check of Metal Curtain Walls for Water Leakage
- AAMA 1503.1-2009: Voluntary test method for thermal transmittance and condensation resistance of windows, doors, and glazed wall sections. U-Factor class is in terms of hundredths of a Btu/hr•ft2•ºF (i.e. class U20 has a maximum tested U-Factor of 0.20 Btu/hr•ft2•ºF).
- AAMA/WDMA 1600/I.S.7-00 Voluntary Specification for Skylights. Specifications include material and finish requirements as well as performance requirements for air infiltration, water resistance, and structural loading.

- AAMA 1605.1-82 Voluntary Standard Uniform Load Test Procedure for Thermoformed Plastic Domed Skylight

- AAMA 1601-1993 Voluntary load bearing specification for plastic skylight domes. Presents recommended strength values for exterior one piece thermoformed plastic skylight domes. No safety factors have been applied to these domes.

- AAMA 1607-04 Installation Guidelines for Unit Skylights.

ANSI - American National Standards Institute

- ANSI-Z97.1-2009: Standard For Safety Glazing Materials Used In Buildings - Safety Performance Specifications And Methods Of Test

ASTM - American Society for the Testing of Materials

- ASTM D1929-12 Standard Test Method for Determining Ignition Temperature of Plastics

- ASTM D1003-11e1 Standard test method for Haze and Luminous Transmittance of Transparent Plastics.

- ASTM D4364-05 Standard Practice for Performing Outdoor Accelerated Weathering Tests of Plastics Using Concentrated Sunlight equivalent to ISO877.2-1991 Method C.

- ASTM E167-96 Standard Practice for Goniophotomery of Objects and materials

- ASTM E283-04(2012): Test Method for Rate of Air Leakage Through Exterior Windows, Curtain Walls, and Doors

- ASTM E330-02(2010) Standard Test Method for Structural Performance of Exterior Windows, Curtain Walls, and Doors by Uniform Static Air Pressure Difference

- ASTM E331-00(2009): Standard Test Method for Water Penetration of Exterior Windows, Curtain Walls and Doors by Uniform Static Air Pressure Difference

- ASTM E972-96(2007) Standard test method for solar photometric transmittance of sheet materials using sunlight

- ASTM E1423-06 Standard Practice for Determining the Steady State Thermal Transmittance of Fenestration Systems

- ASTM F588-07 Standard test methods for measuring the Forced Entry Resistance of Window Assemblies, Excluding Glazing Impact

- ASTM F1233-08 Standard Test Method for Security Glazing and Systems

- ASTM G90-10 Standard Practice for Performing Outdoor Accelerated Weathering Tests of Nonmetallic Materials Using Concentrated Sunlight

CPSC - U.S. Consumer Product Safety Commission

- 16 CFR 1201 - Consumer Product Safety Commission Standard for Architectural Glazing Materials

CSA - Canadian Standards Association

- CSA Standard A440-08 North American Fenestration Standard/Specification for windows, doors, and skylights

ICBO - International Conference of Building Officials

- ICBO Evaluation Service: Acceptance Criteria for Plastic Skylights. Durability, safety, water leakage, flame spread are combined under one acceptance criteria. Does not address energy issues of U-Value, Solar Heat Gain Coefficient or Visible Transmittance.

- Uniform Building Code: Section 2409 - Sloped Glazing and Skylights: mainly safety considerations for glass skylights and frames. Section 2603 - Light Transmitting Plastics: This covers acceptable construction, size limitations etc. of plastic skylights (2603.7), and requirements for light diffusers (2603.8)

- Uniform Building Code Standard 15-7 Automatic Smoke and Heat Vents

ISO - International Standards Organization

- ISO 877 Methods of exposure to direct weathering, to weathering using glass filtered daylight, and to intensified weathering by daylight using Fresnel mirrors.

NFRC - National Fenestration rating Council

- NFRC 100 Procedure for Testing determining fenestration product U-Factors. Currently NFRC procedures for determining U-Values are based on a vertical tilt and thus underestimate heat loss.

- NFRC 300 Procedure for Determining Solar Optical Properties for Simple Fenestration Products

- NFRC 400 Procedure for Determining Fenestration Product Air Leakage.

OSHA - Occupational Safety and Health Administration

- 29CFR Part 1926 Subpart M – Fall Protection. This has a generic description of methods of fall protection, but is not an explicit test standard.

UL - Underwriters Laboratories

- UL 972 Burglary Resisting Glazing Material

Chapter 4: Daylighting Controls

This section explains how to design and operate daylighting controls for electric lighting systems. The phrase "daylighting controls" is used in a specific way throughout these Guidelines. Here, daylighting controls are devices that regulate the level of illumination from electric lighting in response to the presence of daylight.

Saving Energy with Skylights

Without daylighting controls, a skylit building will not save any energy. Indeed, if it is heated or cooled, it may consume more energy than if it had no skylights. This is very important to understand.

However, with daylighting controls, a skylit building can reduce its energy use for lighting by ½ or more, and also see significant savings in cooling costs. These savings can range from about $.05/sf to $.75/sf depending on building type, operation, location, and energy costs. SkyCalc allows a designer to quickly assess the magnitude of those savings for a given building design, operation and location.

Control over the electric lighting can be exerted through an automatic device (automatic control), human intervention (manual control), or both. Some degree of manual control is usually desired, but in most situations a properly designed and commissioned automatic system is more likely to bring about guaranteed, sustained energy savings. For this reason, most building energy standards include requirements for automatic controls.

Occupancy versus Daylight Availability

Daylight is usually available during those hours when most nonresidential buildings are occupied. The amount of lighting energy savings is a function of daylight availability, occupancy pattern of the building, and daylighting control strategy. For example, an elementary school classroom typically operates from 9am to 3pm. Even though daylight is available after 3pm, there will not be electric lighting savings during those hours if the space is not occupied. Similarly, if a retail store does not open until noon, there will be no lighting savings during the morning daylight hours. A restaurant that only serves dinner may have very minor savings from daylight controls. Those buildings where operating hours include the most hours per year when daylight is available will have the greatest savings from daylighting controls.

An abundance of daylight is available during those hours when peak demand for electricity is most problematic for utilities, typically noon to 6pm during summer months. At these times, the retail cost of electricity for nonresidential buildings, which typically have time-of-use rates, is most expensive. With controls on electric lights, skylights may reduce peak demand and time-of-use charges.[1] As utilities increase implementation of time-of-use electricity rates, the ability to achieve energy savings during peak hours through daylighting will become increasingly valuable.

Manual Lighting Controls

With manual lighting control, the occupants are responsible for switching off the lighting when there is adequate daylight. Because it requires no additional hardware, manual control is by far the least expensive lighting control system—if it is used. For large, complex commercial buildings, manually controlled lighting is unlikely to result in significant energy savings since there are many variables, and individual responsibility for and access to controls is often unclear. However, for small or single space commercial or industrial applications (retail boutiques, simple warehouses) where a single manager can adjust the electric lighting according to current daylight conditions, manual controls may be effective.

Although manual controls can be effective in some situations, readers should note that the 2013 California Building Energy Efficiency Standards will require automatic daylighting controls in all Skylit Daylit Zones (see Chapter 3 for more information on energy codes).

The reliability of manual switching is dependent upon the following:

1. *Accessibility* of the switch to the users. If it is not easy to get to, no one will use it.

2. *Size* of the control zones relative to the number of people using the space. The person controlling the switch should have authority over the space. Thus a building manager may control the whole floor of a warehouse, while each individual should control the switch in their own private office.

3. *Vigilance* of the user. Past assumption has been that occupants are highly unreliable in controlling lights for energy savings. However, there is growing evidence that these assumptions have been too pessimistic. Building managers charged with saving energy are often very vigilant in controlling electric lights. Occupant training can also increase the energy saving potential of manual lighting

1 This is less true in areas with utility peaks that occur during humid, cloudy conditions. In those areas, even though a skylighting system will save energy overall, it probably will not reduce demand charges, since it will not significantly lower energy demand during the one-time peak condition upon which demand charges are usually based.

controls. For example, studies have shown that when given the option, building occupants will decrease their electric light levels, or turn lights off completely, when provided with sufficient daylight or indirect light.[2]

The opportunity for manual control of lighting is very important psychologically. Numerous studies have shown that people are happier when they have some control over their work environment. A light switch is an important symbol of such control. However, as mentioned above, in large buildings and where required by code, automatic controls are necessary to increase the likelihood of ongoing energy savings.

Automatic Lighting Controls

While automatic control does not depend upon the daily decisions of the building occupants, its success is dependent upon a number of crucial factors:

1. *A Clear Controls Narrative*. The narrative sets expectations for what the lighting controls system is intended to do, helping the designers communicate their intent to specifiers, bidders, installers and commissioning teams,

2. *Selection* of the proper equipment. This manual provides some guidance, but a knowledgeable electrical engineer should have full responsibility for the final specifications.

3. *Commissioning* of the system. The system must be calibrated and adjusted to suit the unique conditions found at each building site. Failure to commission is the single greatest cause of daylighting control systems' failure to perform properly. The system must also be capable of being easily readjusted if conditions change, such as with a change in building interiors layout.

4. *Understanding* by the building manager and occupants. Photosensor controls remain rather mysterious to the average person. It is an excellent idea to explain the system to the people who will be living with it. Without basic understanding and training, strange things can happen, as shown in the examples below:

As an example of the need for occupant understanding of daylighting control systems, a grocery store manager worked in a building with skylights and photosensor controls for three years, yet never understood why the lights would sometimes turn off. The manager did not know how to answer employees' questions about the lights. Finally, an electrician was hired to 'fix' the problem. The electrician, of course, disconnected the photosensor.

In one recently constructed daylit building, automatic daylighting controls were provided with a photosensor mounted in the ceiling. However, no electrical connections were made during construction. The company had occupied the new building for over a month when the controls team returned to

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2 Pacific Gas and Electric Company, "Codes and Standards Enhancement Initiative (CASE): Bi-Level Control Credits Final Report," October, 2003, p 15.

connect the photosensor controls and commission the system. They found, to their surprise, that the occupants had already taped over the photosensors. Why? The system certainly couldn't have been causing any problems since it wasn't even functional yet. Did they think they would get more light? Or stop lighting conditions from changing? Did they dislike the idea of an "automatic" system? Probably the best explanation is that they just didn't understand the system.

Although acceptance testing procedures in energy codes like California's Title 24 are designed to avoid these types of situations, the most important proviso with an automatic system is: "Always remember the human factors!"

Automatic Daylighting Control Strategies

The following sections address the specifics of how to design and implement a successful automatic daylighting control system.

Components

An automatic daylighting control system consists of the following components:

Light source: The type of electric lighting system to be controlled. Critical decisions include the type of light source (fluorescent, metal halide, LED, etc.), the type of ballast driving the light source (on/off, dimming, hi-lo), the wiring to the fixtures (standard, split), the number of fixtures per circuit, and the physical layout of the fixtures.

Control unit: The control unit is the physical device, either a dimmer or a switch, which varies the amount of power applied to the light source. A dimmer is capable of continuously varying the amount of electric power flowing to the light source, thus providing a wide range of light output from the source. A switch (or relay), on the other hand, is a control unit that can only switch its load on and off. A switch provides less control flexibility than a dimming unit, but is also typically less expensive.

Photosensor: Automatic systems use a photosensor to measure the illumination entering or within a daylit building space. The photosensor provides a signal to the controller.

Controller: The controller translates the photosensor signal into a command to the control unit, based upon an algorithm or set of 'if/then' instructions. For dimming applications, the controller reads the photosensor signal and then commands the control unit to dim in proportion to the intensity of the signal representing available daylight. Thus, the electric lights will dim significantly if there is an abundance of incoming daylight but only slightly if the daylight is low. For switching applications, the photosensor signal is compared to a preset value and the control unit is commanded to switch lights on or off depending on the comparison.

Controllers can range from complex digital systems controlling multiple zones across an entire building, to units that integrate the entire control system (including a photocell) into individual fixtures. The choice of what kind of controller, or control system, to use depends heavily on the needs of the space and the lighting system. Establishing a clear lighting controls narrative early in design can simplify the design process and increase the likelihood that controls are appropriate and properly installed.

Control Zones

During the design phase, electric lights that are to be controlled together should be organized into control zones. All the lights in a control zone are dimmed (or switched) together and are regulated by one controller (and one photosensor). Zones should be determined by identifying areas with:

1. similar task illumination needs
2. similar lighting schedules
3. similar daylighting conditions, and
4. similar electric lighting systems.

The designer should have information about what types of tasks are to be performed in each major area of an installation, including the location and heights of any major light obstructing objects, such as storage racks, tall equipment or high partitions. Although this seems simple, lack of this knowledge is a very common reason for poorly performing control systems. The designer often does not have the luxury of waiting until all interior partitions and shelving are located before laying out lighting circuits. However, there are a few helpful hints discussed in Chapter 2 to increase the probability of success.

From an electrical standpoint, all the fixtures in a control zone are typically on one lighting circuit or subcircuit (switchleg). The size of control zones can also be limited by the electric current capacity of the lighting circuit. For the 30-amp breakers common in most commercial building lighting electrical systems (277 VAC), this corresponds to a maximum control zone size of about 6000 Watts, or approximately 5,000 sq. ft.

Switching versus Dimming

The choice of a switching or a dimming system is an important design decision which affects the potential for energy savings, user acceptance, and initial cost.

Although dimming systems are more expensive than automatic switching systems, as daylighting and multi-level control requirements in the 2013 Building Energy Efficiency Standards come into effect in California, the cost of dimming systems is expected to continue to decrease. As with all control system, the complexity and granularity of dimming control systems also heavily impacts cost. Since dimming systems alter light output continuously, they are more likely to be acceptable to the building occupants, especially those working at a fixed task. Dimming systems that have been properly specified, installed, and commissioned follow the pattern of daylight availability very closely, and thus tend to produce more energy savings, especially in areas with highly variable cloud cover.

Dimming systems also have one other important feature that can lead to additional energy savings. Since dimming systems are designed to maintain a fixed illuminance, such as 50 footcandles, the system will also respond to decreased light output due to dirt accumulation or aging of the lamps. Most lighting systems are over-designed by 15-25% to account for these “depreciation factors.” Thus, the initial light output of a lighting system is typically 15-25% higher than at the end of its life. A photosensor controlled dimming system can reduce the light output at the beginning of system life to the target illumination level (instead of target plus 25%) and then gradually increase power to maintain light output as the lamps age. This process, often called the “lumen maintenance” effect, can result in an additional 5-10% energy savings over the life of the lamps.

Switching systems create larger differences in light output as they switch between illumination levels in response to changing daylight conditions. Rapid changes in electric light level may be confusing or annoying to some building occupants, although the changes in illuminance will often go unnoticed. Being simpler, switching systems are typically less expensive than dimming systems. They tend to be most effective at saving energy in areas with fairly constant daylighting conditions, either all sunny or all cloudy. Switching systems also tend to be more acceptable to occupants who are moving around a great deal, such as shoppers or workers in a warehouse. The use of switching systems should be carefully considered in hazardous environments, such as around fast moving machinery, if sudden shifts in lighting conditions might cause dangerous momentary distractions.

The choice of dimming versus switching should also be influenced by the type of lighting system selected. Fluorescent lamps and many LED fixtures work well with either system. They can easily be dimmed, or switched on and off, and suffer only minor shifts in color when operated at less than full power. High intensity discharge (HID) sources, such as metal halide, are more problematic. HID lamps take a while to restart after being turned off, in some cases as long as several minutes, making them difficult to use with a switching system. Dimming ballasts for HID lamps are available, but still relatively rare. An alternative approach is to use ballasts that can operate at two levels of light output, which solves the restarting problem. However, metal halide lamps tend to shift in color appearance when operated at low power. Because of these limitations, HID lamps are more common in manufacturing, warehouse and discount retailing applications where lighting quality and fast system response are less important.

The pattern of illuminance achieved under three control strategies is illustrated in Figure 4-1. Two-step switching shows the largest shifts in illumination levels, while the dimming pattern very closely follows the daylighting pattern. Three-step switching defines a middle ground between the two. It should be noted that these curves show typical illuminance patterns for a clear, sunny day. A day with variable clouds would show even more variation in illumination levels.

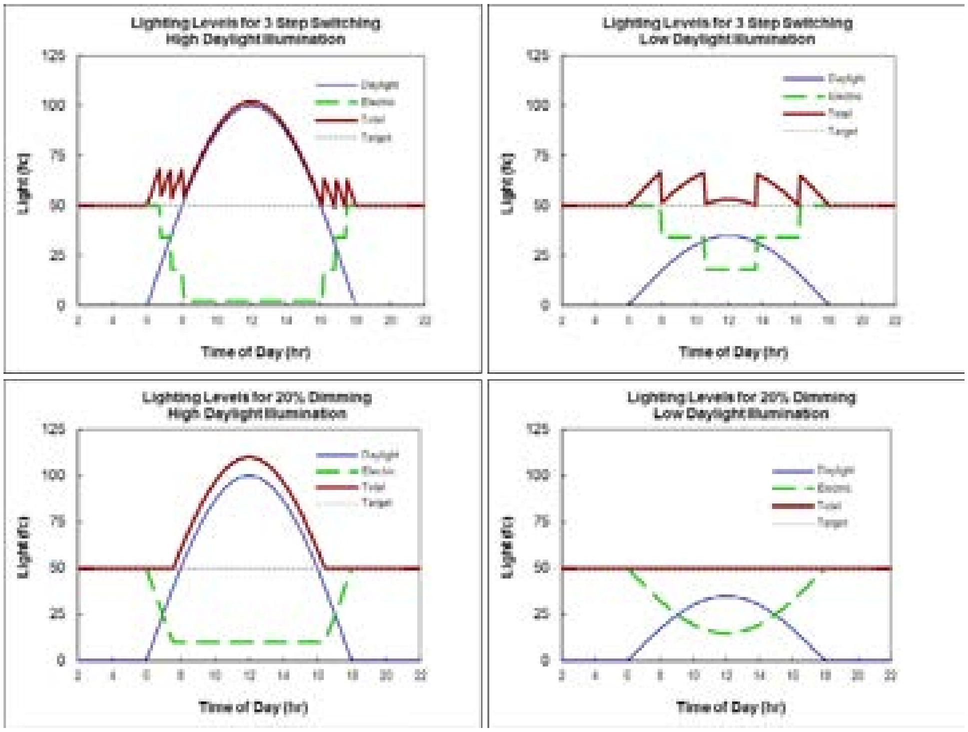


FIGURE 4-1:
Switching versus Dimming Controls Illumination Patterns

Dimming Controls

For most commercial applications, dimming ballasts at the fixture level are used to dim fluorescent or HID fixtures. Similarly, LED fixtures require dimming power supplies or drivers. Large circuit-based dimmers are also available to dim large blocks of fluorescent lights, but this practice is rare. As a rule, it costs more to dim many small groups of fixtures than one large group. However, some digital control systems allow more complex control zoning without the need for complicated and expensive circuiting and wiring. Also, the more substantial the reduction in light output at which a dimming system can be operated, the greater the cost of the system. Thus, a system which only dims the lights down to 20% will cost less than one that can dim the lights all the way down to 1%.

Dimming Ballasts

Controllable electronic ballasts dim fluorescent lamps, typically in groups of one to four lamps. The most common dimming ballasts are capable of dimming fluorescent lamps to a minimum of 5% to 10% of full output. Ballasts that dim to 1% or less are available, although usually at higher cost. Controllable electronic ballasts have the added feature that they are designed to preserve lamp life by assuring that proper fluorescent lamp electrode power is maintained throughout the dimming range.

Electronic dimming ballasts for HID are usually used for controlling individual HID lamps. HID dimming ballasts have less of a range than the equivalent technology for fluorescent lamps, typically providing stepped dimming to only 50% of light output.

It should be noted that all ballasts are less efficient when operating at partial power. The precise relationship between light output and power input depends on the specific product. Specifiers are advised to seek this information from manufacturers. Figure 4-2 illustrates some typical efficiency relationships for various products.

Dimmable LEDs

Although LED sources are inherently dimmable, LED fixtures or arrays must include dimmable power supplies or drivers in order to allow dimming. Some fixtures include dimming capability as a standard feature, while others offer it as an option. Similarly, the same LED fixture may have multiple power supply options that offer different minimum dimming levels. For example, an LED fixture may have two different options, allowing dimming down to 10% or to 1%. As noted above, typically the lower the dimming level, the higher the cost. Designers and specifiers should keep these issues in mind when working with LED fixtures.

Switching Controls

Switching controls create discrete changes, or steps, in illumination levels, rather than the smooth transitions provided with dimming controls. The smaller the steps, the less noticeable they are. Also, many smaller steps will save more energy than a few large steps. As described in Chapter 3, the 2013 California Building Energy Efficiency Standards require most commercial linear fluorescent systems to have at least four control steps, plus "off." These four control steps must be achieved through step dimming, or through separately switching individual lamps within a fixture only if that fixture has at least four lamps. The Standards also require HID sources to have at least one control step between 50-70% light output in addition to full output and "off."

As a rule of thumb, people generally do not notice changes in illumination levels that are less than 1/3 of the current illumination level. Thus, changing from 30 footcandles to 40 footcandles is barely noticeable, and changing from 30 footcandles to 35 footcandles is generally imperceptible. Similarly, if illumination levels are set at 100 footcandles, an increase to 130 or a decrease to 70 footcandles will probably not be noticed by most people.

Stepped controls can be implemented in two ways, with step ballasts or split-wiring. Step ballasts have at least two levels of light output. Split-wiring also provides multiple levels of light in a control zone. Split wiring involves having separate circuits driving different lamps within fixtures that can be controlled independently. The 2013 standards no longer allow controlling entire fixtures separately to meet the multi-level controls requirement.

Step Ballasts

Step ballasts are specially designed ballasts that can operate lamps at multiple light output settings. Since these systems only have to produce a few discrete light levels, the ballast manufacturer can optimize the energy performance at each designated light level. Thus, all other things equal, step systems can provide a few light levels slightly more efficiently than a continuous dimming ballast.

Step ballasts are available for both fluorescent lamps and HID lamps. Fluorescent step ballasts typically offer multiple light output options. HID two-level systems are usually full and about one-half light output, or "high and low."

Fluorescent step ballasts are available and meet California Title 24's requirement for multi-level switching. As fluorescent step ballasts have a relatively small market, they are typically only slightly less expensive than a much more capable dimming system.

For HID lamps, a step ballast solves a very important problem. When an HID lamp is switched off, it has to cool off before it can be restarted. For some lamps, this "re-strike" period can be as long as 20 minutes. However, when an HID lamp is powered down to a low light output level, it can resume full light output almost immediately, within seconds. Thus, HID step ballasts allow an HID system to have the same nearly instant response to photosensor controls as a fluorescent system. A key characteristic of an automatic control system is the relationship between the light output of the electric lighting system and the input power. This is shown graphically in Figure 4-2. Note that both the stepped control and dimming systems are somewhat less efficient at dimmed or stepped levels than at full power.

Step Switching

With the exception of track lighting, the 2013 California Building Energy Efficiency Standards only allow step switching—separately switching individual lamps within a fixture—if each fixture has enough lamps to meet the minimum number of control steps required. For example, most linear fluorescent fixtures would need to have four lamps, one for each required control step, to meet the multi-level control requirement. HID fixtures must have at least two lamps.

A common technique for obtaining stepped control from fluorescent lights is to use split-wiring that separately controls each lamp within multi-lamped fixtures. An example of a split-wired fluorescent lighting system is shown in Figure 4-3. Here, a single ballast drives one lamp in each of two or more fixtures. Thus, a fixture can be operated with one, two or three lamps on, providing four equal levels of illumination.

One of the successes of step switching has as much to do with psychology as it does with good lighting practice. It is extremely common for occupants of buildings to want to have at least one lamp per fixture operating at all times, even if it is not needed for illumination. The fact that a lamp is visibly "on" is commonly interpreted to indicate that a building or a space is "open;" the store is open; the librarian is in; the class is in session. If one light is always left on in the first approach, there are still two gradual increases in illumination available, which can respond to subtle changes in daylight availability.

FIGURE 4-2:
Control Type Response

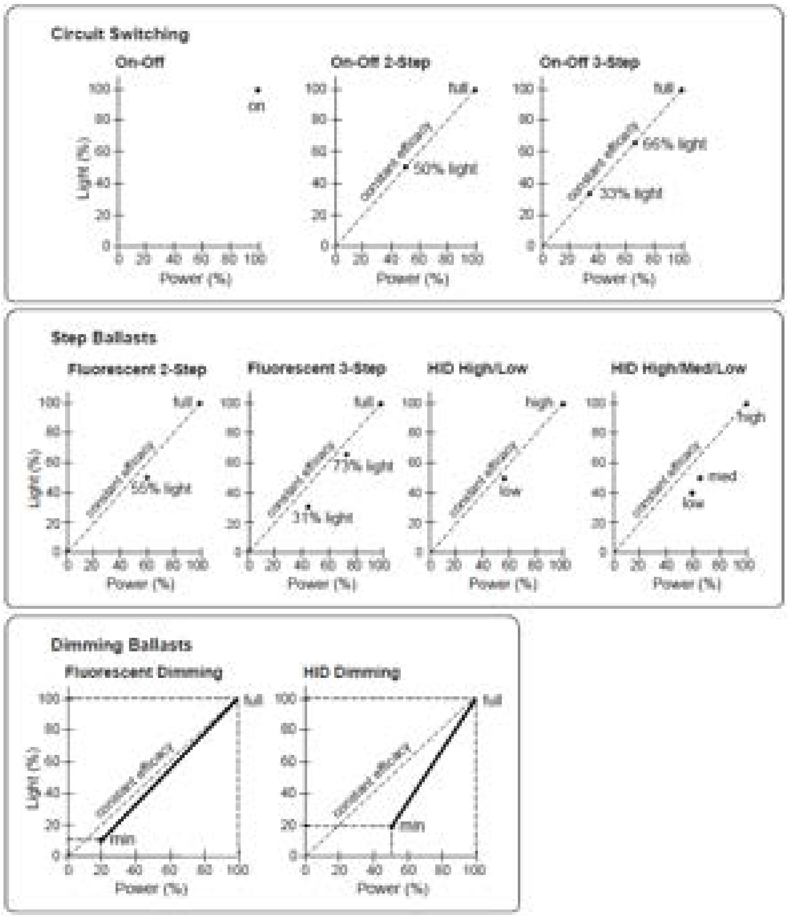
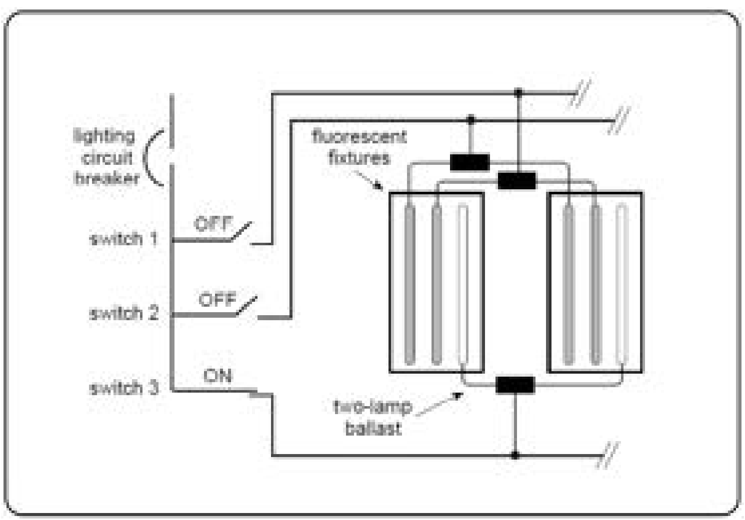


FIGURE 4-3:
Fluorescent Three Level Switching



Although HID fixtures typically only have one lamp per fixture, split wiring of lamps within fixtures can apply if there are two or more lamps. It is possible to combine multi-level switching systems with step ballasts for even greater control of light levels. This is especially true of HID systems, where the individual lamps could be operated on step ballasts to insure instant response to demands for increasing light levels.

Photosensors

Automatic daylighting control systems use a photosensor to measure the daylight illumination entering the skylit building space. The photosensor produces an electrical signal that varies according to the amount of light striking its light-sensitive surface. The photosensor typically consists of a photocell, a light diffuser and a rugged housing, all in one unit that can be mounted in a skylight well, on the ceiling, or integrated into a light fixture.

A wide range of photosensor products are available on the market. However, not all photosensors are appropriate for all applications. Designers and specifiers should ensure that the chosen photosensors are appropriate for the application. Important considerations when choosing a photosensor include the following:

- *System compatibility:* photosensors must be compatible with controllers or control systems. Different controls systems may require different signal types. Some control systems may also require the use of proprietary photosensors.

- *Sensitivity range:* photosensors may be sensitive to different ranges of light levels. Specifiers should ensure that the sensitivity range of the chosen photosensor is appropriate to the application.

Photosensor Placement Issues

There are several options for photosensor placement for daylighting control systems. Photosensor locations are generally referred to by one of three different control system types: open loop, closed loop, and dual loop.

Open loop systems consider only the incoming daylight contribution in a space, with photosensors located in skylight wells, just inside of windows, or on the building exterior. Open loop systems work best for spaces where the daylight contribution is relatively uniform and predictable, such as that from diffusing skylights.

Unless the manufacturer recommends otherwise, the photosensor for most open loop applications should be mounted high within a representative skylight well, with the light sensing element aimed vertically upwards. The advantage of locating the photosensor in the skylight well is that it is protected from the weather, and it senses the available daylight through the filter of the skylight, including any dirt accumulation or shadows falling on the skylight.

Although some manufacturers recommend mounting photosensors directly on the surface of the light well, most open loop photosensors should preferably be mounted to a standoff so that it is at least 1 ft. from the nearest face of the skylight well (see Figure 4-6). This mounting location reduces any confusion to the photosensor by self-shadowing of the skylight curb.

Closed loop systems consider all light sources within a space. Typically mounted on the ceiling, or integrated into electric lighting fixtures, photosensors in closed loop systems measure the combined contribution of daylight and electric lighting. Closed loop systems are ideal for spaces with more variable conditions, such as spaces that have a wide variation in daylight conditions, spaces that have both skylight and sidelight daylight contributions, or in spaces where occupants may adjust the amount of daylight coming into the space with blinds or shades.

Dual loop systems utilize two photosensors, one that measures only the daylight entering the space, and one that measures the overall illumination in the space including the electric lighting. Dual loop systems are a relatively new technology, where, by using two sensors, the control system can determine whether changes at the closed loop sensor are the result of daylight changes or interior changes, and adjust accordingly. Potential advantages of dual-loop systems include the ability to "self-commission," where the control system uses the nighttime electric illumination levels, measured by the closed loop sensor, as the baseline for electric lighting adjustments under daylight conditions. This self-commissioning feature can also automatically adjust to changing interior conditions, such as reconfigured retail or warehouse storage spaces, providing more or less light as needed depending on how those changes impact illumination in the space.

In all system types, it is very important that photosensors be located in the most representative area. For example, if a photosensor is located in a well that is shaded by a cooling tower in the late afternoon, it could cause the lights in the building to turn on unnecessarily. On the other hand, if a tall building were located next door that casts large shadows that move across the building during the day, the photosensor should be located so that it is in the shadow for most of the time, rather than on the edge of the shadow. Similarly, in some cases it may be necessary to shield a photosensor from a nearby electric light that could result in inaccurate readings.

Energy Design Resources provides a free software tool called The Sensor Placement + Optimization Tool (SPOT) that can provide guidance on photosensor placement in a wide variety of daylit spaces. SPOT can be downloaded from the Energy Design Resources website: http://energydesignresources.com/

Controllers

The controller takes the electrical signal from the photosensor and converts it into a control signal to the dimming ballast or switch. The controller is the "brains" of an automatic control system, since it determines how electric light output varies as a result of changing illumination on the photosensor.

As discussed above, controllers and control systems vary widely. At the most basic end, a controller can serve as a simple automatic switch to turn a single circuit or fixture on or off. At the other extreme are whole-building automated control systems which can control multiple zones over an entire building, handling multiple control inputs and various control programs and schedules. These more complicated systems are frequently also capable of controlling other building systems such as HVAC. Because this wide range of product types and capabilities cannot be adequately addressed here, this section focuses on application considerations.

Types of Controllers

There are two basic types of controllers for daylighting applications:

1. proportional controllers, which are used in dimming applications, and

2. setpoint controllers, which are used for switching systems.

A *proportional controller* imposes a linear relationship between the electric light output and the photosensor signal. This relationship is such that an increase in photosensor signal (i.e. an increase in the light detected by the photodiode) results in a decrease in electric light output. Simply stated, as the photosensor sees more light, the electric lights dim in proportion. With a proportional controller one can adjust how much the electric lighting system will dim for a given change in photosensor illuminance. This ability to change system sensitivity allows one to tailor the lighting system response to the specific conditions within the space. Sensitivity adjustment in the field is particularly advantageous since it is rarely possible to precisely predict during the design phase the range of daylight conditions that will occur at the photosensor location.

A *setpoint controller* is used with switching systems to determine at what daylight levels the electric lighting will switch on and off or step up and down.

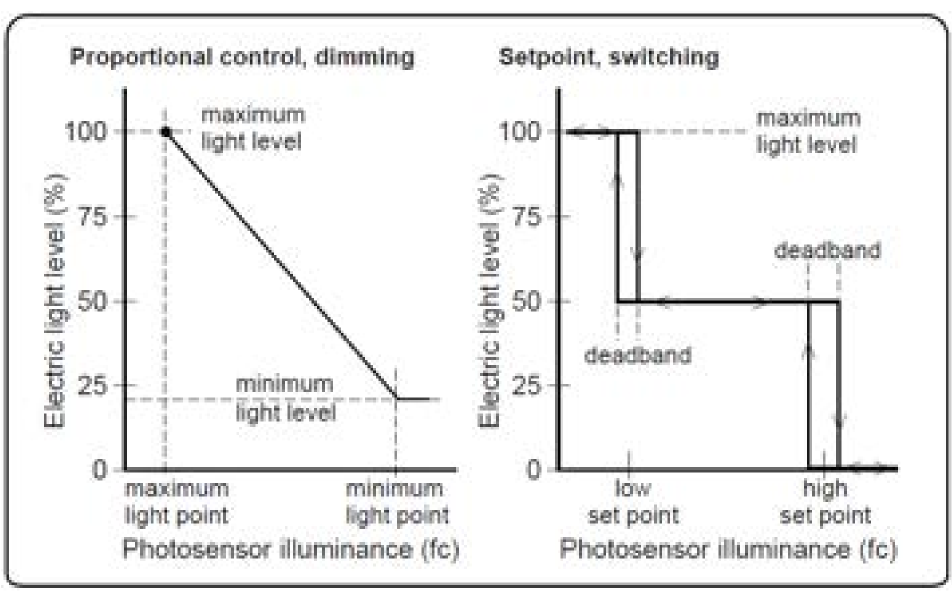


FIGURE 4-7: Proportional and Setpoint Controller Responses

The responses of the two types of controllers are shown in Figure 4-7. The proportional controller has a simple linear relationship, with a selected minimum and maximum. A setpoint controller also has a selected minimum and maximum, with a sudden drop between these readings. With a setpoint controller, as the daylight detected by the photosensor increases, the electric light output remains at full until the photosensor illuminance hits the first setpoint. As soon as the photosensor exceeds the lower setpoint, the step control is commanded to produce 50% light output. Additional daylight on the sensor does not cause any additional light reduction until the second setpoint is exceeded at which time the lights are commanded off. A three or four step controller would be similar but with additional intermediate setpoints.

To avoid rapid switching between light levels under rapidly changing daylight conditions, such as from partly cloudy skies, setpoint controllers incorporate a "deadband." For example, with a deadband, a lighting system set to switch from "high" to "low" state once the photosensor illuminance is exceeded, say at 1000 footcandles, would not restore the lighting to "high" until the illuminance had dropped below 900 footcandles. With this 10% deadband, the lighting would be less likely to cycle between on and off states, thus improving user acceptance even under difficult daylighting conditions. Some manufacturers allow the deadband to be adjusted in the field.

Besides deadbands, manufacturers can also build in time delays to setpoint controllers, typically on the order of minutes, which also reduce the amount of switching even if the daylighting conditions vary rapidly near the switching illumination threshold. Finally, scheduled lockouts can also be used. These are most common in conjunction with an energy management system (EMS). With scheduled lockouts, daylight-triggered light level changes are limited to specific times of day. This approach clearly is not optimal from an energy efficiency standpoint, but may be appropriate under certain conditions, such as shift changes at factories or scheduled classroom changes in schools.

Commissioning

Automatic daylighting control systems must be calibrated after they are installed. This should be done after the building is occupied. All major room furnishings, obstructions and window treatments should be installed to assure that the lighting control system is commissioned under typical lighting conditions. In a supermarket, the shelves should be stocked, so that the light reflected from the shelves is typical of normal operation. In a warehouse, the storage racks should be partially filled with boxes. In an office building, the furniture and office partitions should be in place.

The calibration adjustments are usually physically located at the controller. The controller should therefore be easily accessible to authorized personnel and there should preferably be line-of-sight between the controller and the corresponding controlled area.

Calibrating a dimming control system ensures that the electric lights will dim an appropriate amount for each increase in daylight level. Calibrating a switching system ensures that the step down in electric light occurs at appropriate daylight levels. Commissioning comes at the tail end of the construction process, and there is an unfortunate tendency to push it aside in the last minute shuffle to move in. However, several studies have shown that failure to commission control systems is the single greatest reason for failure of daylighting systems to save energy.

A True Story

A building in Santa Barbara, California was designed to be a showcase for efficiency, daylighting and a high quality work environment. The building's architecture employs an extremely effective daylighting design to allow ample natural light in the building, while limiting direct solar heat gain in the hot summer months. To "harvest" the daylighting, automatic photosensor dimming controls for the fluorescent lighting system were designed. However, as often happens, the project was "value engineered," including eliminating commissioning of the building systems to save first costs of $60,000-$70,000.[1]

Following about a year of operation, the facility manager noticed that electricity bills for the building were higher than expected. A building audit by Southern California Edison revealed that although the building was operating below typical energy use for office buildings, there were additional energy savings opportunities that were not being realized. Due to the lack of commissioning following installation, the automatic daylighting controls were not working properly, and building occupants had disabled the controls by taping over the photosensors, eliminating all energy savings from daylight.[2] In addition, the Energy Management System had not been programmed properly, resulting in excessive HVAC energy use.

Repairing the problems identified in the audit report resulted in a further energy savings of 28%, or over $13,000 per year, based on typical electricity rates at the time.[3]

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1 Energy Design Resources, "Designing Green – A Collaborative Approach." http://energydesignresources.com/resources/videos/designing-green.aspx

2 Building Energy Audit, prepared by Southern California Edison, January 24, 2007

3 Per conversation with the project engineer auditor, a Technical Specialist, Southern California Edison.

Calibrating Lighting Levels

The trick to successful commissioning is knowing the best daylight conditions for undertaking the calibration. The best time to calibrate is when the daylight level at the task is close to, but not exceeding, the design target light level. For example, for a 50 footcandle design level, the system should be calibrated when the illuminance from daylight alone is between 40-50 footcandles. If the system is calibrated when the daylight levels are particularly low (such as on a rainy day or in the morning on a winter day), the lighting system would not be dimmed enough to calibrate the system even roughly. On the other hand, calibrating the system at a time when there is an overabundance of daylight could lead to a mis-calibration, resulting in minimal energy savings. It is also important to calibrate during stable weather, when lighting conditions will not be changing quickly.

SkyCalc can be used to estimate the ideal time for calibrating the system:

> Example. Let the design level be 50 footcandles (fc) and the electric lighting system capable of dimming down to 10%. With these conditions, calibrate when the daylight level is at 90% of the design level, or about 45 fc (50 x (100% * 10%) = 45 fc). After determining the target daylight level for calibration, use *SkyCalc* to find when those conditions are likely to occur for a given month. Run a daylight illuminance summary for the installation using *SkyCalc* and inspect the table of daylight illuminances. Look up the row corresponding to the current month. Find those cells with values within 20% of the target daylight calibration level and look up the corresponding hours of the day. These are a good estimate of when to best calibrate the dimming system during that month.
>
> One caveat about using *SkyCalc* for this purpose: *SkyCalc* calculates daylight illuminances based on average conditions for each month. If a month typically sees a mixture of cloudy and clear skies, then the average illuminance will be substantially different than on a perfectly clear day. Thus, in those instances, it would be wiser to choose an earlier hour, when the daylight illuminance will be lower on clear days.

Because there are so many types of daylighting control systems, it is not possible to produce generic calibration instructions for these types of systems. Thus, when calibrating a daylighting control system, follow the manufacturer's specific calibration procedure. In addition, when calibrating the control system, it is helpful to have special equipment (specifically a photosensor simulator) that is available from the manufacturer.

A controller also provides additional functions such as the ability to set a lower limit on the dimming level, a maximum output level, a time delay, and sometimes the fade rate. These additional controls are useful for reducing any lamp flickering that might occur at very low light output levels and for adjusting how rapidly the electric lighting dims or brightens upon a sudden change in photosensor illuminance (as might be caused by a passing cloud).

Control System Maintenance

If commissioned correctly, a lighting control system should only need occasional maintenance, usually once annually (or follow manufacturer's recommendation). Maintenance consists of dusting and cleaning the photosensors, and assuring that the system is dimming an appropriate amount for the amount of available daylight. Photosensors in some dusty or dirty environments may need to be cleaned bi-monthly. Since the photosensors may be located in hard to reach areas, special equipment may be required to give maintenance personnel access to the photosensors. It is a good idea to consider maintenance accessibility to this location before the photosensor is installed and calibrated. Air brushes used for cleaning photographic equipment are an excellent dusting tool. Similarly, using lens tissue for cameras will avoid scratches to the photosensor surface.

Photosensors are long-lived devices and should operate as long as the lighting system if not abused. If a photosensor is found to be inoperative, make sure that it is replaced with an equivalent model and then re-calibrate the system upon installation. Manufacturer's installation instructions should always be followed as the replacement photosensor can be damaged if installed incorrectly.

Problem Signals

The following symptoms with a daylighting controlled lighting system indicate a need for expert assistance:

1. No dimming (or switching) action even under bright daylight conditions. Indicates improper calibration, or a defective or disconnected photosensor.

2. Over-frequent switching between light levels (especially under partly cloudy skies). Indicates insufficient deadband or time delay.

3. Excessive end-lamp blackening of fluorescent lamps. This indicates that the system is providing inadequate cathode voltage during dimming.

4. Striations running along the fluorescent lamp under full dim conditions (also called "raccoon-tailing" or "barber pole effect"). This indicates unstable lamp performance.

5. Frequent lamp burnouts. Typically indicates either a faulty ballast or fixture wiring, or voltage problems.

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Chapter 5: Optimizing the Design

Once all of the options for skylights and photosensor controls are understood, it is important to be able to select products and design a system that will optimize the performance of the skylighting system and produce the most cost effective design. The essential questions are:

- How much of the time will daylight levels meet or exceed the desired illuminance levels?
- What is the optimum skylight system to reduce energy consumption and cost?
- How should the skylighting system be designed to ensure quality daylighting for occupants and improve occupant comfort?

This chapter discusses how different variables and choices in skylighting design affect the energy performance of the building, and shows examples that compare the relative effects of each. Each of the following variables are addressed:

- *Climate:* Climate is the most important influence on the energy performance of a skylighting system, especially how the availability of illumination varies daily, seasonally, and between locations.
- *Heating and Cooling:* Heating and cooling energy losses and/or savings provide a secondary effect on the savings achieved with a skylighting system.
- *Building Type:* The hours of operation, the lighting power density, the internal heat gains, and the heating and cooling setpoints are all important determinants of skylighting savings.
- *Glazing Materials:* Choices of glazing materials determine how much daylight gets into a building, and also how much heating or cooling requirements are affected.
- *Automatic Daylighting controls:* Automatic Daylighting controls are essential for any energy savings from skylights. Switching and dimming systems produce different patterns of savings.

Designers should understand how these variables interact before embarking on their own skylighting designs. The following sections address the various considerations that designers must understand in order to execute a successful skylighting design.

To illustrate each of these issues the discussion in this chapter will use *SkyCalc* simulations for a generic building, with only one of these variables changing at a time. The resulting graphs give a sense of the relative impacts of each variable; they are not, however, absolute answers for any system. *SkyCalc* allows for comparison of alternate designs for a particular building and location, in order to generate specific savings values for that situation.

Understanding Daylight Patterns

The relationship between daylight illumination and the desired illumination in a building is the single greatest determinant of skylight savings. Heating and cooling impacts are important, but they are generally a second or third order effect. Therefore, the first consideration is to determine how much electric light and daylight in a space is appropriate.

Design Target Illuminance

The first step in designing a daylighting system is to determine the desired illuminance for the tasks to be performed.

The desired level of illuminance in a room will depend on the general function of the space and on the visual requirements of the task to be performed. The Illuminating Engineering Society of North America (IESNA) has established general categories of illuminance, ranges of illuminance values, and a procedure for selecting illuminance levels depending on the type of activity in the space. Figure 5-1 summarizes the IESNA recommendations for a number of common tasks, for a specific type of activity and occupant. These mid-range values, given in footcandles and lux, are representative only.

The IESNA procedure for determining recommended illuminances specifies a range of illumination values for any given task. There are a number of factors which should be taken into account to determine which part of the range should be used. The assumptions used in Figure 5-1 are noted in the caption.

Building use changes over time and it would be wise to provide enough flexibility to accommodate potential changes. Remember also that illuminance levels do not necessarily correlate to lighting quality, which depends on the properties of the entire visual environment.

Many occupancies, like retail, manufacturing, schools, and churches require special consideration of the specific tasks, the interior design, and equipment and/or aisle layout to understand appropriate illumination levels. Refer to the IESNA Handbook, and to other Recommended Practice Documents published by IESNA, for more detailed recommendations on illuminance values for specific applications and space use.

IESNA recommended illuminances are usually considered the minimum illuminance required for a given task. Additional illumination is not generally considered a problem, and is often a bonus, as long as glare is prevented.

However, energy codes have functioned to set a maximum lighting power density for spaces, based on the implementation of these recommended illuminances, and based on the application of reasonably efficient technology and design. The interaction of IESNA recommendations with energy codes has narrowed the range of expected interior light levels from electric lighting systems.

The 10th Edition of *The Lighting Handbook*, published by the IESNA in 2011, includes recommendations that distinguish between ambient and task illuminance levels. Although relatively high illuminance levels may be required at specific task areas within a space, such as at a desk in an open office, lower illuminance levels may be sufficient for other areas of the space, such as circulation areas. This distinction allows for greater flexibility in design parameters to meet the specific needs of a space.

Activity Area	Footcandles	Lux
Dining Room, ambient	1-20	10-200
Storage, infrequent use	5	50
Storage, frequent use	10	100
Lounge or Waiting Room, ambient	4	40
Waiting Area, Reading	15	150
Locker Room, Washroom	5-15	50-150
Stairway, Corridor	5-10	50-100
Office Tasks	15-50	150-500
Low Activity Retail	7.5-40	75-400
Retail Checkout	30	300
Retail Fitting Room	30	300
Commercial Kitchen	20-50	200-500
Printing Plants	75-150	750-1500
Mail Sorting	30	300
Classroom	50-100	500-1000
Elementary School Gymnasium	50	500
Sewing, Cutting, Inspection	150-500	1500-5000

Figure 5-1: Representative Illuminances for Typical Tasks

Assumptions: Occupants aged 25-65, room surface reflectances 30-70%, demand for speed and/or accuracy important. This information based on recommendations in the IESNA Handbook, 2011.

Having determined the desired illuminance for the primary tasks in the daylit space, the next question is how to size and design the skylight system to provide that illuminance. This is not the same kind of task as sizing and designing an electric lighting system to provide a given illuminance level on a task surface. Electric lights produce a nearly constant light output, day and night. Daylighting systems provide a constantly changing light input to the building, which varies hour by hour and season by season.

The question of how to size the skylight system does not have a single answer. Even a very small skylight can provide the minimum desired task illuminance some of the time; a very large skylight system may provide more than the desired illuminance most of the day. If the skylight system is too small, it may not save enough energy and money to warrant the investment. If it is too large, it will provide more light than is needed, and could unnecessarily increase heating or cooling energy consumption.

The variability of daylighting is one of its most appealing aspects, and one of the reasons people respond so well to skylights. The task illuminance provided by a skylight system may range from zero at night, to three to four times the task minimum during the day. Usually, the extra light is a positive benefit, provided illuminance levels are not so high as to cause visual discomfort problems.

Daylighting illumination *per se* is not regulated by energy codes, nor is it treated differently than electric light by the IESNA recommendations. In looking to size skylights appropriately, start by understanding the percentage of "daylight saturation" that will occur with a skylight design.

Daylight Saturation

A room is said to be saturated with daylight when the illuminance levels from daylight meet or exceed the design target illuminance for that space. For example, if an office requires 50 footcandles of ambient illumination, then daylight saturation would occur whenever there are more than 50 footcandles of daylight available in the space.

From the perspective of reducing electric lighting requirements, the point of daylight saturation represents the point when maximum electric lighting savings occur, i.e., the lights are dimmed to their lowest level or turned off. Although additional daylight will not result in additional electric lighting savings, it can still provide a benefit to occupants in the space. As long as glare is controlled, daylight levels above and beyond target illuminance levels typically improve occupant comfort.

Daylight saturation is influenced by three primary factors:

- *Desired illuminance levels:* the amount of light needed for the visual tasks to be performed
- *Skylight effective aperture:* a measure of the quantity of light that will make it through a given skylight design, based on the gross skylight to floor ratio (SFR), the visible transmittance of the glazing material and the light well design
- *Daylight availability:* the characteristics of available daylight outdoors, as influenced by latitude and local climate conditions

The graphs in Figure 5-2 were generated by *SkyCalc* for a grocery store in San Bernardino (Climate Zone 10, Rialto) which set its design target illumination at 50 footcandles, and which used double glazed, white acrylic skylights. The graphs illustrate how daylight saturation changes with increasing number of skylights, resulting in a higher SFR, or gross skylight aperture. The light shaded areas indicate the hours of the day when daylight is available (more hours in summer, less in winter) to provide at least 10% of the target illuminance in the space. The white areas indicate the hours of daylight saturation (more than 50 fc of daylight) on an average day in each month.

SFR is used here for simplicity sake. Since in this analysis all the other properties of the skylight are held constant, an increase in SFR is the same as an increase in effective aperture, which accounts for all visible transmission properties of the skylight system. *SkyCalc* uses hourly weather data to calculate illumination levels for the energy analysis. However, for these summary graphs, the information is collapsed into an average illumination level for a representative day for each month.

FIGURE 5-2: Daylight Saturation with Varying Skylight Aperture—2%, 4% and 6%

Dome Skylight Effective Aperture = 0.61%, Skylight to Floor Ratio (SFR) = 2.03%

Average daylight footcandles (fc)

	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	17	18	19	20	21	22	23	24
Jan	0	0	0	0	0	0	0	2	11	19	25	27	27	24	17	10	2	0	0	0	0	0	0	0
Feb	0	0	0	0	0	0	0	5	16	25	33	36	37	33	26	17	6	0	0	0	0	0	0	0
Mar	0	0	0	0	0	0	2	10	20	28	35	40	42	38	32	22	11	2	0	0	0	0	0	0
Apr	0	0	0	0	0	1	6	16	24	31	36	39	39	36	30	23	13	4	0	0	0	0	0	0
May	0	0	0	0	0	2	7	14	22	29	36	40	42	40	35	27	17	7	1	0	0	0	0	0
Jun	0	0	0	0	0	3	10	18	26	34	39	41	40	39	34	26	18	8	1	0	0	0	0	0
Jul	0	0	0	0	0	2	10	19	28	38	45	48	47	44	38	29	20	9	1	0	0	0	0	0
Aug	0	0	0	0	0	1	7	16	24	33	39	42	41	39	33	25	15	6	1	0	0	0	0	0
Sep	0	0	0	0	0	0	5	13	22	29	35	39	39	37	30	21	10	2	0	0	0	0	0	0
Oct	0	0	0	0	0	0	2	9	18	25	30	33	32	27	20	11	4	0	0	0	0	0	0	0
Nov	0	0	0	0	0	0	1	6	13	19	23	24	22	19	13	6	1	0	0	0	0	0	0	0
Dec	0	0	0	0	0	0	0	3	11	19	24	26	25	21	14	6	1	0	0	0	0	0	0	0

Design Illuminance = 50 fc

< 1 fc; < 25 fc; < 50 fc; > 50 fc;

Dome Skylight Effective Aperture = 1.23%, Skylight to Floor Ratio (SFR) = 4.05%

Average daylight footcandles (fc)

	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	17	18	19	20	21	22	23	24
Jan	0	0	0	0	0	0	0	5	22	39	49	54	53	48	35	19	4	0	0	0	0	0	0	0
Feb	0	0	0	0	0	0	0	11	32	50	65	73	73	66	51	34	13	1	0	0	0	0	0	0
Mar	0	0	0	0	0	0	4	20	40	57	70	81	83	76	63	44	23	3	0	0	0	0	0	0
Apr	0	0	0	0	0	1	13	31	48	61	73	78	78	72	61	45	26	8	0	0	0	0	0	0
May	0	0	0	0	0	4	14	29	43	59	72	80	83	81	71	55	34	14	1	0	0	0	0	0
Jun	0	0	0	0	0	6	19	36	53	68	78	82	81	78	69	53	35	16	2	0	0	0	0	0
Jul	0	0	0	0	0	4	20	37	56	77	91	96	94	87	76	59	40	19	2	0	0	0	0	0
Aug	0	0	0	0	0	1	14	32	49	65	79	84	83	78	67	50	31	12	1	0	0	0	0	0
Sep	0	0	0	0	0	1	9	25	43	59	71	78	79	73	60	41	20	4	0	0	0	0	0	0
Oct	0	0	0	0	0	0	5	19	36	49	60	65	63	54	40	22	7	0	0	0	0	0	0	0
Nov	0	0	0	0	0	0	1	12	26	38	46	48	45	38	26	12	1	0	0	0	0	0	0	0
Dec	0	0	0	0	0	0	0	6	22	38	49	53	51	42	29	13	1	0	0	0	0	0	0	0

Design Illuminance = 50 fc

< 1 fc; < 25 fc; < 50 fc; > 50 fc;

Dome Skylight Effective Aperture = 1.81%, Skylight to Floor Ratio (SFR) = 5.97%

Average daylight footcandles (fc)

	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	17	18	19	20	21	22	23	24
Jan	0	0	0	0	0	0	0	7	32	57	73	80	79	71	52	29	6	0	0	0	0	0	0	0
Feb	0	0	0	0	0	0	0	16	47	74	96	107	108	97	76	50	19	1	0	0	0	0	0	0
Mar	0	0	0	0	0	0	5	30	59	83	104	119	123	112	93	64	34	5	0	0	0	0	0	0
Apr	0	0	0	0	0	2	18	46	70	91	107	115	115	106	89	67	38	11	0	0	0	0	0	0
May	0	0	0	0	0	5	21	42	64	87	108	118	123	119	104	80	50	21	2	0	0	0	0	0
Jun	0	0	0	0	0	8	29	53	78	101	115	120	119	115	102	78	52	24	3	0	0	0	0	0
Jul	0	0	0	0	0	6	29	55	82	113	134	141	139	128	111	87	58	28	3	0	0	0	0	0
Aug	0	0	0	0	0	2	21	47	72	98	118	124	122	115	98	74	46	18	1	0	0	0	0	0
Sep	0	0	0	0	0	1	14	37	64	86	104	114	116	108	88	60	29	5	0	0	0	0	0	0
Oct	0	0	0	0	0	0	7	28	53	73	89	98	93	80	59	33	11	0	0	0	0	0	0	0
Nov	0	0	0	0	0	0	1	17	39	58	67	71	66	56	39	17	2	0	0	0	0	0	0	0
Dec	0	0	0	0	0	0	0	9	32	58	72	78	75	62	43	19	2	0	0	0	0	0	0	0

Design Illuminance = 50 fc

< 1 fc; < 25 fc; < 50 fc; > 50 fc;

The three graphs above in Figure 5-2 show how daylight saturation varies as the number of skylights increases. In the top graph, at a SFR of two percent, the average monthly conditions show that the target illumination level of 50 footcandles is never met. (In reality, it might occur on occasional bright sunny days, but this graph simplifies the information by only presenting the average condition for each hour of the month.) *SkyCalc*, in doing an hourly calculation using typical weather data, also reports in one of its summary tables that full daylight saturation would not normally be achieved in this case.

In the middle graph, with the SFR doubled to 4 percent, there are many hours where full daylight saturation is achieved during the middle of the day, spring through fall. The *SkyCalc* summary tables also report that for this building design in San Bernardino, daylight saturation would be achieved for 1454 hours per year, about one third of the possible daylight hours. Up to 86 footcandles can be expected in mid-summer, about 1.75 times the target illumination.

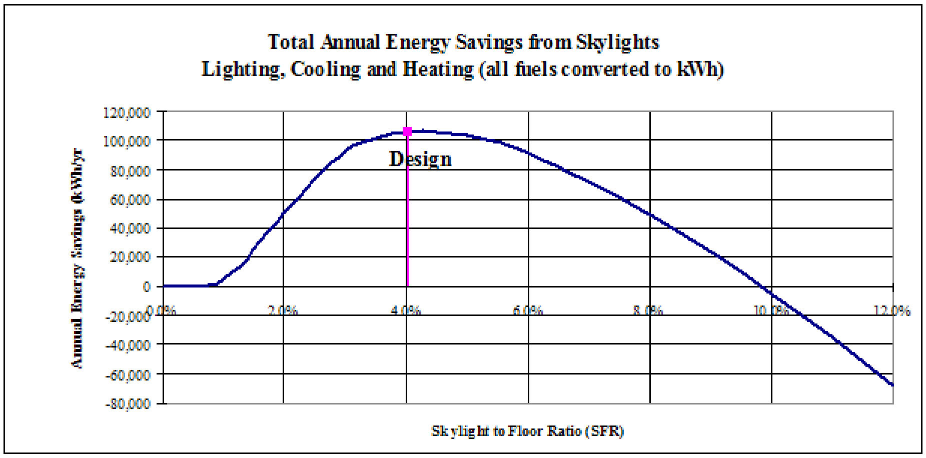
In the bottom graph in Figure 5-2 the grocery store achieves full daylight saturation for three to eight hours every month of the year with an SFR of six percent. *SkyCalc* tells us that 50 footcandles or more would be available for 2159 hours per year, about one half of the possible daylight hours. Illumination levels rise up to 129 footcandles in the middle of summer, over 2.5 times the target illumination level.

There are several useful points to be observed about daylight saturation:

- As effective aperture increases, the hours of daylight saturation increase.
- As the effective aperture increases from .02 to .04 to .06, the hours of daylight saturation do not increase proportionately. Rather, at first they increase quickly, then gradually level off, up to the maximum number of daylight hours available in a year.
- For a given effective aperture, there are fewer hours of daylight saturation for higher desired illuminance levels.

Figure 5-3 shows the *SkyCalc* optimization curves for the same building and location illustrated above in the three daylight saturation graphs. The middle condition, with the skylight aperture at four percent is shown. An analysis of all energy uses in the building shows that while four percent SFR is about optimum for whole building energy savings, six percent is closer to optimum in terms of cost savings. Thus, in this case, the higher SFR options, with greater daylight saturation, and illumination levels typically above the design target, are seen to have the best overall cost savings.

In general, a skylighting design will be optimized when it provides substantially higher levels of illumination than the design target illumination for much of the year.



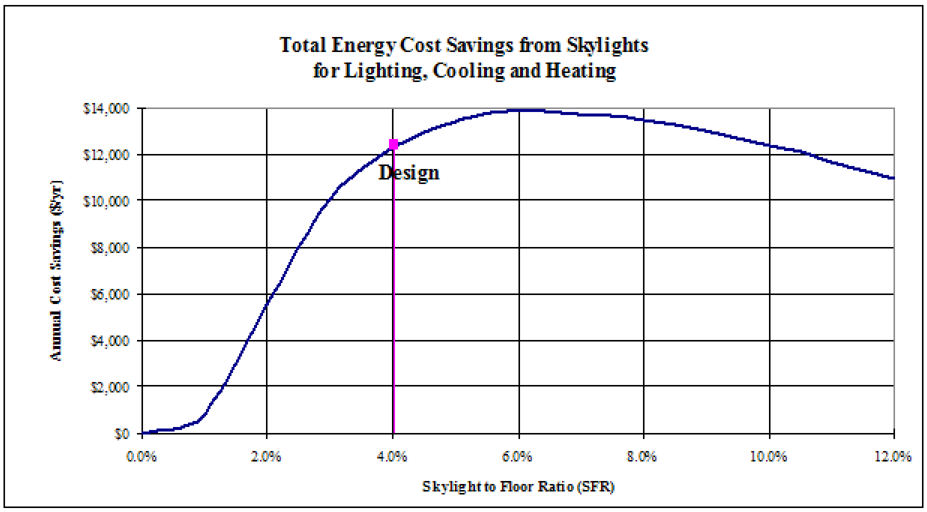


FIGURE 5-3:
Optimization Graphs-
San Bernardino
Grocery Store

Yearly Illumination Patterns

One of the important reasons that skylighting systems generally should provide more than the design target illumination in a space is the extreme variability of daylight illumination during a year. A plot of the number of occurrences of daylight illumination levels within a prototypical space throughout a typical year clearly shows that there is no one condition that is most common. Beyond those lowest light levels which regularly occur early in the morning and late in the evening, there is almost an even distribution of all other possible light levels.

FIGURE 5-4: Yearly Illuminance Plots, Two Contrasting Climate Zones

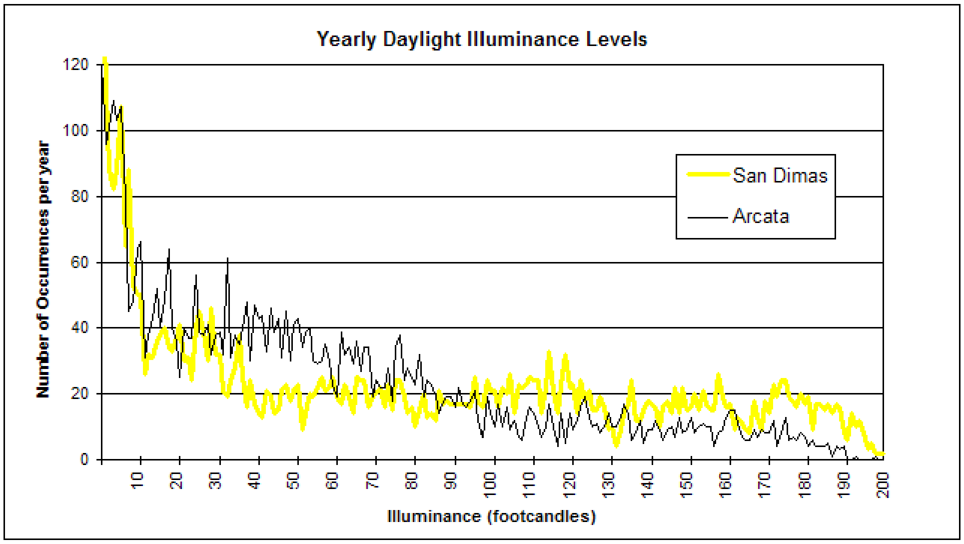


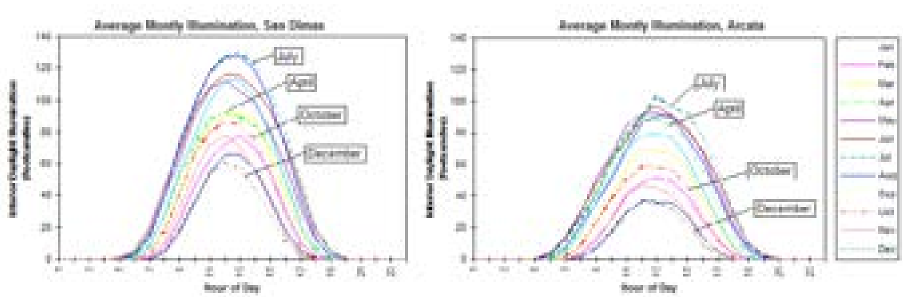
Figure 5-4 plots the number of hours of interior daylight illumination levels, from 1 to 200 footcandles, for a prototypical building design in two distinctly different California climate zones. Arcata, at the far northern end of California, is a small coastal city with a fairly foggy climate. San Dimas, sits at the foot of the San Gabriel Mountains in Los Angeles, with generally clear skies and an almost desert climate typical of the Los Angeles interior valleys. The Arcata daylighting system has about 25 percent more hours under 100 footcandles, and San Dimas has about twice as many hours above 100 footcandles.

Despite these differences, the two yearly illumination patterns are strikingly similar. There is no clear "design condition" that occurs the majority of the time. For both of these climate zones a control system for this building that was designed to turn off electric lights above 50 footcandles would find about just as many daylight hours per year above the target level as below. For San Dimas, there is an almost equal distribution of number of hours of illumination levels that occur from 40 footcandles to 180 footcandles, which is a substantial range in indoor illumination.

Monthly Illumination Patterns

The two average monthly plots shown in Figure 5-5 illustrate the variations in illumination due to latitude, time of year and climate for the two contrasting climates of San Dimas and Aracta.

FIGURE 5-5: Average Monthly Illumination, San Dimas and Arcata, CA



San Dimas is at about 34° latitude and Arcata, 440 miles north, is at about 41° latitude. Thus, the lowest levels of illumination in December in San Dimas are similar to the mid-levels of illumination seen in Arcata in October. Average illumination is also lower in Arcata due to cloudier and more variable weather throughout the year that tends to reduce the average.

The average monthly illumination shows a fairly regular parabolic type curve, because all irregularities in the weather have been evened out through the averaging process. It is reasonable to assume that actual illumination for a given day could vary substantially from these average values, as described below.

Weekly Illumination Patterns

Figure 5-6 plots the interior illuminance due to skylighting for the prototypical building in San Dimas during the first week in January for a typical year. This week was chosen as it shows a passing storm and represents one of the more variable seasons in Los Angeles. This graph illustrates some of the variability that can be found in illuminance levels on a day to day basis.

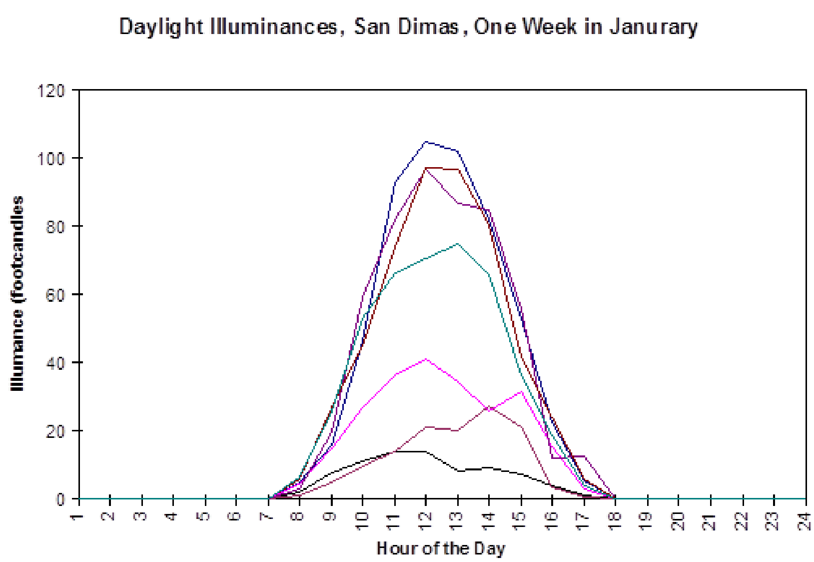


FIGURE 5-6: Weekly Illuminance Patterns

It is apparent from the graph that daylight illumination levels during the week vary from a noon low of 14 footcandles to a noon high of 105 footcandles: the high is 7.5 times greater than the low. Within a given day, the daily high illumination could potentially occur from anytime between 9 a.m. and 4 p.m., depending on cloud patterns. The average illuminance pattern for this month is about 20 percent lower than the maximum values shown here.

Designing for Savings

Given the natural variability in daylighting described in the previous section, designers are faced with a wide range of potential illuminance levels from skylights. The best approach is generally to design a system that will optimize yearly energy use and energy costs for the whole building. *SkyCalc* assists in this effort by calculating skylight energy performance using hourly weather data for a chosen climate.

The following sections look at how a limited set of variables affect the pattern of energy and cost savings for a given skylighting design. *SkyCalc* was used to generate a series of energy and cost savings curves for each variable. These curves are not generic. They are specific to the building type, operation and location studied. They do not indicate which set of variables will perform better in all cases, or what the actual energy or cost savings are likely to be for a different building. However, they do identify how the different sets of variables may affect relative performance, and suggest potential strategies to optimize the design.

The following studies used a standard building, described as an office building in San Bernardino, California (climate zone 10, near the Rialto weather station), with a lighting power density of 0.75 W/sf producing a target illumination level of 50 footcandles, and using 10% dimming controls. The skylighting system used a double glazed white acrylic skylight with a shallow, one foot deep light well. All other *SkyCalc* defaults were used throughout. All the cost savings graphs in this chapter were calculated using an average electricity cost of 12¢ per kWh and $1 per therm for gas heating.

In each case, two curves are presented side by side, the one on the left for yearly energy savings, the one on the right for yearly cost savings. In all cases the horizontal axis is skylight to floor ratio (SFR).

Heating and Cooling Effects

The three main energy uses that influence the performance of skylighting systems are lighting, cooling and heating. The interaction of the three determines the whole building energy and cost savings that can be achieved with a skylighting design, and determines at which point the design will reach optimum savings. Figure 5-7 illustrates this relationship between the three different components of the whole building energy savings equation for the typical office design in San Bernardino described above.

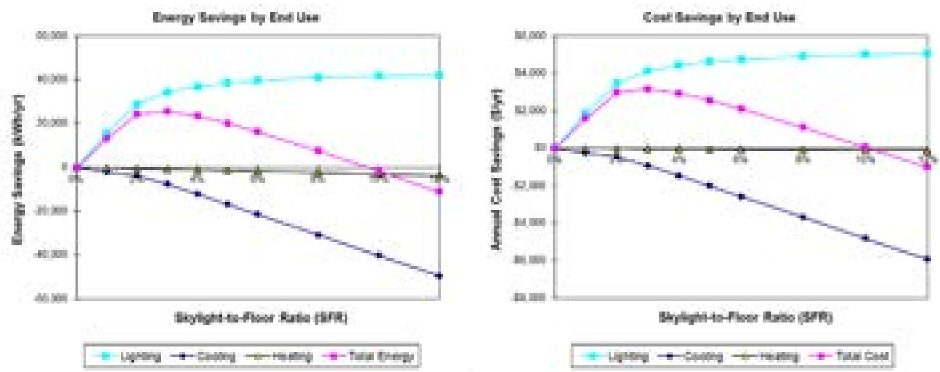


FIGURE 5-7:
Annual Energy and Cost Savings by End Use - San Bernardino Office

Lighting energy savings are the primary driver, initially rising sharply and then continuing to rise, but at slower pace as the skylight aperture is increased. Heating energy is generally flat in all cases. For this case, the most significant factor in energy losses is cooling energy, which is negative throughout.

Both the energy and cost curves optimize at about three percent gross aperture.

The relative energy impacts of these three systems—lighting, heating, and cooling—along with their relative costs, determine where the optimum size for skylights will fall. In colder climates, or in areas with relatively less expensive electricity, the influence of the heating component will be more significant.

Savings by Climate Zone

The same building performs differently in different climate zones. The relative influences of the heating and cooling components are evident among four illustrated California climates. San Diego, a coastal city in southern California, has the mildest climate. San Bernardino sits in a valley at the foot of the San Gabriel mountains east of Los Angeles. It has clear skies with more extreme highs and lows than a coastal town. San Francisco, on the central coast, has a cooler, foggier climate. Mt. Shasta in northern California has cold winters with snow.

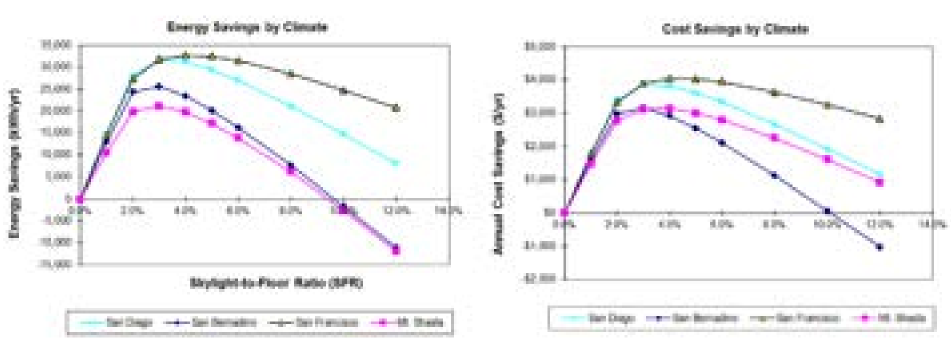


FIGURE 5-8:
Annual Energy and Cost Savings by Climate Zone - Office

Figure 5-8 indicates that San Diego and San Francisco, with the mildest climates, have the greatest potential for energy savings, and Mt. Shasta, with the coldest winters, has the least potential energy savings. A skylighting system in San Francisco optimizes with a 33% greater size than a similarly designed system in Mt. Shasta.

The cost savings graph, however, tells a different story. The cost savings differences between the four climates are less extreme since the heating losses have less influence, due to the significantly lower cost of heating energy. (The same energy costs were used for each city.) Mt. Shasta, for example, indicates a positive cost savings even for systems that have overall negative energy savings. San Francisco indicates a nearly level graph, with about 25% reduction in cost savings between 4% to 12% aperture.

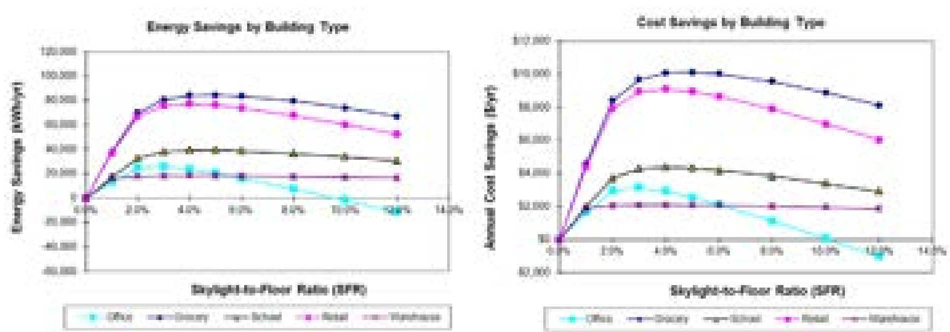
The Mt. Shasta and San Bernardino energy savings graphs are somewhat similar, but the Mt. Shasta cost graph crosses above the San Bernardino graph at some point. This is consistent with the observation that more expensive cooling losses are a bigger concern in San Bernardino, while lower cost heating losses are the more significant influence on the Mt. Shasta energy savings graph.

Savings by Building Type

Different building types also perform differently with skylighting systems. Figure 5-9 illustrates the impact of five different building types and operations on energy and cost savings. To generate these curves, similarly sized buildings with identical skylight and control systems, all located in San Bernardino, were simulated in *SkyCalc*. The buildings vary by schedule of operation, design target illumination, lighting power density, and internal loads. These were set to the building type defaults used in *SkyCalc*. All of the buildings were fully conditioned with a gas fired furnace and an electrical air conditioner, with the exception of the warehouse, which was only semi-conditioned to prevent temperatures from dropping below 35 degrees or going above 100 degrees Fahrenheit.

This set of graphs clearly illustrate that the magnitude of savings is highly dependent on hours of operation and lighting power density, for any given skylighting design.

FIGURE 5-9:
Annual Energy and Cost Savings by Building Type - San Bernardino



Retail stores and grocery stores both have 7 day a week schedules, and thus stand to save the greatest amount of energy. In Figure 5-9 the retail and grocery stores, with the highest lighting power density, show the highest savings potential.

Although school and offices have similar operating schedules, schools show higher savings as SFR increases due to higher lighting power densities, and hours of operation that are concentrated during daylight hours.

Warehouses show consistent savings as SFR increases due to the lack of heating and cooling energy use in this space type.

Savings by Glazing Type

The selection of the glazing assembly for a skylighting system can have a profound effect on its energy performance. There are three interrelated variables that need to be addressed: visible transmittance (T_{vis}), solar heat gain coefficient (SHGC), and unit U-value.

For the purpose of this discussion, the first two variables are combined into a single value: skylight efficacy (SE). A high or very high SE represents a glazing assembly where the ratio of T_{vis} to SHGC is between 0.8 and 1.5, meaning that the skylight allows a high amount of light relative to the heat gain. A low SE, typically between 0.4 and 0.5 represents a glazing assembly that allows more solar heat gain relative to the amount of light that passes through. This could be achieved with glazing materials that absorb much of the light and/or a deep light well that also acts to absorb much of the light. The unit U-value is dependent primarily on the number of insulating layers in the glazing assembly, and secondarily on the insulating properties of the skylight frame. To model these three variables the following assumptions were used:

- *High SE* (single glazed, SE=1.0; double glazed, SE=0.8) using a four foot by four foot clear, but diffusing, acrylic skylight, with about a one foot deep light well.
- *Low SE* (single glazed, SE=0.5; double glazed, SE=0.4) using a four foot by four foot white acrylic skylight with a six foot deep light well.
- *Very high SE* (SE=1.5) using a triple-glazed low-e glass with a one foot deep light well.

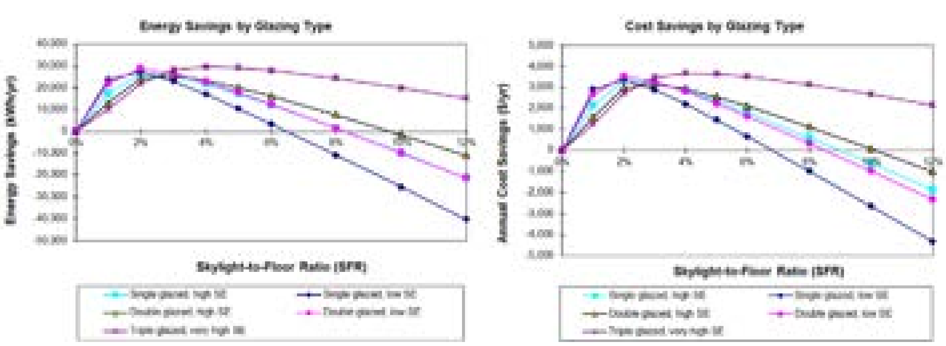


FIGURE 5-10: Annual Energy and Cost Savings by Glazing Type - San Bernardino Office

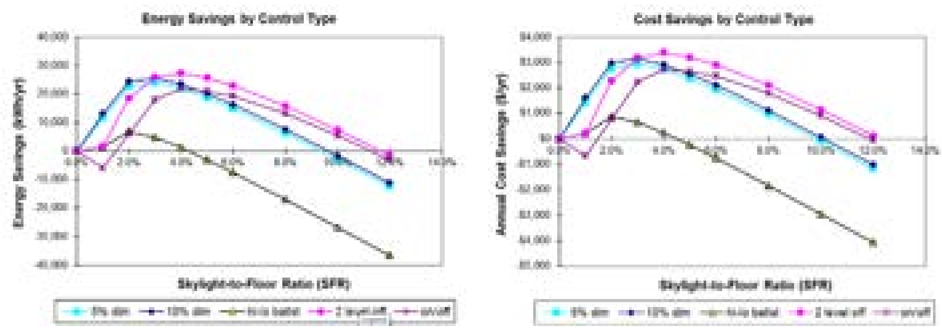
Figure 5-10 shows how differences in transmission, solar heat gain coefficient, and insulation levels affect energy performance of this office building in San Bernardino. In this relatively mild climate, moving from single to double glazed skylights improves the energy savings and increases the optimum skylight aperture. Triple glazing improves both performance and savings, but savings is only optimized at higher SFR values.

In most cases, the high SE skylights perform better than the low SE options. Although a single glazed, high SE product may perform better than a double glazed low SE option single glazed skylights are frequently not permitted under energy codes.

Savings by Control Type

The comparison of savings due to variation in control types is also instructive. Figure 5-11 looks at five control types: 5% and 10% dimming, on/off and 2 level switching plus off, and a hi/lo ballast. All systems were compared for a fluorescent lighting system at 50 footcandles and 0.75 W/sf.

FIGURE 5-11:
Annual Energy and Cost Savings by Control Type - San Bernardino Office



The on/off system has the interesting effect of starting with negative savings at the lowest skylight apertures. This is because in this sample building the lighting levels rarely get high enough to turn off the lights. Thus, there are insufficient lighting energy savings to counterbalance the resulting heating and cooling losses. However, at the larger apertures, this system outperforms all but the 2 level plus off system, and sees some of the largest potential cost savings. This is because, with dimming and hi/lo systems, some percentage of the electric lighting power is always left on, while with a switching system the electric lights are turned 100% off when there is sufficient daylight. That additional increment of lighting energy savings from full switching can outweigh the greater heating and cooling losses at higher apertures.

It should be pointed out that on/off switching systems also tend to be simpler and less expensive than dimming systems. The cost effectiveness of a switching system in this example, for instance, is significantly higher than the dimming or hi/lo systems. Thus, the choice to specify a dimming or hi/lo control system in this climate would probably be made more for operational or user acceptance reasons than for life cycle cost savings.

The results could be very different in another climate, with lower daylight illuminance levels, or in another building, with a higher design target illumination. In either of those cases full daylight saturation would be achieved less often, and dimming systems may perform significantly better than the simpler switching systems.

Switching systems also perform the best in daylight climates that are very consistent, with either fully sunny days or fully cloudy days, so that there are fewer occasions for switching between levels. Climates with frequent days of highly variable clouds will see better energy savings with dimming systems. This is because dimming systems can save more lighting energy at partial daylight saturation, and they also provide a more gradual transition as daylight illumination levels vary.

Putting It All Together

The designer's job is to understand the building program requirements as well as the constraints which will influence the building design, and to optimize the design with an integrated, whole building approach. No one single issue should ever control all of the design decisions made about a building, as that may prove to be detrimental to the final design. Thus, the optimization of the skylighting system will be only one among many issues that a designer will consider in the development of any building project.

There will always be many other issues which will affect the choices about a skylighting system besides those of optimizing energy performance and cost savings. The *SkyCalc* tool helps to facilitate decision making in the development of a skylighting system. This section also presents some rough, if simple, rules of thumb to guide thinking in the early stages of design about the impact of skylights on energy performance, and to help provide some guidance on the trade-offs inherent among the basic choices.

The over-arching objective for optimum energy performance is to design skylights that will provide more daylight to the building for less cooling and heating losses. The challenge, as well as the reward, is in balancing all of these concerns. The following will provide some "rules-of-thumb" for effective skylighting design:

Visible transmittance

- The higher the visible transmittance of the skylight glazing, the smaller the aperture needed to produce the same daylighting levels. The smaller the aperture, the less the heating and cooling losses.

Solar Heat Gain Coefficient

- The lower the solar heat gain coefficient the better the skylight glazing material will be at preventing unnecessary heat gains from the skylights.

- The hotter the climate, the more important the solar heat gain coefficient becomes.

Light to Solar Gain Ratio

- An important concern in skylight performance is the ratio of visible transmittance to solar heat gain. A high ratio will increase lighting savings while reducing cooling losses.

Diffusing Properties of Glazing

- The more diffusing a glazing material, the more efficiently a skylighting system can achieve uniform illumination levels.

Light Well Design

- The shallower, and/or more splayed, the light well, the more daylight will make it through to the space below.

- The brighter, more reflective the surfaces of the light well, the more daylight will make it through to the space below. White paint is usually an excellent choice for the surface of light wells.

- The deeper the light well, the less important the diffusing qualities of the glazing material. With a carefully designed light well which provides excellent diffusion, a clear, highly transmissive glazing material is possible (if allowed by energy code).

Unit U-value

- The colder the climate, and/or the more expensive the heating fuel, the more important a low U-value is for a skylight.

Lighting System

- The higher the lighting power density of a building, the more energy can be saved with skylighting

- The longer the daylight hours of operation of a building, the more energy can be saved with skylighting

- The lower the interior design target illumination levels, the more efficiently a skylighting system will meet the building's lighting needs. This is because at low target illumination levels, smaller effective aperture can achieve high daylight saturation while avoiding heating and cooling losses.

Control Choices

- The more daylight saturation achieved in a building throughout the year, the better switching controls will perform. The lower the percentage of daylight saturation, the better dimming controls will perform.

- Switching systems will generally save more energy in climates with consistent daylight illumination conditions, either sunny or cloudy all day long.

- Dimming controls will save more energy in climates with highly variable daylight illumination, where the interior daylight illumination level moves between full saturation and partial saturation many times per day.

Heating and Cooling Systems

- The more efficient the heating and/or cooling systems, the more cost effective skylighting will be.

- The lower the cost of heating fuels relative to electricity, the larger the optimum effective skylight aperture will be.

Ceiling Height

- The higher the ceiling height, the larger and/or further apart the skylights can be for uniform illumination levels.

- The higher the ceiling height, the more forgiving all of the visual quality concerns are for skylighting.

Partitions and Shelves

- The higher and/or narrower the partitions or shelves within a building, the more lighting power density will be needed to light the building effectively, and thus the more energy skylighting could potentially save.

- The higher and/or narrower the partitions or shelves within a building, the more difficult it is to achieve uniform illumination from skylights, and the more carefully the control system and placement of skylights must be considered.

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Chapter 6: *SkyCalc 3.0* User's Guide

As described in Chapter 5, there are many factors to keep track of while sizing skylights. We have reduced the tedium of optimizing skylight design with a simple-to-use spreadsheet that identifies the energy savings and cost savings, and shows the effects of changing various aspects of the system. This Microsoft Excel® spreadsheet, named *SkyCalc*™, predicts the lighting and energy outcomes of a given skylighting system over a range of skylight to floor area ratios. It graphs the overall energy and cost savings for lighting, heating and cooling. This helps a designer to quickly pinpoint the optimal sizing of skylights to maximize energy or cost savings.

The current version of *SkyCalc* is Version 3.0 and can be downloaded from the Energy Design Resources website: http://www.energydesignresources.com/resources/software-tools/

Getting Started

SkyCalc consists of a Microsoft Excel template file, `SkyCalc.xls`, and a number of weather data files with a `*.wea3` filename extension. You can save the `SkyCalc.xls` file anywhere on your computer.

Optionally, you can save *SkyCalc* as an Excel Template for easy access as `SkyCalc.xlt` or `SkyCalc.xltm`. To do that, open the downloaded `SkyCalc.xls` file in Excel. Then click `File - Save As` and select `Excel Template (*.xlt)`, or if using later Excel 2007 or above, select `Excel Maco-Enabled Template (*.xltm)`. By default the program saves templates into the Microsoft\Templates folder on your computer (This exact location of this folder varies by the version of Excel you have).

The weather data files can be stored anywhere on your computer. For ease of accessing them later, we advise you to copy them into a folder with a descriptive name such as SKYCALC or SKYWEATHER.

If the *SkyCalc* spreadsheet template has been copied to the Templates directory, it can be accessed by starting Excel and then by clicking on the `File` menu and selecting the `New` menu item, and clicking on `My Templates`. A copy of *SkyCalc* named `SkyCalc#.xls` (`SkyCalc1.xls`, `SkyCalc2.xls` etc.) will be ready to assist you with a skylighting design. Note in version of Microsoft Excel 2007 or above, the extensions will be `SkyCalc.xlsx`.

SkyCalc uses Macros to run its internal calculations, so after opening a copy of `SkyCalc.xls` on your computer, enable macros when prompted.

Using *SkyCalc*

SkyCalc is intended to help designers correctly size a skylighting system, and to calculate savings from skylighting. Because designers will be relying on the information *SkyCalc* provides, it is important to understand what the spreadsheet can and cannot do, and what key assumptions it makes about your specific skylighting system. *SkyCalc* assumes:

- That you will be using diffusing skylights positioned to provide uniform lighting over your space
- That you are modeling a single story building, or just the top floor of a multi-story building
- That the average energy prices you specify will give reasonable estimates of cost savings
- That the weather data you select is representative of average weather conditions for your site
- That you have correctly described your building and lighting systems in the inputs

Because you will probably want to use *SkyCalc* at various stages in your design process, we have designed it to accept three levels of input:

1. *Basic Inputs* – Provide only the minimum amount of information that *SkyCalc* needs to do an analysis; all of the other inputs are defaulted to reasonable values for your building.
2. *Optional Inputs* – Improve on the default values by providing more detailed input values as more design information is available.
3. *User-Defined Schedules and Values* – Establish user defined schedules, lighting control curves, building types, and other technical information to the *SkyCalc* analysis.

We recommend that you use *SkyCalc* early in your building design process to develop a preliminary design and estimate of savings. This only takes a few minutes, and it will give you a realistic design target. As your building design takes shape, with structural, mechanical and lighting systems, you can refine your *SkyCalc* analysis and see if its efficiency if improving. Finally, when the design is nearly complete, you can use *SkyCalc* to refine your final design and quantify the expected energy savings.

SkyCalc is organized into separate worksheet tabs. Most users of the program will only be interested in the four primary worksheet tabs. These tabs are entitled Inputs, Optional_Input, Graph_Results, and Table_Results. The two input tabs are used to describe the building, and the two results tabs present findings of the *SkyCalc* analysis.

- The Inputs worksheet tab asks for the most basic information needed to evaluate a skylighting system. A first pass analysis can be run after the inputs on this one tab are filled out.

- The Optional_Input worksheet displays the default values that result from the choices made on the Inputs worksheet and provides the means to modify these values for a more customized design.

- The Graph_Results worksheet illustrates the expected indoor daylight illuminance by hour and by month a design. It shows, on average, which hours of the day and year will have daylight in excess of the lighting setpoint(s), and which will have less. Two other graphs illustrate the energy and cost savings for the design, and how it compares to a range of other skylight to floor area ratios. Because the graphs on this worksheet require a large amount of calculations to generate, they are only updated when you click on the update SFR button on the sheet. Be sure the graphs are updated before you rely on them as results.

- The Table_Results worksheet tab summarizes the energy characteristics of the skylighting design in a simple table format.

All of these worksheets can be printed out as reports on the skylighting design and expected design performance.

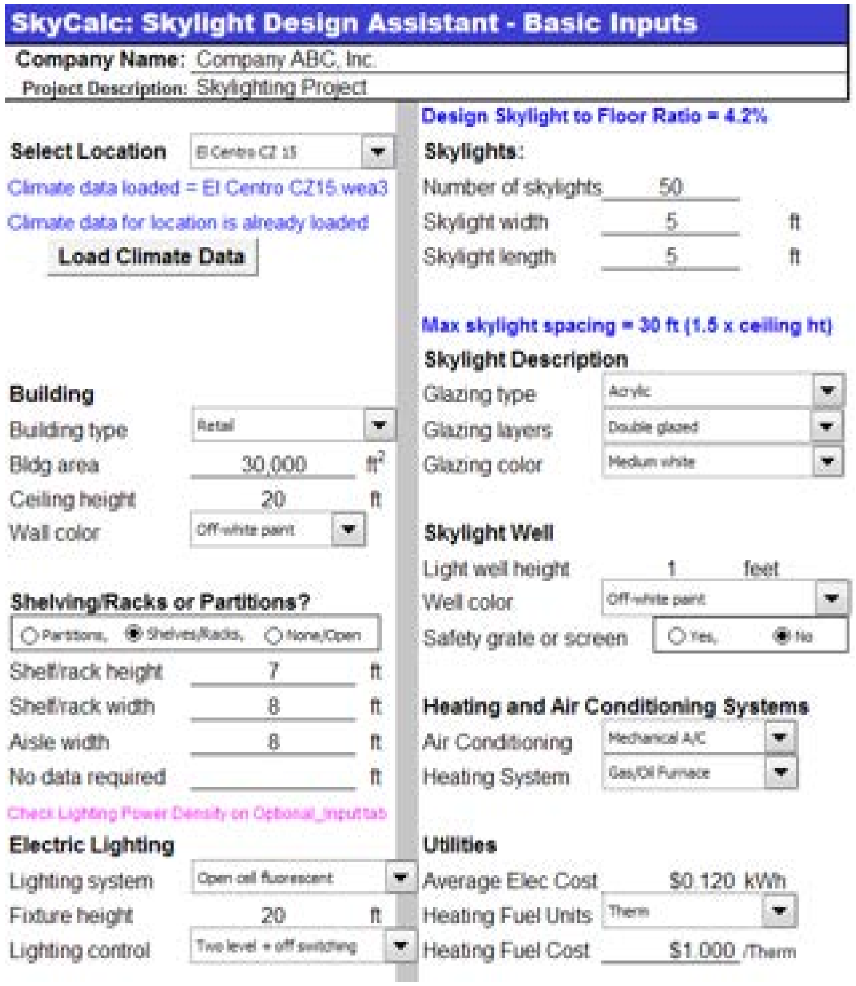
The other worksheet tabs in *SkyCalc* contain the data and the equations used for the calculations. These include Schedules, Lighting, Bld_Defaults, Skylights, Climate and Module1. They are of interest only if you wish to add user-defined defaults or schedules, or if you are interested in the mechanics of how the *SkyCalc* spreadsheet works. Much of this data is write-protected to prevent the accidental overwriting of defaults. However, most of the screens also have sections of data in a red font that are specifically unprotected for adding user-defined values, schedules etc.

The following sections are organized by tab to provide more detailed discussions of each of the *SkyCalc* inputs and results.

The Inputs Tab

The Inputs worksheet tab asks you to provide the minimum information needed to evaluate a given skylighting system. This information results in reasonable default values being applied to your skylight design. During schematic design of a new building, when few of the details about the building and the skylights are known, the basic inputs on this first tab provide the appropriate level of accuracy for this stage of design.

FIGURE 6-1:
SkyCalc - Basic Inputs



You enter the information either directly into the spreadsheet cells or by selecting from pull-down menus. Once you fill in these basic inputs, you can generate a savings estimate and analysis for your building in a few minutes. All of the information that is not entered on this tab is provided from default values selected by *SkyCalc*.

The following sections describe each of the inputs asked for on this tab.

Company Name and Project Description

A simple description of your project helps you to keep track of your files, and also makes the reports you printout from your *SkyCalc* analysis more informative. Typing your company name and project description at the top of the Inputs tab also places this header information on the next three tabs.

Location - Importing Weather Data

The *SkyCalc* analysis is sensitive to the weather data that is used. This data tells the program how much daylight is available, how much solar heat gain there is, and how much heating and cooling will be needed. On the pull down menu to the right of the topic *Select Location*, select the city with the climate most representative of your skylighting project. The pull down list of climate data is sorted by order of the 16 climate zones defined in the California Nonresidential Building Energy Efficiency Standards (Title 24). Arcata for Climate Zone 1 is listed first and Mt. Shasta for Climate Zone 16 is last.

In selecting a representative climate zone, the availability of daylight should be the primary point of comparison. Heating and cooling conditions are a secondary consideration, but there should not be large differences between your project location and the representative climate location.

FIGURE 6-2:
Map of California Climate Zones

The cell below the *Select Location* pull-down menu displays the city name for the climate data currently loaded in the spreadsheet. If the climate data is already loaded for the location you selected, cell A7 will read "Climate data for location is already loaded". You can move on to the next section, describing your building.

If the weather data for the city you have selected from the pull-down list is not already loaded on the spreadsheet, the next cell down will display the name of the climate data file that you need to load into the spreadsheet. Make a note of this file name and load the climate data by pushing the *Load Climate Data* button.

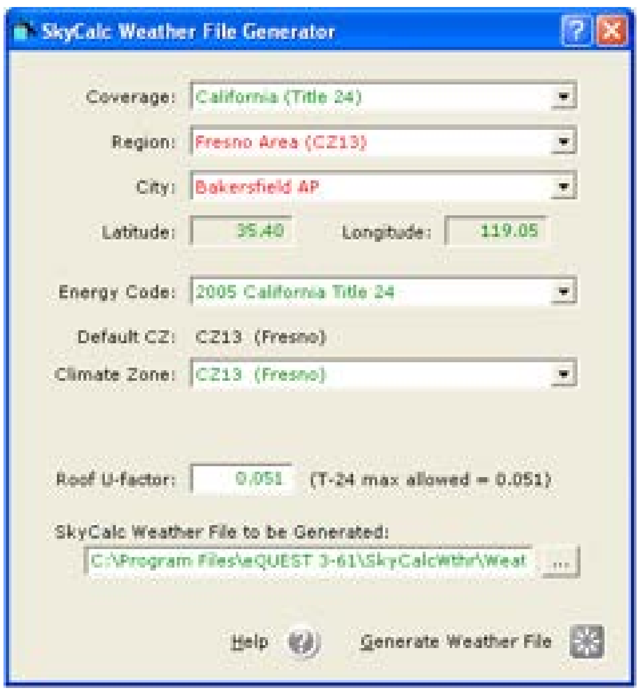
An Open dialog box appears with a listing of files. Navigate to the folder where you have stored the weather files. Select the weather file for the city you picked, and click on the *Open* button: the data will be imported into the *SkyCalc* spreadsheet.

Generating a SkyCalc weather file

New to *SkyCalc 3.0* is the ability to generate a SkyCalc weather file (`.wea3`) for any location worldwide that has a TMY2 weather file (`.bin` format) available.[1] To do this, the user needs to download and install the eQuest (version 3.61b or higher), hourly whole building energy simulation program, also available free from the Energy Design Resources website: http://www.energydesignresources.com/resources/software-tools/.

As a user starts up the eQuest program, on the first screen two primary choices are presented: Create new / open pre-existing building model, or Generate *SkyCalc* weather file. Selecting the Generate *SkyCalc* weather file option takes the user to a one-page input screen.

FIGURE 6-3: eQuest *SkyCalc* weather file generator



Coverage: Select one of three choices for this input:

- *California/Title24* - limits the weather file choices to the sixteen California climate zones
- *All eQUEST Locations* - provides U.S.-wide weather file choices

1 Note that because the weather files used in SkyCalc 3.0 do not adjust results based on TDV, the absolute value of the savings estimated may be conservative compared to a Title-24 compliance-tool that uses TDV-adjusted data.

- *User Selected* - allows the user to browse his/her machine/network for any standard DOE-2 weather file (`.bin` format)

Region/City: Contextual input for weather region and city:

- Depending on your selection of coverage, Region lists the sixteen California climate zones or the 50 U.S. states, plus Canada, the Pacific Islands, Puerto Rico, and the Virgin Islands. Select a city that is closest to your desired location.

Energy Code: Select the Compliance code for the location (Note: although these are not the most current code versions, this selection is only used to determine the appropriate climate zone choices):

- *2005 California Title24* - provides climate zone choices of sixteen California climate zones.

- *ASHRAE 90.1-2004* - provides climate zone choices of eight ASHRAE 90.1 climate zones.

Climate Zone: Select the Climate zone for the energy code:

- This input is used to calculate the default roof U-factor. The default selection for the California Title-24 energy code is based on the region selected by the user. The default ASHRAE climate zone is selected based on a mapping of city (selected by the user) to HDD and CDD values.

Roof Type: Select the type of roof. Displayed only if Energy Code = "ASHRAE 90.1-2004" (see above)

- Choose from one of the three roof types, or specify a custom U-factor. This is the roof type that will be used for the "DOE2 Reference Building" for the weather file generation. For more details on this subject, refer to Section 6.8.

Roof U-factor: Input the roof U-factor. (Note: Roof U-factor can also be changed in SkyCalc, however choosing the correct U-factor at the creation of the weather file will ensure greater accuracy.)

- A default U-factor is provided based on previous inputs. User may leave the default value or change the Roof U-factor here.

Work efficiency tip: If most of your projects are in a particular region, you may want to open the SkyCalc template, SkyCalc.xlt, and update the weather data directly on the template. From then on, new SkyCalc spreadsheets will be pre-loaded with the weather data you are most likely to use.

To open the template file, click on the File menu in Excel and select open. Then navigate to the Templates directory on your computer and select the SkyCalc.xlt file. (The location of the templates folder varies by Excel version but is typically located under Microsoft\Templates folder on your computer.) Update the weather data as described above. Then save the SkyCalc.xlt file or you can use "save as" to rename the file with a name reminds you of the city which is loaded, such as SkyLA.xlt for Climate Zone 6 in Los Angeles.

- The maximum allowed U-factor as per the selected energy code, climate zone and roof type, is reported on the side for reference.

Defining the Building

This section asks you to briefly describe the basic characteristics of the building, including type, floor area, ceiling height, and room reflectances. Choose the building type that most closely matches your building. The Building Type pull-down menu sets many of the default schedules and intensities of use for people, equipment, lighting, heating and cooling. If you like, you can later fine tune the building parameters. Fill in the other building data as requested. For guidance on surface reflectances see Chapter 3.

Note: The calculations in the spreadsheet assume a simple, one story rectangular floor plan based upon total floor area. SkyCalc should only be used to evaluate the daylit areas in the building. Rooms or areas of buildings with substantially different uses, configurations, schedules, light levels, etc. should be evaluated separately.

Shelving/Racks or Partitions

If the room of the building you are evaluating includes partitions, shelves or racks, you can select either the *Partitions* or *Shelves/Racks* options and proceed to describe their dimensions. When *None* is selected, the program changes these topic headings to No data required, and you can disregard filling in data for the height, length or width of partitions.

The program assumes that the obstructions you describe are evenly distributed across the whole area of the building. When the *Shelves/Racks* button is selected, fill in *Shelf height*, *Shelf width* and *Aisle width*. The length is assumed to be the width of the building.

All these obstructions absorb considerable amounts of both daylight and electric light, and the calculations are adjusted accordingly. If *SkyCalc* determines that the lighting power density assigned to the building type will not be sufficient to provide adequate illuminance, a warning to *Check Lighting Power Density on Optional_Inputs tab* appears. This is a prompt to the user to increase lighting power density in the Optional_Inputs tab.

Please note that the calculation of illumination levels and lighting power densities for areas with shelving or partitions is a rough approximation, based on the "floor cavity" approach of the lumen method. The method loses accuracy as the shelves get higher in proportion to ceiling height. For greater accuracy, we recommend that you use a lighting design program to determine more refined values for lighting power densities for a given illuminance target. Those values can then be input directly into the Optional_Inputs tab.

Electric Lighting

This section asks you to describe the basic characteristics of the proposed electric lighting system and its controls. *SkyCalc* calculates a default lighting power density for the system, based on the footcandle setpoint, the fixture type and other characteristics of the proposed building. You can, of course, adjust these default values on the Optional_Input tab.

The Lighting system pull-down menu defines the lighting system type for general lighting. Only one lighting system can be modeled at a time.

The Fixture height entry asks for the distance from the floor to the bottom of the light fixture, in feet.

The *Lighting Control* pull-down menu selects the electric lighting control strategy. The *Lighting Control Graph* below the pull-down menu illustrates the relationship between the lighting power draw by the electric lighting system and the available daylight inside the building for the selected control strategy. It also indicates the current illumination target in footcandles. One of the options on the *Lighting Control* pull-down menu is *No Daylight Control*. This allows you to evaluate just the heating and cooling energy impacts of skylights with no daylighting controls.

User-defined lighting systems and controls can be created on the Lighting tab. See the Advanced Modifications section below for more details.

Skylights

The information entered here describes the physical characteristics of the skylights and light wells. From this information, *SkyCalc* selects typical lighting and thermal performance characteristics for the type of skylights selected.

First, you are asked to enter the number of skylights and the dimensions of a unit skylight. Note that the skylight dimensions are in feet. *SkyCalc* determines the gross percentage of roof area which this number and size of skylights represents, and displays it in blue as the *Design Skylight to Floor Ratio* = __%. This value is an important indicator of skylight sizing, and it is used in the graphic results to show how the proposed design relates to an optimum design.

SkyCalc also calculates *Max skylight spacing* = __ *ft (1.5 x ceiling ht)*. This is to inform the designer that to achieve uniformity of illuminance skylights should be no more than the max skylight spacing indicated. *SkyCalc* uses a simple rule-of-thumb that skylights should be spaced at or less than 1.5 x ceiling height from edge-to-edge. This allows you to determine if there are enough skylights to provide uniformity.

If *SkyCalc* determines that the number of skylights input by the user will not achieve uniform illuminance, a warning message that *At least __ skylights needed for uniform daylighting* appears just below the *Skylights* section. When this message appears, you may increase the number of skylights and reduce unit skylight area to maintain an optimal skylight to floor area ratio, while ensuring uniformity.

Note that uniformity of illuminance here is calculated without using any of the inputs about shelving, racks or partitions. Spaces, especially those with very high shelves or racks may need more number of skylights to achieve uniformity.

The pull down menus for *Glazing Type*, *Glazing layers*, and *Glazing Color* are used to define the default values for visible transmittance, solar heat gain coefficient and thermal transmittance (U-value) of typical skylights with the specified glazing characteristics. For an acrylic or polycarbonate skylight choice, *SkyCalc* by default assumes a domed skylight with a dome rise of 1.25 ft. These and other inputs can be changed in the Optional_Inputs tab.

The Light Well height should include the height of the curb. Note the units of the Light Well height are in feet. The Well color pull down menu lists a range of materials used in Light Wells. For the Safety grate or screen entry, select yes only if the skylights will have safety grates or insect screens that block some of the light (i.e. not screens that are on the opaque sides of a vented skylight). Other detailed options for the Light Well can be specified in the Optional_Inputs tab.

Heating and Air Conditioning Systems

The pull-down menus in this section ask you to describe the heating and air conditioning (HVAC) system types for the building. *SkyCalc* uses this information in its calculations, allowing you to evaluate the effect of skylights on heating and cooling energy consumption. The first item on both of these menus is None. Some buildings, such as unconditioned warehouses, are neither heated nor cooled. This would be indicated by selecting *None* on both the *Air Conditioning* and *Heating System* pull-down menus. Most buildings, however, will have one or both types of systems.

SkyCalc is not a full energy simulation program, so the heating and cooling calculations are rather simplified. It only reports on the net change in heating and cooling energy use that results from the skylighting system.

Utility Costs

SkyCalc estimates the energy cost savings (or increases) for lighting, heating and cooling, and sums them up to give you a net impact that can be expected in the building's energy costs. *SkyCalc* assumes that lighting and cooling systems use electricity, and that the heating system may use electricity or other fuels.

Enter the average yearly cost of electricity per kWh. This can be found by dividing the total electricity costs on a bill by the total consumption of electricity in kWh for that period. This cost is typically substantially higher than the quoted usage cost per kWh of electricity because it includes other charges, such as peak electrical demand costs. If you don't have utility bills for the building or a similar building, the electric utility representative for the area where the building will be located should be able to provide average electricity costs for your building type.

The *Heating Fuel Units* pull-down menu allows you to specify the costs of heating fuels in the units the supplier provides, eliminating the need for unit conversions. Thus you can list the cost of fuel in terms of $/therm for natural gas, or $/gal of oil, etc. In the case of electric heating, the units would be kWh, and the cost may be different from the cost for lighting and cooling electricity specified above.

The Optional Input Tab

As your design for the skylighting system becomes more complete, you will have more detailed information about the characteristics of the design, which could affect its overall performance. You may, for example, have the actual specifications of the skylight glazing materials, or a more accurate lighting power density for the lighting system. As this information becomes available, you may visit the Optional_Input tab to refine the inputs, and then review the results tabs to see how the system performance has improved.

The Optional_Input tab is used to modify the many default values used in the *SkyCalc* analysis. Filling in any data in the Optional_Input worksheet is optional; in many cases the entries from the Inputs worksheet will sufficiently describe your building and your skylighting design. You only need to adjust these values if your design is substantially different or if you have better information about your system components.

The Optional_Input tab has 4 columns:

1. Input Description

2. Default

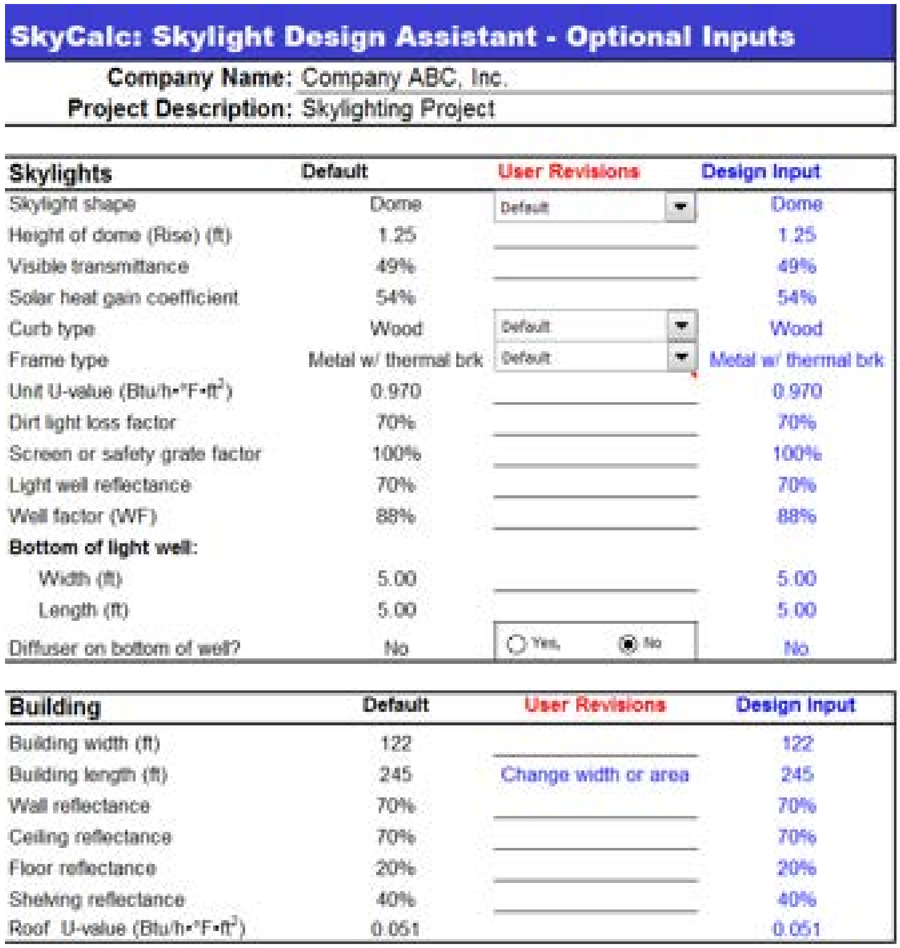
3. User Revisions

4. Design Input

The *Default* column displays the default values that *SkyCalc* uses based on the choices made on the Inputs worksheet tab. The *User Revisions* column allows replacement of the default value with a custom value that more closely represents the project. (Make sure that any user revision values are expressed in the Units specified!) The *Design Input* column displays the values actually used by the spreadsheet to calculate results, either the default or the user-revision.

Once you have entered a user-revision value, it will remain operative in the file until you change it. Thus, if you want to start a new analysis in the same file, be sure to recheck your user-revision values.

FIGURE 6-4:
SkyCalc, Optional Inputs Tab



SkyCalc: Skylight Design Assistant - Optional Inputs

Company Name: Company ABC, Inc.
Project Description: Skylighting Project

Skylights	Default	User Revisions	Design Input
Skylight shape	Dome	Default	Dome
Height of dome (Rise) (ft)	1.25		1.25
Visible transmittance	49%		49%
Solar heat gain coefficient	54%		54%
Curb type	Wood	Default	Wood
Frame type	Metal w/ thermal brk	Default	Metal w/ thermal brk
Unit U-value (Btu/h•°F•ft^2)	0.970		0.970
Dirt light loss factor	70%		70%
Screen or safety grate factor	100%		100%
Light well reflectance	70%		70%
Well factor (WF)	88%		88%
Bottom of light well:			
Width (ft)	5.00		5.00
Length (ft)	5.00		5.00
Diffuser on bottom of well?	No	Yes / No	No

Building	Default	User Revisions	Design Input
Building width (ft)	122		122
Building length (ft)	245	Change width or area	245
Wall reflectance	70%		70%
Ceiling reflectance	70%		70%
Floor reflectance	20%		20%
Shelving reflectance	40%		40%
Roof U-value (Btu/h•°F•ft^2)	0.051		0.051

The following sections describe these inputs in detail.

Skylights

For an acrylic or polycarbonate skylight choice, *SkyCalc* by default assumes a domed skylight with a dome rise of 1.25 ft. The default skylight shape, height of dome (Rise), visible transmittance (T_{vis}), solar heat gain coefficient (SHGC), and thermal transmittance (U-value) values result from glazing selections made on the Inputs tab and modifications made to the defaults on the Optional_Input tab. If you are specifying a particular skylight, ask the manufacturer for their test results on visible transmittance, solar heat gain coefficient, and unit skylight U-value and enter these numbers under *User Revisions*.

If you have the unit U-value, it is not necessary to fill out the *Curb Type* and *Frame Type* details. Note that the U-value relates the overall thermal transmission of the skylight to the nominal area that the skylight covers. For skylights that project out substantially from the surface of the roof such as barrel vaults or pyramids, the U-value should be adjusted upwards to reflect the increased surface area.

The selections under *Curb Type* are: wood curb (the default); integral frame, where the curb material is the same as the skylight frame material; and flush mount, which would be typical for a site assembled skylight.

The *Frame Types* are organized by increasing thermal resistance: metal, metal with a thermal break, metal clad wood, wood or vinyl.

The *Screen* or *Safety Grate* factor should represent how much of the light gets through the screen or grate (i.e. a screen that obstructs 10% of the light has a factor of 90%). Note that a screen in the opaque side of a skylight assembly would not affect the light entering, so the factor would be 100%.

The *Light Well* reflectance default results from the choice of surfaces listed on the *Skylight Well* color pull-down menu on the Inputs tab. The light well reflectance can be fine-tuned by taking site measurements of reflectance, or asking the paint manufacturer to report the reflectance of the paint to be used in the light well.

Well Factor is a calculation based on inputs of light well reflectance, bottom dimensions, and presence of diffuser. Unless the user has used a coefficient-of-utilization or similar formula to calculate this, the default should not be overridden.

The *Bottom of Light Well Length* and *Width* describes the dimensions of the light well at the ceiling plane. The default condition is a straight sided well. You can indicate a splayed light well by increasing the bottom of light well width and length.

> **Example:** A 4' by 5' skylight, with a 2' deep light well, will have a default bottom of light well width = 4' and a length = 5'. To describe the same skylight with a light well that is splayed at 45°, the bottom of light well dimensions should be width = 8' and length = 9' (for each one foot of well height, the bottom dimensions are also increased one foot).

Building

The *Building* section of this tab describes in greater detail the building characteristics that are used in the *SkyCalc* analysis. Keep in mind that, by building, we mean the skylit space that is being analyzed, which may actually be only a portion of the actual building. In *SkyCalc*, the default building is assumed to be one story and twice as long as it is wide. One can override this assumption by revising the building width. The length will be recalculated based upon the overall area of the building. Ceiling, wall, floor and shelving reflectances can also be revised here, if better values are available.

The default roof U-value is the maximum value allowed by the prescriptive requirements of the California Nonresidential Building Energy Efficiency Standards (Title 24) for the selected climate zone. Note that this describes the U-value for the opaque sections of the roof only and is NOT the overall U-value of the entire roof including skylights. *SkyCalc* assumes that the skylights are replacing an equivalent area of opaque roof with no changes to the roof insulation levels.

Electric Lighting

This section describes the characteristics of the electric lighting system and its schedule of operation. The operation schedule is important because *SkyCalc* assumes that the lighting control system automatically turns down the electric lighting when daylight is available only while the lights are scheduled to be on. The lighting power density, in Watts per square foot, is calculated from the design lighting setpoint, the type of lighting system, and the shape and reflectances of the building and shelving.[2] More accurate lighting power densities, taken either from your experience or from a more exacting lighting design calculation, can be entered in the *User Revisions*. Task height describes the height of a horizontal task surface above the floor, for instance a desk surface. If the primary activity of the space is walking, as in a lobby for instance, the task height would be zero (the floor).

The *Fraction of Lighting Uncontrolled* describes the fraction of the ambient lighting system that is not controlled in response to daylight; for example, 10% of the lighting fixtures might be operated on an emergency circuit that leaves them on at all times. The *Room and Luminaire Depreciation* describes how much light will typically be available from the electric lighting system in several years' time, as compared to the light available from a new fixture and a building with clean surfaces.

Note that the *Lighting Schedule* (the fraction of the lights that are on during a given hour) can be revised via a *Lighting Schedule* pull-down menu. This graph displays three schedules: weekdays (M-F), Saturdays and Sundays. The *Lighting Schedule Graph* instantly updates when changes in the *Lighting Schedule* are selected. The *Lighting Schedule* pull-down menu includes the possibility of specifying user-defined schedules that can be modified in the Schedules tab. See the Advanced Modifications section below for more details on creating a user-defined schedule.

Internal Loads

This section describes the amount of heat generated internally (other than electric lighting handled in the previous section). The number of people and the process (plug) loads entries refer to the peak, or highest, values expected over the course of the week. In an office setting, for example, the process loads are the computers and other equipment that give off heat. In a warehouse setting, the process loads result from any equipment such as forklifts or packaging equipment. Note that plug loads are in units of Watts per square foot of floor area.

The actual values for number of occupants or process loads for any given hour are usually some fraction of their peak value. These hourly fractions are defined in the *Occupancy Schedule* and *Process Schedule* selections. When a selection is made on the *Occupancy Schedule* and *Process Schedule* pull-down menus, the corresponding graphs are immediately updated so you can see the shape of the load profile selected. Note that both of these pull-down menus have a "default" entry as the first menu item; this refers back to the building type entry made on the Inputs tab.

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2 *SkyCalc* uses the lumen method as defined by the 8th Edition of the Handbook of the Illuminating Engineering Society of North America. See the Advance Modifications section for more information on assumptions about light sources and fixture types.

HVAC

This section describes the operating characteristics of the HVAC system that was specified on the Inputs tab. The HVAC system has a 0 or 1 schedule. When the HVAC schedule is 1, the specified heating and cooling setpoint temperatures are maintained in the space for that hour. When HVAC schedule is 0, the heating setback and the cooling setup temperatures apply. One can specify an economizer which brings in outside air to provide cooling when the outside air is cool enough. The economizer setpoint defines a temperature above which the economizer is not used. All temperatures are in degrees Fahrenheit.

The Graph Results Tab

The Graph_Results tab displays the key results of the *SkyCalc* analysis in three simple graphs:

5. Average Daylight Footcandles

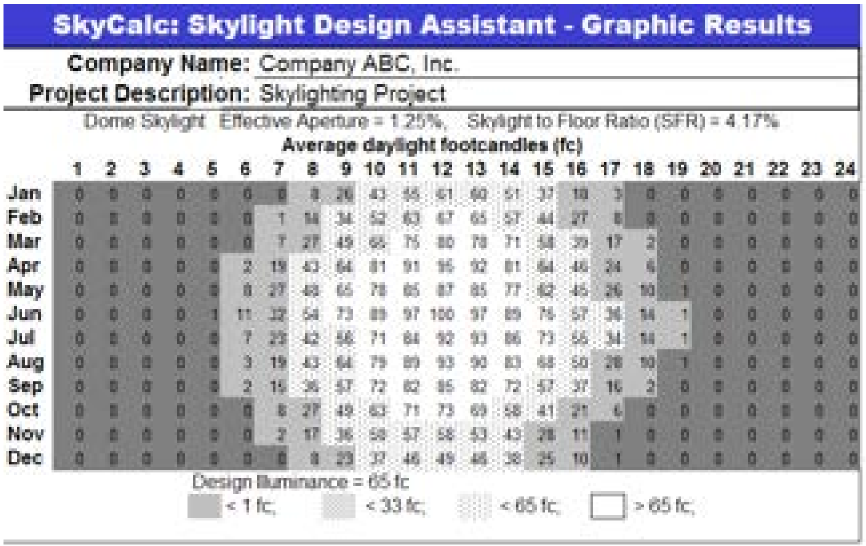
6. Total Energy Savings from Skylights

7. Annual Cost Savings from Skylights.

The first graph shows the daylight illuminance levels achieved with your skylighting design. The second two help identify the optimum skylight to floor area ratio, given all the other parameters you have entered. These graphs can be updated as you modify the *SkyCalc* inputs. The first graph updates automatically, while the second two update using the *Update SFR* button. This makes it easy to see the impacts of changes to your skylighting design.

Average Daylight Footcandles Graph

The *Average Daylight Footcandles* graph displays the average indoor daylight illuminance, taken at a single point in the space, in footcandles for each hour of each month for the skylighting system you have defined.


SkyCalc: Skylight Design Assistant - Graphic Results

Company Name: Company ABC, Inc.

Project Description: Skylighting Project

Dome Skylight Effective Aperture = 1.25%, Skylight to Floor Ratio (SFR) = 4.17%

Average daylight footcandles (fc)

	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	17	18	19	20	21	22	23	24
Jan	0	0	0	0	0	0	0	8	26	43	55	61	60	51	37	18	3	0	0	0	0	0	0	0
Feb	0	0	0	0	0	0	1	14	34	52	63	67	65	57	44	27	8	0	0	0	0	0	0	0
Mar	0	0	0	0	0	0	7	27	49	65	75	80	78	71	58	39	17	2	0	0	0	0	0	0
Apr	0	0	0	0	0	2	19	43	64	81	91	95	92	81	64	46	24	6	0	0	0	0	0	0
May	0	0	0	0	0	8	27	48	65	78	85	87	85	77	62	45	26	10	1	0	0	0	0	0
Jun	0	0	0	0	1	11	32	54	73	89	97	100	97	89	76	57	36	14	1	0	0	0	0	0
Jul	0	0	0	0	0	7	25	42	56	71	84	92	93	86	73	56	34	14	1	0	0	0	0	0
Aug	0	0	0	0	0	3	19	43	64	79	89	93	90	83	68	50	28	10	1	0	0	0	0	0
Sep	0	0	0	0	0	2	15	36	57	72	82	85	82	72	57	37	16	2	0	0	0	0	0	0
Oct	0	0	0	0	0	0	6	27	49	63	71	73	69	58	41	21	6	0	0	0	0	0	0	0
Nov	0	0	0	0	0	0	2	17	36	58	57	58	53	43	28	11	1	0	0	0	0	0	0	0
Dec	0	0	0	0	0	0	0	8	23	37	46	49	46	38	25	10	1	0	0	0	0	0	0	0

Design Illuminance = 65 fc

< 1 fc; < 33 fc; < 65 fc; > 65 fc;

FIGURE 6-5:
AVERAGE FOOTCANDLES GRAPH

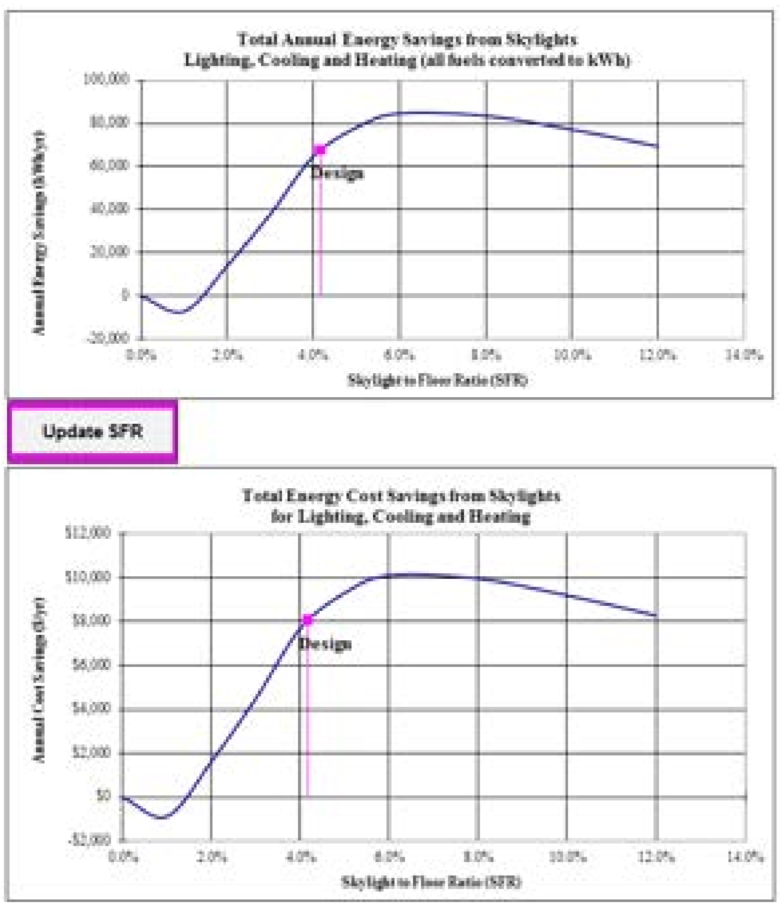
This gives an indication of how bright it will be inside from daylight only. The calculations are based on the average weather conditions for each hour of the month, using typical weather data (TMY) for the location selected. Of course, on any given day, the value may be higher or lower, depending on the actual weather. The shading on the graph, which is relative to the design target illuminance of the electric lighting system, indicates what hours the electric lighting system will be completely on, at minimum power, or somewhere in between.

Total Energy Savings and Cost Savings Graphs

The two graphs in Figure 6-6 show how close your skylight area is to the optimum. With all other variables held constant, the skylight to floor ratio (SFR) varies from 0% to 12% along the X-axis. The resulting performance curve is plotted both for whole building energy savings and dollar value of those savings on the Y-axes. The performance of the proposed design is also indicated.

If you were to change the size or number of skylights in your proposed design, the shape of the curve would change little. If, however, you were to change the physical characteristics of the skylights, the daylighting control system, energy costs, or details about the building and its operation, then the shape of the curves would change more significantly.

FIGURE 6-6:
Skylight Area Optimization Graphs



These graphs help you to quickly identify the skylight area, in terms of SFR, which yields the maximum energy and cost savings. In addition, these graphs show where your skylighting design lies along the continuum of energy and cost savings.

In many cases the optimum SFR for maximizing energy savings will be different from the optimum SFR for maximizing cost savings. This is due to the different unit costs for electricity versus heating fuels, and the relative impacts on heating and cooling energy uses by the skylighting system.

To the right of these graphs are the tables of numbers used to generate them. Looking at the numbers in the tables may help you in understanding the patterns displayed in the graphs. The graphs display only the whole building savings, while the tables break the information down into effects on heating, cooling and lighting energy. Typically, the heating and cooling numbers will show negative savings, because the skylights have increased the heating and cooling loads on the mechanical system. If the skylights are not oversized, however, the lighting savings will offset these increased loads. Another graph to right of the tables provides energy savings by the three components of *Lighting, Heating and Cooling*. This graph is similar to the total annual energy savings graph and shows the components of the annual energy savings numbers. This can also be used to help understand the opposing directions of lighting energy savings (positive) and heating and cooling energy losses (negative) that result in the total energy savings graph.

The Table Results Tab

The Table_Results tab summarizes the key information used to calculate energy savings from skylights in tabular form. This tab also presents the energy and cost savings results for the skylighting system defined from the inputs.

Most of the terms on this tab are defined in the Glossary. The terms that are specific to the Table_Results table are defined below:

- Full Daylighting hours per year - this is the number of hours that the interior daylight levels were above the lighting setpoint.
- Overall Skylight System Tvis - this is the fraction of the light from the sky that leaves the skylight well. It is the product of the visible transmittance of the glazing, the well efficiency, the dirt factor and the screen or safety grate factor.
- Skylight CU - the fraction of the light leaving the skylight well that makes it to the "work plane". In addition to Tvis, this is also a function of the geometry and reflectances of the interior space.

Savings from Design Daylighting System

The *Savings Table* itemizes the savings from the proposed skylighting system, as compared to the same building with no skylights, for lighting, heating and air conditioning. Note that negative savings means that the skylighting system will use more energy for that component. It is quite typical for a well-designed skylighting system to have negative heating or cooling savings; but this is overshadowed by substantially larger lighting energy savings. If the total skylight area gets too large, the negative savings can overwhelm the positive savings.

If there have been no changes to the inputs since you last updated the *Total Energy Savings* and *Cost Savings Graphs* then the energy savings figures are current. Otherwise press the *Update Results* button to view the energy impacts of the revised skylighting design.

Advanced Modifications

Most occasional users of the *SkyCalc* spreadsheet will be interested in only the two primary inputs tabs and the two outputs tabs. This provides sufficient detail for 90% of the buildings and designs likely to be encountered. The other tabs store the default schedules and values used in the calculations. These are available for examination. The data fields are write-protected to avoid inadvertent data loss.

It is also possible to create your own values for user-defined inputs on these tabs. This section describes the data in more detail, and explains how to add user-defined options. A general caveat: customization of *SkyCalc* as described in this section should not be undertaken by users who are not reasonably familiar with Excel and its operations. The instructions which follow assume this familiarity and will appear cryptic to users who lack it.

The fields available for entry of user-defined values are shown in red text in these tabs. The features that can be modified are:

- Schedules
- Lighting Controls
- Lighting Technologies
- Lighting Fixtures
- Building Type
- Skylight Properties

Manufacturers or distributors of skylights, controls equipment or lighting fixtures can create user-defined properties or schedules that describe their equipment. Frequent users of *SkyCalc* may also want to customize some of the above features to reflect design choices they typically make.

Schedules

SkyCalc comes with 9 default schedules (Classroom K-12; Class University; Grocery; Hotel Lobby; Office; Restaurant; Retail; Warehouse; and 24_hour) for lighting, occupancy, process (plug) loads, and HVAC operation.[3] You may have a project where none of these pre-existing schedules adequately describes the pattern of energy consumption for some of these loads. You can create a user-defined schedule that matches the consumption pattern in the building you are evaluating.

The Schedules worksheet tab contains four tables with the schedules for lighting, occupancy, process (plug) loads, and HVAC operation. The tables are organized so that the columns describe the hour of the day (1 to 24) and the rows describe the type of day: weekdays (M-F), Saturdays (Sat.) and Sundays (Sun). To the left of the weekday data is a schedule name which appears on the pull-down menus in the Optional_Inputs tab.

The schedules designed to be modified are those in red text and are named user-defined-1, user-defined-2, etc. Enter data into the cells for each day type (M-F, Sat, Sun) and each hour of the day. Copying and pasting data speeds up the data entry but it is important not to move cells. Change the schedule name from user-defined-1 to a more descriptive name for your project, such as Gym_Light for a gymnasium. When changing the schedule name it is important that you use a name that is not already used by another schedule.

The schedules for lighting, occupancy and process (plug) loads describe the hourly fraction of some maximum value for each of these loads. These schedules should contain numbers between 0 and 1. The HVAC schedule describes whether the heating and cooling system is in normal mode or off-hour mode. There should only be either 0 or 1 values found in each hour of the HVAC schedule. Off-hour operation is represented by a 0 and normal operation by a 1.

Lighting Controls

SkyCalc has an extensive list of predefined lighting controls. This list has three sections: controls with performance characteristics that are common to all lighting technologies (switching controls); controls with performance characteristic that are specific to the lighting technology (dimming and hi-lo ballasts); and user-defined controls. Thus, the second section of the *Lighting Controls* pull-down list can change depending upon which lighting system you choose. The performance of lighting controls can be quickly observed on the Inputs worksheet by selecting various controls on the *Lighting Controls* pull-down menu and viewing the *Lighting Control Graph*. If it appears that none of these controls are appropriate for the lighting system type you have selected, you can create a user-defined lighting control curve.

The *Electric Lighting Controls Table*, found near the top of the Lighting worksheet tab, describes the fraction of power used by electric lights for differing amounts of interior daylight available. The first column labels the interior illuminances for each row. Each of the following columns describe, for a

3 The schedules are based on data collected by Southern California Edison from a large set of monitored buildings representative of each building type.

specified control type, the fraction of power drawn by the controlled electric lighting system as the interior daylight contribution increases from 0 to 100 footcandles by 2 footcandle increments.

Directly above each of these columns are two numbers which describe the minimum fraction of rated light output and the minimum fraction of rated power output for dimming and hi/lo ballasts.[4] The performance curves assume that the performance of dimming ballasts can adequately be characterized by a straight line (linear interpolation) between the minimum light output and minimum power input to full light output and full power input. The hi/lo ballast and switching control performance curves are designed so that combined daylight and electric lighting provides at least the footcandle setpoint without any deadband.

If you want to create a user-defined control curve for a given electric lighting control, you can change the minimum light output and the minimum power input values for either the dimming, hi/lo or 3 phase hi/lo strategies. The minimum light output and the minimum power input variables for the user-defined controls are in red text to indicate that they are specifically intended for modification. If you desire to have a control function that is neither linear nor a step function, the sheet can be unprotected and the equations overwritten with values that you choose. Note that the target design illuminance is listed just to the right of this table and can be used in your control function.

Lighting Technologies

When you select a specific lighting system on the Inputs tab, it is used to determine the amount of lighting power needed to achieve your design target illuminance.[5] The pre-defined lighting systems in *SkyCalc* are:

- Open cell fluorescent - deep cell parabolic fixtures containing T-8 fluorescent lamps and electronic ballasts.

- Lensed fluorescent - lensed troffers containing T-8 lamps and electronic ballasts.

- Direct/Indirect fluorescent - suspended fixtures with reflector grid, with 39% uplight and 32% downlight, with T-8 lamps and electronic ballasts.

- Indirect fluorescent - suspended luminous bottom indirect fixtures with 66% uplight and 12% downlight with T-8 lamps and electronic ballasts.

- Industrial fluorescent - industrial strip fixtures with a porcelain enameled reflector, T-8 lamps and electronic ballasts.

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4 Performance curves are based on averages of manufacturer provided data, using two or three typical products when available, or only one product when no competitors could be located.

5 *SkyCalc* uses the lumen method as defined by the 8th Edition of the Handbook of the Illuminating Engineering Society of North America.

- High Bay Metal Halide - high bay intermediate distribution ventilated reflector with clear metal halide lamp and magnetic ballasts.

- Low Bay Metal Halide - low bay lensed bottom reflector unit with a clear metal halide lamp and magnetic ballasts.

- High Bay HPS same as high bay metal halide except with clear HPS lamp.

- Low Bay HPS same as low bay metal halide except with clear HPS lamp.

The performance of these fixtures are as defined in the IESNA Handbook. Reference numbers for each fixture can be found starting at cell D-84 on the Lighting worksheet.

If you wanted to specify a light source with a different efficacy, such as metal halide lamps with a high efficiency ballast, you can create a user-defined lighting system that reflects the changed efficacy.

To create a user-defined lighting system:

- On the Lighting worksheet tab below the *Electric Lighting Controls Table* is the *L_type Table*. The first column lists the types of electric lighting systems - these are the items you see when using the *Lighting System* pull-down menu. The *Maintained Luminous Efficacy* column lists the light source efficacy, including lamp lumen depreciation at 40% of rated life of the lamp. Enter a maintained source efficacy for your lighting system.

- The next column, *Table L_intens Column#* references the appropriate column in the *L_Intens Table* to describe the luminance distribution of the fixtures used in the lighting. Select the column number for the appropriate fixture type. The remaining columns are for reference and are not designed to be modified.

Lighting Fixtures

If you would like to add another fixture type that has a different light distribution from any of the light fixtures listed, this can be accomplished by entering in the *L_Intens Table* the luminous intensities for the desired fixture. The *L_Intens Table* is below the *Electric Lighting Controls Table* and to the right of the *L_type Table*. These luminous intensities in candelas are normalized per 1,000 source lamp lumens and must be listed for the midpoint of each 10° conic solid angle. The format of this table and the source of more data for other fixture types can be found on page 443 of the 8th Edition of the IESNA Lighting Handbook.

Building Type

When you make a selection from the Building type pull-down menu on the initial Inputs worksheet, it controls a wide array of defaults, from the lighting setpoint to the HVAC schedules. You can create new user-defined building types that describe building types that you are frequently asked to evaluate.

Go to the *Bldg Table* on the Bld_Defaults worksheet tab. The headings of the columns are descriptive of the data required for a user-defined building type. When creating a default schedule, it is best to reference the cell containing the schedule name rather than typing the name in. This way, if the name of the schedule is changed, the *Bldg Table* is automatically updated. See the other pre-defined schedules for examples of how the schedule name is referenced.

Building types in the red font have been set aside for user modifications. Use these rows for new building types. You can change the name of the building type to something more descriptive than "user-defined-1," but be sure to give it a unique name.

> **Example - How to reference a schedule name:** Suppose that you want to create a new building type called manufacturing (instead of user-defined-1) and you want to use the 24_hour lighting schedule. You have overwritten user-defined-1 with manufacturing, by typing "manufacturing" in cell A18. In the cell for *Lighting Schedule* (cell B18), you type an = sign and then click on the Schedules tab. On the Schedules tab, find where the 24_hour light schedule name is referenced (cell E29). Click on the cell and then hit return on your keyboard. The manufacturing building type now references the 24_hour light schedule.

Skylight Properties

The *Glazing Type*, *Glazing Layers* and *Glazing Color* pull-down menus on the Inputs worksheet, and the *Curb Type* and *Frame Type* pull down menus on the Optional_Input worksheet build up a description of the skylights that is used to look up default performance characteristics of the skylights specified. The resulting performance characteristics of visible transmittance, solar heat gain coefficient, and thermal transmittance (U-value) are presented on the *Default* column of the Optional_Input worksheet.

If you occasionally design with a specific skylight in mind and you have performance test results from the manufacturer, changing the default values that return from the skylight pull-down menus is probably not worth the effort. The simplest method of using these skylight specific performance results is to ignore the skylight pull down menus and enter the data directly in the *User Revisions* column on the Optional_Input worksheet for visible transmittance, solar heat gain coefficient, and U-value (Btu/h•°F•ft2).

However, if you frequently specify a particular skylight, or if you are a skylight manufacturer who wishes to make it easy to evaluate designs using your skylights, you may wish to add these specific skylight products to the pull down menus.

How to add a new skylight product:

- At the top of the Skylights Worksheet tab is the *G-type Table* that contains the listing of glazing types available. Replace the entry *User Defined* in red font with a more descriptive name, such as the skylight manufacturer's name and product number.

- To the right of the *G_type Table*, past the *G_layers* and *G_color* tables, is the *Glazing Layers Table*. The names in the *Glazing Layers Table* describe any categories that will have an influence on visible transmittance and shading coefficient, other than glazing color. These influences might be number of glazing layers, glazing thickness etc. The results of this table are also used when defining the overall U-value of the skylight. Enter your choice of names in the last column of this table; the text in these cells is in red font to indicate the cells are available to be modified.

- To the right of the *Glazing Layers Table* is the *Glazing Colors Table*. In the last column of this table, describe the color or other glazing characteristics that affect visible transmittance and solar heat gain coefficient only.

- Below the *G_type Table* is a large look-up table which lists the visible transmittance (T_{vis}) and the solar heat gain coefficient (SHGC), for all the combinations of glazing types, layers and colors. At the bottom of this table are listed the glazing type and glazing layer names which you defined earlier. Enter the visible transmittances and solar heat gain coefficients for the skylights you are defining in the appropriate column. The cells you can change are indicated by a red font.

- Below the *Glazing Layers Table* is the U-Values for different *Frame and Curb Configurations Table*. This table contains U-values for combinations of glazing types, layers, curbs and frame types. Note that the option is not available to modify the frame or layer types. If you have only one frame and curb type, you may want to put the same U-value across all the frame and curb types so the correct result is obtained regardless which curb and frame type was selected. Fill in the corresponding U-values in the cells highlighted with red text for the skylights you have defined.

The Calculations

SkyCalc is a simple daylight and building simulation spreadsheet. It considers the following effects that skylights have on building energy consumption:

- Reduction of electricity consumption by electric lighting (when daylighting controls are used)

- Reduction of internal heat gains by electric lighting (when daylighting controls are used)

- Increased solar gains

- Increased thermal transmittance of roof.

The thermal effects cannot be simply added together to find the overall energy impacts of skylights. On a cold day, the solar gain is not necessarily increasing cooling electricity consumption – it might be reducing heating load. Whether the building is in heating or cooling mode depends upon other factors such as how many people are in the building and how much process equipment (plug loads) is operating. Thus, a good estimate of overall energy impacts of skylights requires some knowledge about the rest of the building.

The climate data for *SkyCalc* is actually an hourly output file from a DOE-2 simulation of a "reference" building. These outputs are modified to represent the building with the skylighting design and a "base" building similar to the skylit building in all ways but one – the base building doesn't have skylights.

The *SkyCalc* spreadsheet has four major components for calculating the performance of skylighting systems:

- Simple user inputs
- A database of default schedules, skylight performance characteristics, and material properties
- Hourly climate data generated by the DOE-2.1E building energy simulation program containing interior illuminances, sensible heat gains, solar heat gains and outdoor dry bulb temperatures for a reference building.
- Calculation algorithms embedded in cell equations, user defined functions and subroutines.

The extensive defaults convert simple user inputs such as "white paint" into values the spreadsheet can use, such as "reflectance = 80%." This combination of simple user inputs and defaults creates a detailed description of the building, its loads, electric lighting and skylighting systems.

The DOE-2 reference building has the default characteristics outlined below. These default values may need to be revised to reflect current standards:

- 100' by 100' building with a 20 foot ceiling, task height is 2.5 feet above the floor
- 4% skylight to floor ratio, shading coefficient = 1, effective aperture = 2% (overall Tvis = 0.5)
- Roof U-Value = 0.057, Skylight overall U-Value = 1.0 Btu/h•ft2•ºF, adiabatic walls
- Both lighting and equipment power density are 1.5 W/ft2
- Occupant density is 1 person per 100 ft2
- Setpoints: Cooling 72º, Heating 68º
- All schedules (lighting, occupancy, process loads) are set at 100% for 24 h/day and 7 day/wk
- Daylighting controls are disabled.

Simple ratios are used to relate the illuminances in a skylight design to the reference building. The two factors to be compared are the effective apertures and coefficients of utilization. The effective aperture describes what fraction of the light impinging upon the roof makes it through the skylight and light well. The coefficient of utilization describes what fraction of light exiting from the bottom of the light well makes it to the task. The lumen method algorithm as published in Chapter 9 of the 8th Edition of IESNA Lighting Handbook is used to calculate the coefficient from skylights. The key assumptions of this method are:

- The skylights are completely diffusing (Lambertian distribution) and uniformly spaced

- Each surface in the room is diffusely reflecting

- Each major surface of the room is uniformly illuminated

Thus, this method will not accurately model clear skylights, non-uniform spacing, or high partitions.

The lumen method, using luminance distribution patterns for specific light fixtures and a light source efficacy, calculates the default electric lighting power density for the lighting setpoint selected.[6] In this manner, lighting levels, lighting power density and interior daylight are all interrelated.

The corrected interior daylight levels for each hour of the year and the daylighting control function modify the base case electric lighting power for that hour. Thermal losses due to skylights are modeled using a simple UA (conductance area product) equation. This steady state heat transfer method does not consider thermal storage of heat in the mass of the building. In contrast, the solar heat gain model, which scales the hourly solar loads from the DOE-2 reference building by the relative area of the skylights and their solar heat gain coefficient, does reflect the thermal capacitance of the reference building. The other thermal loads of occupancy and equipment are also added in to arrive at the total zone heating or cooling load for that hour.

At this point, the zone loads for each hour and the sum of electricity consumption for electric lighting for both the base case building without skylights and the skylit designed building have been stored. The maximum cooling load is also stored for sizing of the heating and air conditioning systems.

A HVAC systems model then evaluates the energy consumption required by the hourly building loads. This model allows the user to specify an outside air economizer that can displace some, or all, of the cooling load when the outside air is cool enough. This model also varies the heat pump efficiency depending upon outside temperature (as the outside temperature drops, the heat pump needs more electricity per Btu of heat generated).

Savings are calculated by subtracting the energy consumption of the daylit building by component (lighting, cooling and heating) from the base building without skylights. These savings are recorded in the results table and graphs.

6 Note the caveats about high partition or rack areas hold for electric lighting. We recommend that you modify the lighting power density in high rack areas with values that are consistent with a more sophisticated lighting design tool or your design experience.

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Appendices

Glossary and Symbols

Ambient lighting: Lighting throughout an area that produces general illumination.

Ballast: A device used with a fluorescent or high intensity discharge (HID) lamp to obtain the necessary circuit conditions for starting and operating.

Coefficient of utilization (CU): the ratio of luminous flux (lumens) from a luminaire calculated as received on the workplane to the luminous flux emitted by lamps. When used with skylights, the coefficient of utilization is the ratio of the luminous flux from skylights received on the workplane to the daylight entering the room from the bottom of the light wells.

Daylight saturation: The condition where the interior daylight illuminance level equals or exceeds the specified design illuminance level and the lighting control system thus provides maximum lighting energy savings. At saturation, any further increase in daylight illuminance will not produce additional lighting energy savings.

Diffuse (Lambertian) surface: A surface that emits or reflects light uniformly in all directions and has a constant luminance regardless of viewing direction. See also specular reflecting surface.

Effective aperture (EA): A measure of the light transmitting ability of a fenestration system. Effective aperture is the product of the skylight-to-floor ratio (SFR), the visible transmittance (T_{vis}) and the well factor (WF). EA values range from 0 to 1.0 and are typically less than 0.1 for most practical skylight systems.

Fenestration: Any opening or arrangement of openings for the admission of daylight, including any devices in the immediate proximity of the opening that affect distribution.

Fixture: The housing for a light source, usually providing attachment to the building, housing for the ballast and lamps, and connection to the power source.

Footcandle (fc): A unit of illuminance. One footcandle equals one lumen per square foot (or the illuminance produced on a surface all points of which are one foot from a directionally uniform point source of one candela).

$$1 fc = 10.76\ lux = 10.76 \frac{lumens}{m^2}$$

Glazing Efficacy (GE): The measurement of the ability of the glazing material to transmit visible light, in relation to the amount of solar heat it admits into the building. Glazing efficacy is the visible light transmittance divided by the shading coefficient. Glazing efficacy is the same as the coolness index (CI).

High intensity discharge (HID) lamp: electric discharge type lamps that include metal halide, high pressure sodium, and mercury vapor lamps.

High performance glazing: Typically defined as glazing with T_{vis} > SHGC (glazing efficacy >1).

Illuminance: The density of the luminous flux incident on a surface, expressed in units of footcandles (or lux).

Integral curb: The attachment between the roof and the skylight frame (curb) is pre-manufactured as part of the skylight frame, typically of the same materials as the frame.

Lighting power density (LPD): A measure of the amount of electric lighting installed in a building. Expressed as the number of Watts of lighting power required for the luminaires and lamps installed in a building, divided by the gross number of square feet in the building (Watts/square foot). Also known as unit power density.

Light-to-Solar Gain Ratio (LSG): The ratio of visible light transmittance to solar heat gain coefficient for a glazing assembly. The ratio of the fraction of light transmitted to the fraction of solar heat gain transmitted through a glazing assembly.

Low emissivity (Low-e) coating: a coating applied to glazing that selectively transmits short wave radiation (such as light) but reflects long wave (infrared) radiation. Lower heat losses and lower U-values result from applying low-e coatings to glazing.

Lumen: The luminous flux emitted within a unit solid angle by a point source having a uniform luminous intensity of one candela.

Luminaire: A complete lighting unit consisting of a lamp, or lamps, together with parts designed to distribute the light, to position and protect the lamps, and to connect the lamps to the power supply.

Luminous efficacy (LE): A measure of the luminous efficiency of a radiant flux, expressed in lumens per watt. For daylighting, this is the ratio of visible flux incident on a surface divided by radiant flux on that surface. For electric sources, it is the ratio of the total luminous flux emitted divided by the total lamp or luminaire power input.

Photosensor controls: lighting control system that adjusts the electric lighting power in response to the amount of interior light or ambient daylight available.

Skylight efficacy (SE): The measurement of a skylight system's ability to transmit visible light, in relation to the amount of solar heat it admits into the building. The product of the Light-to-Solar Gain Ratio (LSG) and the Well Factor (WF).

Skylight-to-Floor Ratio (SFR): The ratio of gross skylight opening area to daylit floor area.

Solar altitude: The vertical angular distance of the sun in the sky above the horizon.

Solar azimuth: The horizontal angular distance between the vertical plane containing the sun and true south.

Solar Heat Gain Coefficient (SHGC): The fraction of solar radiation admitted through a glazing assembly; the sum of the transmitted solar energy plus that portion of the absorbed solar energy which flows inward.

Solar transmittance: The transmittance of a glazing material or skylight assembly over the complete solar spectrum.

Specular reflective surface: A surface characterized by the reflectance of light rays striking and leaving the surface at equal angles.

Task lighting: lighting provided to a local area to provide sufficient illumination for specific work task, such as a desk lamp, overhead lighting at shelves, or portable lamps for industrial tasks. Usually paired with ambient lighting, providing a lower level of general illumination.

Unit power density: see lighting power density.

U-value: A measure of a material's heat transfer capabilities when placed between two spaces of different temperatures, typically given in BTU/hr•ft2 •°F. The U-value is the inverse of the R-value, which measures the material's resistance to heat transfer.

Visible transmittance (VT): The transmittance of a particular glazing material or skylight assembly over the visible portion of the solar spectrum.

Well Factor (WF): The ratio of the amount of visible light leaving a skylight well to the amount of visible light entering the skylight. (See Section 3.3)

Well Cavity Ratio (WCR): A parameter used to determine the light well factor. Well cavity ratio is a measure of the geometric shape of the well, and is calculated as follows:

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

A light well with proportions of a cube always has a well cavity ratio of 10. (See Chapter 3 for more information)

Abbreviations

DG: Double glazing

EA: Effective aperture

fc: Foot candle

kWh: Kilowatt-hour

LE: Luminous efficacy

lm: Lumen

lm/W: Lumens per Watt

LPD: Lighting power density

LSG: Light-to-Solar Gain Ratio

R: Reflectance

R-#: R-value, thermal resistance of a material

SE: Skylight efficacy

SF: Square feet

SHGC: Solar Heat Gain Coefficient

SFR: Skylight-to-floor ratio

SG: Single glazing

Tvis: Visible transmittance

U-#: U-value

VDT: Visual display terminal

VT: Visible transmittance

WF: Well Factor

WCR: Well Cavity Ratio

W/sf: Watts per square foot

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