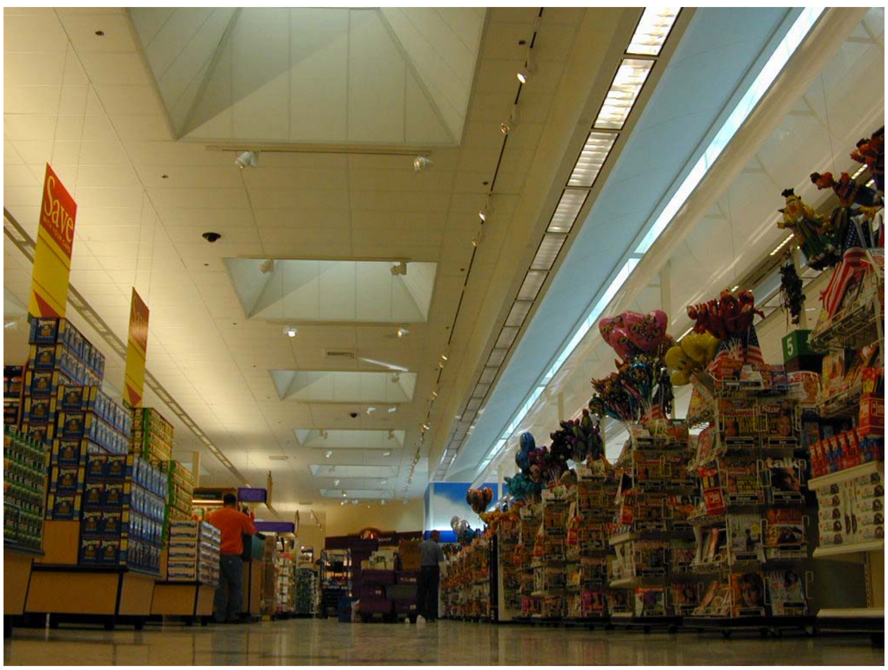
CALIFORNIA ENERGY COMMISSION

Modular Skylight Wells: Design Guidelines for Skylights with Suspended Ceilings



DESIGN GUIDELINES

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CALIFORNIA ENERGY COMMISSION

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Preface

The California Energy Commission's (Commission) Public Interest Energy Research (PIER) program supports research that will bring affordable and energy efficient products to the marketplace. In fulfillment of this PIER objective, the *Design Guidelines for Skylights with Suspended Ceilings* (Design Guidelines) aims to energize the market for modular skylight well systems. It provides guidelines for manufacturers, designers and contractors in the development and design of skylight well products for suspended ceilings. These guidelines describe a step-by-step process for designing modular skylight wells, along with a glossary of technical terms and list of acronyms (listed in Appendix 1).

The Design Guidelines address the main building types that are likely to benefit from skylight wells in either new or retrofit construction, such as those low-rise offices, retail stores and schools that use suspended ceiling systems. In addition, these Guidelines are limited to addressing only those buildings that meet the following criteria:

- Flat or low-slope roofs
- Ceilings not part of a fire rated assembly
- Unit skylights not exceeding 8' width or length
- Ceiling height between 9' and 15'

This document is produced as a public nonproprietary product and is not targeted to a specific construction method or a particular manufacturer. It only discusses requirements of components and connections related to the skylight and skylight well system and not of adjacent systems, such as the roof assembly or suspended ceilings.

The Buildings Program Area within the Public Interest Energy Research (PIER) Program produced this document as part of a multi-project programmatic contract (#400-99-413). The Buildings Program includes new and existing buildings in both the residential and the nonresidential sectors. The program seeks to decrease building energy use through research that will develop or improve energy-efficient technologies, strategies, tools, and building performance evaluation methods.

This document is part of report #P500-03-082 (Attachment A-13 Product 5.4.6-b). For other reports or to obtain more information on the PIER Program, please visit www.energy.ca.gov/pier/buildings or contact the Commission's Publications Unit at 916-654-5200. The Design Guide is also available at www.newbuildings.org

Abstract

The *Design Guidelines for Skylights with Suspended Ceilings* (Design Guidelines) provides a step-by-step guide to designing skylights with suspended ceilings in low-rise commercial buildings. This design assistance can serve as an essential design tool for architects, engineers and other designers, and provide valuable information to manufacturers in the skylight and suspended ceiling industries. The Design Guidelines form a part of the "Integrated Design of Commercial Building Ceiling Systems" study and follows a PIER research report "Modular Skylight Wells for Suspended Ceilings Research" (product 5.4.6b, produced within the same contract as these Guidelines) that summarized the issues in current building practices for skylit buildings with suspended ceilings. The Design Guidelines introduce the concept of modular skylight wells that can be pre-manufactured, are easy to install and replicate, and can gracefully integrate skylights with other building components. Designers can benefit from information contained in these guidelines about the steps in the skylight design process, implications of different design solutions, and codes and performance-related issues. Manufacturers can benefit from market information, nomenclature and definitions, product components' requirements and codes and performance metrics for product evaluation. Skylights in conjunction with suspended ceilings have a potential market of 16.5 million square feet (sf) added each year in California and 120.8 million square feet nation wide. In California, this 16.5 million sf of buildings with skylights and suspended ceilings would save $3.2 million/yr in energy costs. After ten years, the savings from 165 million sf of skylit buildings would result in $32 million/yr of energy cost savings.

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Keywords: Skylights, Daylighting Design Guide, Lightwell, Modular Skylights, Suspended Ceiling, Integrated Ceiling Design, T-Bar Ceiling, Dropped Ceiling, Energy Savings,

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Overview

The Design Guidelines for Skylights with Suspended Ceilings aims to address two audiences: the architects, engineers, designers and project managers who are involved in constructing new buildings that might use skylights, and the manufacturers who produce the various products involved in skylights, skylight wells, lighting control systems, suspended ceiling grids and tiles.

The Design Guidelines aim is to provide designers and project managers with guidelines for incorporating skylights with light wells in commercial buildings that utilize modular suspended ceilings, also called T-bar ceilings, hung ceilings or dropped ceilings. It discusses the design process, implications of different design solutions, and codes and performance-related issues. Designers can use the information to create a custom system for their project in today's market, and they can utilize the coordination and integration information to facilitate work with other construction professionals.

The Design Guidelines' parallel purpose is to jumpstart the modular skylight systems industry by providing product manufacturers with market information, nomenclature and definitions, product components' requirements, and codes and performance metrics for product evaluation. Across the United States, there is a market of 120.8 million square feet per year of new floor space that could readily be constructed with skylights in conjunction with suspended ceilings. California's share of this potential market is 16.5 million sf/yr. If photocontrols are used to reduce electric lighting energy whenever there is sufficient daylight from skylights, this would result in approximately $3.2 million/yr of electricity savings in California alone.

The solutions presented here are based on research results, as well as input from industry members and architects and designers who have installed or designed skylight wells with suspended ceilings.

The recommendations of these Design Guidelines are intended to help support the effective installation of skylight systems that will provide both optimal energy performance and superior lighting quality.

A Case for Skylights and Suspended Ceilings

WHY USE SKYLIGHTS?

"No space, architecturally, is a space unless it has natural light."

- Louis Kahn, architect

Skylights introduce daylight into buildings and provide both excellent lighting quality and more beautiful interior spaces. Skylights bring functional benefits as well. In commercial building applications, the use of skylights combined with photocontrols that reduce electric lighting use can result in substantial energy savings. Daylight provides a highly reliable lighting source, increasing building safety and reducing business risk. There is increasing evidence of a link between daylight and improved productivity, as evidenced in increased retail sales and improved student performance. Skylighting is being successfully applied to a wide range of everyday buildings that also use suspended ceilings, such as schools, offices and retail stores.

Figure 1. Skylight application in an office

Better Light Quality

The most obvious benefit of a skylight is its ability to introduce daylight into interior spaces. Daylight is often considered the highest quality lighting source, flicker-free and with excellent color rendering qualities that are essential to commercial building occupants. Good skylight design will provide a high uniformity of illumination levels throughout a space, while also introducing visual interest via variation in the appearance of the space over the course of a day and a season.

In retail applications, good color rendering is important for accurate product representation, vital to those retail sectors that require customers to choose colors of items such as paints or cosmetics. Better color choices can result in higher customer satisfaction and fewer returns.

In office environments, a properly designed skylit space can provide excellent lighting conditions, potentially improving employee morale and reducing task-related errors (LRC, 1996). In one study of a daylight office building, the floors with skylights had by far the highest rating of employee satisfaction. In schools, a skylit classroom can provide a natural and stimulating environment for teaching and learning.

Figure 2. Grocery store with skylights.[1]

Energy Savings

Skylights produce whole-building energy savings by reducing the need for electric lighting during the day and also by reducing the need for cooling to counter the heat gain from those electric lights. To achieve energy savings with skylights, the electric lights must be turned off or dimmed down during daylight hours, which is best done automatically by photocontrols that sense ambient light levels and adjust electric light levels accordingly. The skylights must also be appropriately sized to provide optimum lighting conditions while avoiding excessive heat loss or heat gain. Figure 2 shows a skylit grocery story where only one fluorescent lamp has been left burning in the center of the pendant light fixture, while the two outer lamps on either side have been switched off. The single, center lamp is unnecessary for adequate illumination, but provides customers with some assurance that the store is open and the electric lights are working as expected.

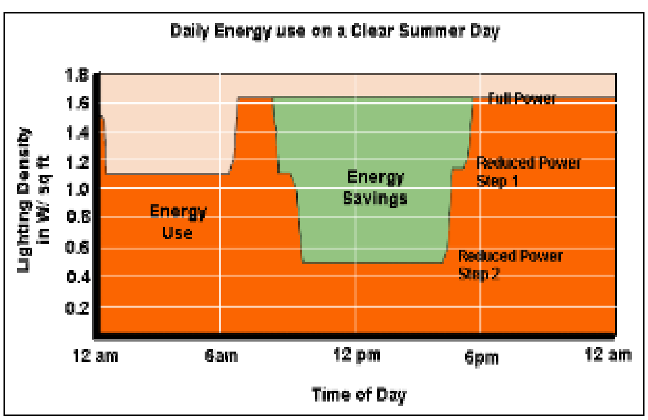

Figure 3. Monitored energy savings of a grocery store.

In a case study of a grocery store in Valencia, CA, (PG&E 1999), the use of skylights combined with daylighting controls resulted in a 30% decrease in lighting energy use over the monitored two week period. Figure 3 illustrates the light energy profile during each hour of the day and shows that electric

[1] PG&E. 1999*: Daylighting Initiative: Retail Applications.* See Reference section.

light use was decreased by two-thirds during peak daytime hours.

Figure 4 illustrates the potential energy cost savings from installing skylights in 100% of the five targeted building types, considering only those spaces that are directly under a roof, that have T-bar ceilings and for which skylights are likely to be feasible. This table shows that one year's worth of new and retrofit construction could save California ratepayers approximately $3.2 million, or after accumulating ten years of additional skylit space the ratepayers would be saving $32 million per year. The building areas available for this application are discussed further in the Market Potential section below, and the calculation procedure is detailed in the report "Modular Skylight Well for Suspended Ceilings Research" (HMGa 2003).

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

Figure 4. Energy cost savings potential from one year's new/retrofit construction for five selected building types in California.[2]

Student Performance Increase

The daylight provided by skylights has also been associated with higher test scores in schools. A study funded by PG&E surveyed the performance of students of three elementary school districts in Seattle, Washington; Fort Collins, Colorado; and Capistrano, California. Standardized test scores were used as the measure of student performance. In all three districts, and controlling for other influences on learning, those students in classrooms with more daylight tested higher or progressed faster (HMGa 1999). In a follow-on study funded by the California Energy Commission, the researchers refined the analysis methodology looking closer at just the Capistrano district, where they found that students with the most daylighting in their classrooms progressed 21% faster on math and reading tests compared to those in classrooms with no daylight (HMG 2001).

Sales Increase

In big-box retail stores, skylights have been associated with increased sales. A prototype Wal-Mart store in Lawrence, Kansas, was outfitted with skylights over one-half of the sales area. Analysis of sales data showed that products located under the skylit areas had significantly higher sales than the products sold in the non-daylit areas of the store (Pierson 1995). Wal-Mart has subsequently chosen to install skylights in all of its major store sites.

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[2] Calculations based on CBECS data of Energy Information Administration. See References

The Skylighting and Retail Sales study (HMGb 1999) completed in 1999 by the Heschong Mahone Group for PG&E (on behalf of the California Board for Energy Efficiency) found a compelling statistical correlation between the presence of skylighting in a chain retail store and higher sales for those stores. This study involved a survey of 108 retail stores of which two-thirds were daylit with skylights. The study controlled for twelve other influences on sales and showed that, all other things being equal, those stores with skylights experienced 40% higher sales than those without skylights. Another study funded by the California Energy Commission (HMGb 2003) surveyed a different chain with 73 store locations in California, of which 24 stores had a significant amount of daylight illumination, provided primarily by diffusing skylights. This study controlled for over thirty other influences on sales, and found that increased daylight was associated with up to a 6% average increase in sales for the daylit stores overall.

A Growing Demand for Daylight

With growing recognition of the benefits of daylight, there is an increasing demand for the incorporation of daylight into everyday buildings. More and more retailers are starting to include skylights in their stores. Educators are looking for ways to bring daylight into classrooms. Office building owners increasingly believe that the provision of daylit workplaces is likely to increase the value of their buildings. This demand for daylight will increase the usage of skylights in all building types.

WHY USE SUSPENDED CEILINGS?

Suspended ceilings are widely used in commercial buildings because they can solve many architectural needs with a simple modular system. They create a ceiling with a clean, uniform appearance and a regular grid for attachment of necessary lighting, heating, fire suppression and other building equipment. The lightweight, detachable ceiling tiles are typically designed to improve light distribution and sound absorption, while simultaneously meeting the safety requirements for buildings. The modular nature of the suspended ceiling system increases building flexibility by allowing easy changes to all of these building systems. Because of regular tenant changeovers, office and retail spaces benefit from this flexibility. Retail, school and office spaces likewise benefit from the improved acoustic control. With so many positive attributes, suspended ceiling systems are often considered the preferred solution in many commercial building environments.

Organizing the Ceiling

The inhabited interior space of buildings requires the provision of many services and functions that all compete for space. Ceiling systems may be penetrated by heating and cooling vents, luminaires, fire sprinklers, audio speakers, structural members, and any number of other electrical, mechanical, plumbing or structural systems. A suspended ceiling, typically with a system of metal T-bar runners that create a grid of structural support, provides an organizing system for the location and attachment of all these other building systems. A two feet modular system, typically 2’ x 2’ or 2’ x 4’, provides sufficient space for the many building systems that compete for ceiling real estate.

Source: www.armstrong.com

Figure 5. Suspended ceiling in an office.

Flexibility

Office and retail spaces experience regular tenant turnovers and often require changes in space layout and building systems. Fixed ceiling solutions, such as gypsum board construction on studs, require extensive work and material replacements to accommodate the constant change in space requirements, lighting layouts and air duct locations. A suspended ceiling system allows for easy access to the electrical, HVAC (heating, ventilation and air conditioning) and plumbing equipment above the ceiling, while the modular nature of the ceiling grid and panels allow easy, less expensive relocation of equipment.

Lighting and Heating

Suspended ceilings are often selected to improve lighting and heating conditions in a space. By reducing the effective volume of a space by lowering the ceiling, the amount of air that must be heated or cooled is reduced, and the ventilation delivery system is brought down closer to the inhabitants. Likewise, in designing a lighting system, reducing the volume of the space will often improve the efficiency of the lighting system. This is achieved both by effectively lowering ceiling height and bringing the lighting fixtures down closer to the task, and by providing a continuous light-reflective surface via white or light colored ceiling tiles.

Acoustic Absorption

Suspended ceilings typically use acoustic tiles, which are designed to increase absorption of sound. Acoustic qualities of ceilings are especially important in school and work environments. Recognizing that good acoustics is indispensable for verbal learning, a new ANSI (American National Standards Institute) standard for classrooms was issued that has strict acoustic specifications for educational spaces (ANSI 2002). This standard limits the reverberation time in classrooms, and will increase the need for high quality sound-absorbing surfaces in classrooms.

In office environments, acoustics also affect the workspace. Noise in the environment negatively affects worker concentration and comfort. Direct research on 13,000 workplace users (BOSTI 2001) estimated a three percent increase in productivity from improved workplace design, with "ability to do distraction-free work" the top design issue—primarily linked to noise.

Concealing Plenum Spaces

Aesthetics is an important design issue in offices, high-end retail stores and classrooms. An exposed ceiling solution requires coordinated design of the mechanical ducts and other equipment to produce an organized appearance. A suspended ceiling system allows the designer to conceal the plenum without resorting to a more extensive design and coordination process and the need to provide a finished appearance for utilitarian equipment. While exposed ceilings are often considered to be less expensive than suspended ceilings, this is not always the case.

In a suburban office case study in Sacramento built in 2001, an exposed ceiling design would have cost an additional $0.40 - $0.60 per square foot more than a suspended ceiling installation because of the additional duct design work and finishing costs. Thus, removing suspended ceilings can both raise construction costs and sacrifice the flexibility, aesthetic and acoustic benefits associated with suspended ceilings.

MARKET POTENTIAL ANALYSIS

The previous discussion of the independent advantages of skylights and suspended ceilings suggests that there is a need for a system that will facilitate the use of the two systems together. In the analysis below, we quantify the probable market demand for such a system, within the most applicable building types. This information on market potential is especially valuable for manufacturers of skylights or ceiling systems interested in expanding their market share in the building industry.

Skylight Market Potential

The potential market for modular skylight well products includes building types that can take advantage of skylight design and that require the use of suspended ceiling systems. These are typically low-rise commercial buildings, such as offices, retail spaces, grocery stores and schools. Together these four building types make up 54% of all new and retrofit construction square footage in California (see Figure 6). With an estimated annual commercial construction volume of 156.5 million square feet (sf) per year in California (Brooks 2002), these occupancies account for approximately 84.8 million sf of new construction. The U.S. national construction volume is estimated at 1,109 million sf annually. Educational, retail and office spaces make up 543 million sf, or 49% of the total construction volume nationwide (EIA 1999). See Appendix 2 for average national annual construction.

The market size for skylights can be determined by the amount of floor area that can be installed with skylights; that is, area that is directly under a roof. Calculations based on the Commercial Building Energy Consumption Survey (EIA 1999) suggest that 68% of all existing non-residential floor space is directly below a roof, as shown in Figure 7. This means that 68% of commercial floor area could potentially be installed with skylights. With national new construction of office, retail and educational space at 543 million sf a year, the potential market for skylight installations is 369 million sf of floor area annually.

Suspended Ceiling Market Potential

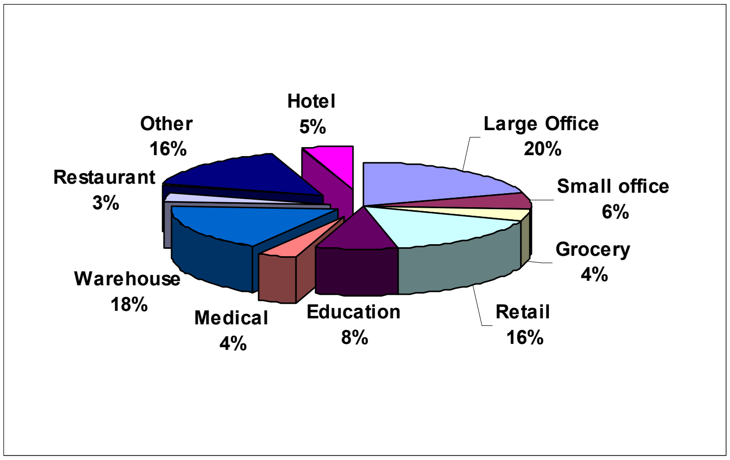

Figure 6. Annual new and retrofit construction in California by building type

The suspended ceiling system is widely used in the commercial building sector. According to a study conducted by Armstrong World Industries in 2002, suspended ceiling systems are installed in:

- 68% of all educational facility floor space
- 45% of all office floor space
- 46% of all store floor space

Floors	Total Area (Million SF/yr)	Fraction of Total	Area Under Roof (Million SF/yr)	Fraction Under Roof
One	563	51%	563	51%
Two	266	24%	133	12%
Three	97	9%	32	3%
4 to 9	132	12%	22	2%
> 9	51	5%	3	0%
Total	**1,109**	**100%**	**754**	**68%**

Figure 7. New construction floor area under roof in the United States (annual average from 1990 to 1999).[3]

[3] Calculations based on Table B13 of CBECS database. See Reference section.

Applying the percentage of floor areas with suspended ceilings by building types reveals that there is approximately 121 million sf of commercial space (see calculations in Appendix 2) built every year in the United States that could potentially benefit from integrating skylights with suspended ceilings, and 16.5 million sf in California alone (see Figure 4).

Developing a New Product

Given the growing demand for daylight in buildings, and given the pervasive use of suspended ceilings, there is likely to be a growing demand for systems that facilitate the marriage of these two systems. A modular skylight well system that simplifies the incorporation of skylights into buildings with suspended ceilings will increase the opportunities for building design with both skylights and suspended ceilings. Without such a system, building owners and designers are likely to choose one or the other to avoid the extra cost of custom design and fabrication.

A modular skylight well that easily and efficiently connects a skylight to a suspended ceiling system is essentially a new product that has not had a clear presence in the construction industry. While there are currently a few commercially available products that might be considered “modular skylight wells” they remain something of orphans within the formal structure of the construction industry. Skylight wells are not addressed in construction manuals or given a number in the CSI (Construction Specification Institute) specification system. There is not a common terminology to discuss the product and its performance. There is not a shared understanding of product performance criteria and manufacturer responsibilities. The rest of this chapter looks at some of the challenges and opportunities of creating such a product and integrating it into the larger context of the commercial building industry.

Product Delivery Options

Manufacturers interested in entering the market for modular skylight wells have different options for product delivery: fabricating only one or two components of the system and integrating with other manufacturers providing other components, or providing the whole modular well system as a kit. Each option has advantages and disadvantages, for both the manufacturer and the consumer, as shown in Figure 8.

	Multiple Manufacturers	**Single Manufacturer**
Description	Different manufacturers will supply the unit skylights and light well components.	One single manufacturer will supply all components associated with a skylight well system as a kit.
Advantages	• Manufacturers can use existing manufacturing expertise and equipment, without having to expand their manufacturing capabilities • Consumers can have multiple sources of interchangeable parts • Consumers can have choice of different solutions • Competition among component suppliers is promoted	• Responsibility and liability rests with one party • Less coordination is required between different manufacturers • Connections between components can be better designed or even be completely eliminated • Manufacturers can differentiate products • An integrated system supplied by a single manufacturer will be more cost-effective
Disadvantages	• No single point of responsibility and liability exists for consumers • Industry standards for connectors are required to allow components from different manufacturers to fit together seamlessly • More coordination work is required during construction • Greater uncertainty exists in the assembled product's overall performance	• Suppliers must expand their manufacturing capabilities beyond their current expertise • Consumers must buy proprietary systems from a single supplier

Figure 8. Advantages and disadvantages of product delivery options.

CURRENT BUILDING PRACTICE

Information on current building practice and needs were gathered from case studies on existing buildings with integrated skylight wells, and from a series of meetings conducted with various industry representatives to understand their needs in a modular skylight well market. Participants included architects, lighting designers and manufacturers of skylights and suspended ceiling systems.

The case studies consisted of twenty existing projects that have integrated skylight installations with a suspended ceiling system (HMGa 2003). Evaluations were based on plan reviews, site visits and interviews with architects and construction managers.

These interactions with industry representatives demonstrated a demand in the building industry for definition of a modular skylight well product or, alternatively, a shared understanding of product terminology, performance criteria and assembly standards.

Current Application Issues

Applications of skylight wells with suspended ceilings were found in both new and retrofit construction projects, including classrooms, grocery stores, big-box retailers and office buildings.

The existing systems were found to be mostly custom-designed and site-built systems. Designers used a variety of systems to guide the daylight through the plenum and to make a finished appearance at the ceiling. Most site-built systems used some combination of a reflective vertical “throat” element to direct light through the plenum and a “splay” which widened the opening at the ceiling, allowing the daylight to spread out farther and providing a finished appearance. The advantages of a splay for skylight wells in a suspended ceiling are discussed in the Section “Advantages of Splays in Light Wells” in Chapter 2. Many different materials were chosen for shaping these two elements, most commonly including gypsum board, sheet metal, and ceiling tiles. In addition, designers included a variety of accessories to improve the lighting and energy performance of the system.

The only pre-manufactured systems observed were tubular skylight systems, where a skylight is combined with a sheet-metal tubular-shaped light well that can adjust to various angles and lengths, and which culminates in a light diffuser mounted at the ceiling plane. Originally developed to fit easily into the 12” or 16” rafter spacing of residential wood construction, tubular skylights have recently been expanding into the commercial building market with ever larger and more sophisticated products. However, even using the largest of the available systems, the tubular skylights observed were substantially smaller than the site-built systems, and did not incorporate a splay. As a result, for the same space, many more tubular skylights are needed to provide the same amount of useful daylight. (While pre-manufactured tubular skylights could potentially be used in conjunction with a splay at the ceiling, no such applications were observed in the case studies.)

Architects and construction managers of the case studies gave extensive information on their experience with the design and construction process. They reported many problems with existing applications. Some of their key challenges, problems and design issues are summarized below.

Quality Control

Site-built systems require on-site modification of components. The use of manual techniques can result in inconsistent workmanship which may compromise the aesthetics of the space, or in the worst case, the safety of occupants.

Figure 9 and Figure 10 illustrate a few detailing inconsistencies found in one case study of a grocery store. A suspended ceiling system was used for the skylight splay construction. Due to the lack of prefabricated splay components, both ceiling tiles and metal grid members had to be cut and bent on-site. Fit of the ceiling tiles into angled shapes was not always perfect, leaving unsightly gaps. Lack of coordination between placement of wells and the structural system resulted in ad hoc detailing as structural columns penetrated angled light well members.

Figure 9. Column going through light well splay.

Figure 10. Ill-fitting acoustic panels in light well splay.

Performance Uncertainty

The skylight well should essentially be considered a part of the lighting system of the building, providing daylight through out a space. However, the light distribution from a custom-built skylight well assembly will currently be an educated guess, at best. The electric lighting industry is mature, with fixtures and luminaires mass-produced in factories with highly consistent quality control. The industry currently provides standardized photometric reports with detailed information on the distribution of light from the fixture in different applications. This information allows designers to select luminaires by their performance and accurately predict the resulting illumination patterns in the space being designed.

Meanwhile, the distribution light from skylights and skylight well systems can only be estimated based on relatively crude calculations. The development of photometric profiles for various unit skylight products is a first step in this direction of improving the accurate prediction of illumination patterns from skylight systems (McHugh et al, 2002). However, the current variability of skylight well systems adds a great deal of uncertainty about the final illumination performance of any skylight installation. Skylights also inherently produce varied illumination levels and heat flows with changes in the climate and solar position. There is not currently an industry standard for comparing the performance of skylight systems under different climatic conditions.

Both skylight and ceiling system industry representatives stressed a need for standards of performance. If they are going to sell modular skylight well systems as part of the lighting system of a building, they need to be able to make accurate predictions about the performance of their system that can be compared to similar statements by their competitors. Prefabricated systems that can be tested according to objective standards will enable specifiers to choose between systems based on performance, and allow manufacturers to compete based on quality of performance rather than just cost.

Maintenance Problems

Maintenance problems resulting from the use of custom parts were also frequently reported. While most ceiling tiles and grid components are standardized and can kept in stock for occasional repair work, any special parts required for a skylight well are unlikely to be kept in stock. If they must be special ordered or re-cut or re-bent, repairs will be delayed. Any delay in maintenance and repair is especially a critical issue in retail applications, where sales floor repair timetables are counted in hours, not days or weeks.

Higher Cost

Some construction managers reported that they would like to see approximately 50% reduction in cost and the availability of a "kit of parts" skylight system to ease installation. One retail case study evaluated different methods of incorporating skylights with a suspended ceiling and found the available options quite expensive (HMGa 2003). While material costs of site-built light wells may be less than for a pre-manufactured skylight well system, labor costs for installation are likely to be much higher.

A custom-designed system necessitates a longer design schedule due to increased coordination work among architects and engineers. In a site-built system, there will also be a longer construction schedule due to on-site cutting, adjustments and installation coordination issues. These additional costs become especially critical for building types that are commonly replicated over and over again, such as chain retail stores, classrooms and speculative office buildings. Thus, in order to reach the target market for this product, a prefabricated system is likely to be a necessary precondition for success.

The Need for Modular Light Wells

The case studies show an evolving demand in the building industry that should be addressed. Many of the problems associated with the current method of custom designing and building skylight wells can be resolved through the use of prefabricated systems. Among the retailers interviewed, one is currently considering using skylights but is uncertain about how to specify light wells that are compatible with suspended ceilings. Two other retailers commonly use skylights and prefer to avoid the use of suspended ceilings. When they acquire a store with suspended ceilings, they do not include skylights in the store design. A major big-box retailer is currently testing a few prototype buildings that integrate skylights with suspended ceilings but has not been trying it on a wider-scale because of lack of a solution coordinated with other building systems like HVAC, sprinklers, etc. All of these major retailers would appreciate a prefabricated system to meet their desire to bring daylight into their stores with prefabricated ceilings. Likewise, school architects and office building owners would like to have a system that could facilitate the incorporation of daylight into their buildings. Architects interviewed expressed a preference for a modular system that would provide guaranteed performance and reduce their design and specification time by constraining the range of choices to a few variations. Their preference was for a modular well system that they could learn about and specify via the same information channels that they follow for all other construction products.

Most of the problems that are associated with the current practice of custom design and site fabrication, such as additional costs, difficulty of quality control, performance uncertainty and difficulty in maintenance, could all be resolved with development of prefabricated, modular systems. These Guidelines are intended to be a first step in that direction. Many more steps will be required from all the interested parties in order to make a successful market for this new construction product a reality.

Proposed Code Changes in California

The market for skylights is likely to be greatly affected by revisions that have been proposed for the 2005 California Energy Code (Title 24). The most notable change that will impact the industry is the proposal to establish skylights as a prescriptive measure (see glossary for definition) for low-rise nonresidential buildings with spaces larger than 25,000 sf directly under a roof and a ceiling height greater than 15' (CEC 2003). For these buildings, at least one-half of the space is required to be daylit with skylights and photocontrols or, alternatively, an energy efficiency measure that saves a similar amount of energy must be installed. The code also places a prescriptive upper limit on Skylight to Floor Ratio (SFR) of 5% for all buildings, except atriums greater than 55' high.

Since the proposed requirement for skylights is in spaces with ceiling heights greater than 15', only a few buildings with suspended ceilings will be directly affect by the code requirements. However, these code requirements for tall spaces may change the expectations of building owners for low-rise buildings.

The standards will also mandate automatic light controls for skylit spaces greater than 2,500 sf. These controls must have two or more steps or be capable of continuous dimming.

CRITERIA FOR A MODULAR SKYLIGHT WELL SYSTEM

The discussion in the chapter above presents the need for a modular skylight well system that will facilitate the use of skylights with suspended ceilings. The following chapters describe the components of such a system and how such a product would fit into the normal building design process. The solutions developed as part of these Guidelines attempt to meet some very real construction challenges and limitations.

Once the need for a product has been understood and the market potential quantified, the next step is to establish the performance criteria for this new product, and what other limitations may constrain its final form. Some of the most important criteria used in evaluating options for skylight well systems are summarized below:

Lighting Quality: Since the primary purpose of a skylight is to provide useful light in the workspace below, the quality of the light provided is key. Daylight from skylights should meet all the same basic criteria for lighting quality as electric lighting systems. Chapter 10 in the Handbook of the Illuminating Engineering Society (9^{th} edition) provides the industry summary of lighting quality issues for various space types. Provision of adequate and uniform illumination through out the space, while minimizing glare sources, is the prime design criteria. Skylight wells should be designed to create gentle variation in brightness among the various surfaces in the room to glare from excessive contrast between very bright and dark adjacent surfaces.

Energy Savings: A skylighting system can pay for itself in energy savings alone. However, energy savings are only possible if the electric lights in the building are turned off or dimmed when sufficient daylight is present. Thus, automatic lighting controls, guided by a photosensor, are an essential component of a skylighting system. In addition, in order to be cost effective, the skylight system needs to optimize useful daylight while minimizing negative impacts on the heating and cooling needs of the building. Thus, the efficiency of the design becomes a driving issue.

Dimensional Adjustments: Skylight wells penetrate vertically through many horizontal building systems. They must connect between a skylight opening, whose position is determined primarily by the structural grid of the roof, and an opening at the finish ceiling, which follows an entirely different grid. In the space between, the position of the skylight well needs to avoid conflict with other building systems, like heating ducts.

Skylight wells typically need to be able to accommodate adjustments of up to one foot in any direction horizontally, two to four feet vertically, angular adjustments to connect a perfectly level ceiling to a slightly sloped roof (up to a 2:12 slope), and construction tolerances of an inch or two to resolve any inconsistencies in final surface locations.

Construction Coordination: Skylight wells are a new element in the design and construction process, and it is important that all professions and trades involved in the building be aware of the position of the skylight well and protect it throughout construction. Installation of skylight well components needs to work well with normal construction schedules, so that, for example, the building is fully waterproofed early on and finish surfaces are not damaged during rough construction. Information about skylight wells needs to fit into the normal communication channels developed by the construction industry.

Safety and Verified Performance: A skylight well system has to maintain the building safety standards, as exemplified in all the various codes and standards which apply to structural, plenum and finish materials. Skylight well components may need to be tested by third party laboratories in order to verify both safety and other performance criteria.

A Throat and Splay System: The systems described in these Guidelines were developed around the concept of a two-part light well system, using a throat and a splay. The throat is the upper part of the well, connecting to the underside of the skylight. The primary purpose of the throat is to channel light as efficiently as possible downward through the plenum. The splay is the lower part of the well, connecting to the ceiling. The primary purpose of the splay is to improve the efficiency of the distribution of light in the space and improve overall lighting quality for the occupants. A splay may improve the cost effectiveness of a skylighting system by allowing the use of fewer and larger skylights within a space for the same given illumination levels and energy savings.

The throat and splay concept increases the flexibility of the system and potentially reduces other construction conflicts. Together, the throat and splay can allow dimensional adjustments between the various structural and ceiling grids. They can also allow the various skylight well elements to be installed in phases in order to avoid scheduling conflicts with other building systems. The connection between the throat and splay can allow resolution of final construction tolerances. All of the components of a throat and splay skylight well could be manufactured by different companies or by the same company. A system of interconnecting and adjustable modular parts is likely to provide the greatest range of design options while reducing handling and installation costs. The concept of a two-part skylight well system, with throat and splay, seems to offer great potential for accelerating the development of a pre-manufactured modular skylight well system.

Nomenclature and Functions

This section defines the basic components of a modular skylight well and establishes the terminology used throughout the rest of the document. The purpose and specific characteristics of each component are discussed in more details in section "COMPONENT REQUIREMENTS." The skylight well system refers to the set of components necessary to deliver daylight from the exterior, through the plenum space, into the building interior. Two important components of light well are: the throat and the splay. Both serve as conveyances of daylight from the skylight to the interior space. The skylight well system encompasses the following components:

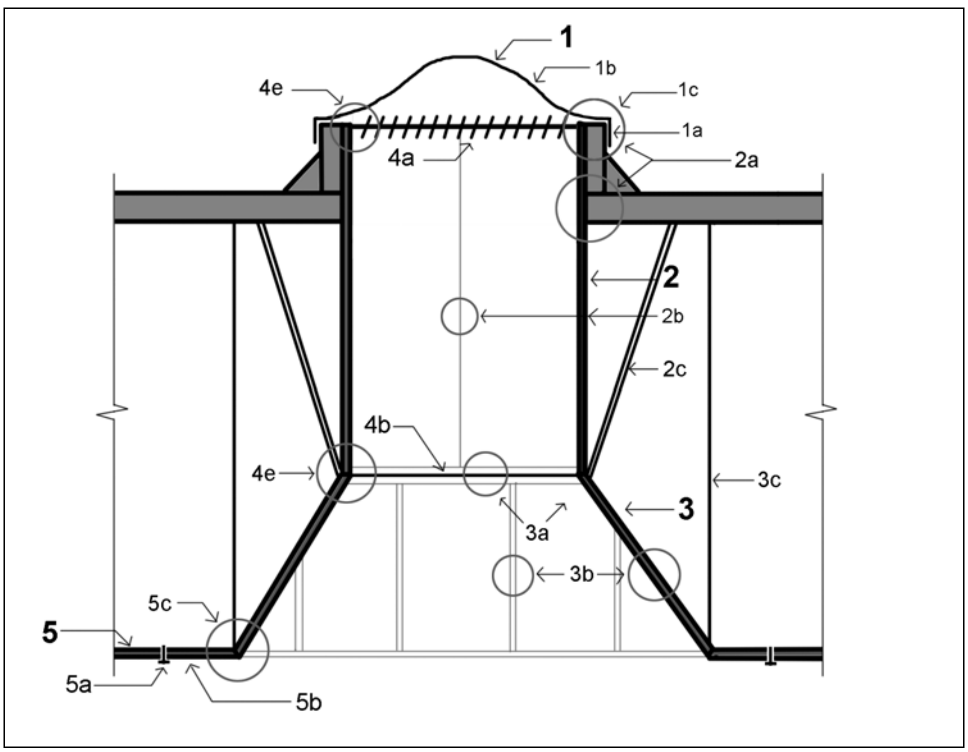

Figure 11. Section of skylight well (refer to text for definitions).

1. Skylight

A skylight is a glazed opening in a roof that admits light. It encompasses the following sub-components:

1a. Frame

The skylight frame is the structural frame supporting the glazing of the skylight. It includes the condensation gutters, seals and gaskets necessary for its installation.

1b. Glazing

The glazing refers to the glass or plastic lenses used to cover the skylight opening.

1c. Skylight-Curb Connector

The skylight-curb connector is the interface between the skylight frame and the rooftop curb. It includes all accessories required for the proper attachment of the skylight, such as fasteners and flashing.

2. Throat

The throat is a vertical component (can be rectangular or circular in section) connecting the skylight to the splay or ceiling. In the absence of a splay, it is attached directly to the ceiling plane. The throat surface can be of any material that is reflective, flexible and easy to install (described in detail in section "Component Requirements"). The throat is comprised of the following components:

2a. Throat Attachment to Structure

This connection refers to the interface between the throat and the building structure. This attachment holds up the throat by providing structural support.

2b. Throat Interconnector

This refers to a component that attaches two pieces of throat material (e.g. gypsum board, acoustic tile, or sheet metal tubes) together.

It may be a rigid connection or an adjustable component that allows for vertical, horizontal or angular displacement of the throat.

2c. Throat Structural Support

This refers to the throat support that provides lateral and seismic stability. It may be a rigid brace, hanger wire or other type of support system.

3. Splay

The splay is the second potential component of a light well. A splay is an angled/tilted transitional component of the light well that starts at the bottom of the throat and connects to the ceiling (Figure 12). The splay surface can be of any material that is reflective, and easy to install (described in detail in section "Component Requirements"). The use of a splay will provide better light distribution into the interior space. Splay angle is the angle between the splay and the ceiling or horizontal plane.

3a. Splay-Throat Connector

The splay-throat connector attaches the splay to the throat. It can be a simple attachment, or it can incorporate an adjustable assembly that allows for horizontal, vertical, or angular displacements.

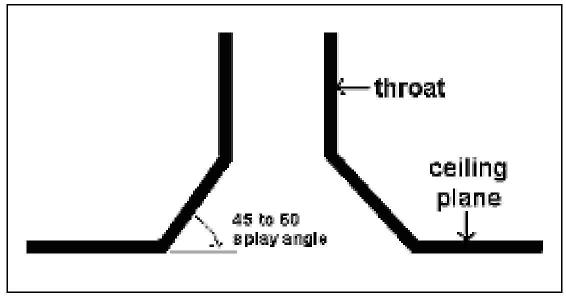

Figure 12. Splay Angle

3b. Splay Interconnector

The splay interconnector joins two pieces of splay material (e.g. gypsum board, acoustic tile or sheet metal tubes). It may be a rigid member or an adjustable component that allows for horizontal, vertical, or angular displacements.

3c. Splay Structural Support

This refers to the support that provides lateral and seismic stability for the splay. It may be a rigid brace, hanger wire or other type of support system.

4. *Light Control Devices*

Light control devices are attachments to the light well that modulate the amount of daylight coming through the skylight. One or more devices can be used at the same time in a light well system, or there could be none present at all, depending on the design requirements. They can potentially be located anywhere from just underneath the skylight glazing to below the ceiling plane. Types of light control devices are:

4a. Louvers

Louvers are adjustable slats attached to the throat that control the amount of daylight passing through them. They can be installed as an integral part of the skylight frame.

4b. Interior Diffusers

A diffuser is any kind of glazing material installed within the light well to optically diffuse the light or otherwise control the distribution of light exiting the diffuser. The most commonly used diffusers are prismatic acrylic lenses installed at the bottom of a skylight well.

4c. Suspended Reflectors (not shown in figure)

Reflectors are accessories made of reflective material installed below the bottom of the light well to redirect daylight onto the ceiling.

4d. Baffles (not shown in figure)

Baffles are opaque or translucent surfaces used to reduce glare by preventing direct view of an overly bright light source or surface.

4e. Device connectors

These connectors attach the light control devices onto the throat or splay, as their design requires.

5. Suspended Ceiling

A suspended ceiling is a ceiling grid system supported by hanging it from the overhead structural framing.

5a. Runners

Runners are cold-rolled metal channels used to support ceiling tiles.

5b. Ceiling Tile

A ceiling tile is a preformed ceiling panel composed of mineral fiber or similar material and a textured finish appearance.

5c. Ceiling-Splay Connector

The ceiling-splay connector joins the splay to the ceiling. It can also serve as a concealment for this junction.

6. Other Accessories

The locations of other accessories are not shown in the figure and may vary depending upon their use. These accessories include: electric light fixtures, photosensors, air diffusers or grills, sprinkler heads and other devices such as smoke detectors, security cameras, etc.

One very important accessory is a safety grate or "burglar bars." This safety device, made of either metal wire (safety grate) or iron bars, is installed inside the curb early in construction and prevents workers from falling through the skylight opening during construction. This also has the benefit of letting in light and letting out fumes during construction. Permanent safety grates are recommended even if the skylight is rated to withstand someone falling on it, since ratings are usually for new skylights, which may become less resilient over time.

System Design

This section lists the important information required to make decisions regarding the skylight well design. This design process can be applicable to site-built system installation or a pre-manufactured product.

Design is an iterative process, and skylight system design is no exception. It begins with simple assumptions and "rule-of-thumb" guidelines, and then proceeds to more detailed and specific analysis. It requires constant refinement due to more comprehensive and intensive design analysis, or as a result of feedback about associated building systems. This iterative process leads to a better-designed skylight system and optimal daylighting benefits.

SYSTEMS COORDINATION

The plenum space and ceiling plane house a number of building services systems, such as the structural elements, HVAC, fire protection and lighting. These elements are located in horizontal "strata" of the plenum space. Since the light well is vertical, it cuts through all of these strata, and requires coordination of trades and industries during both the design and construction phases.

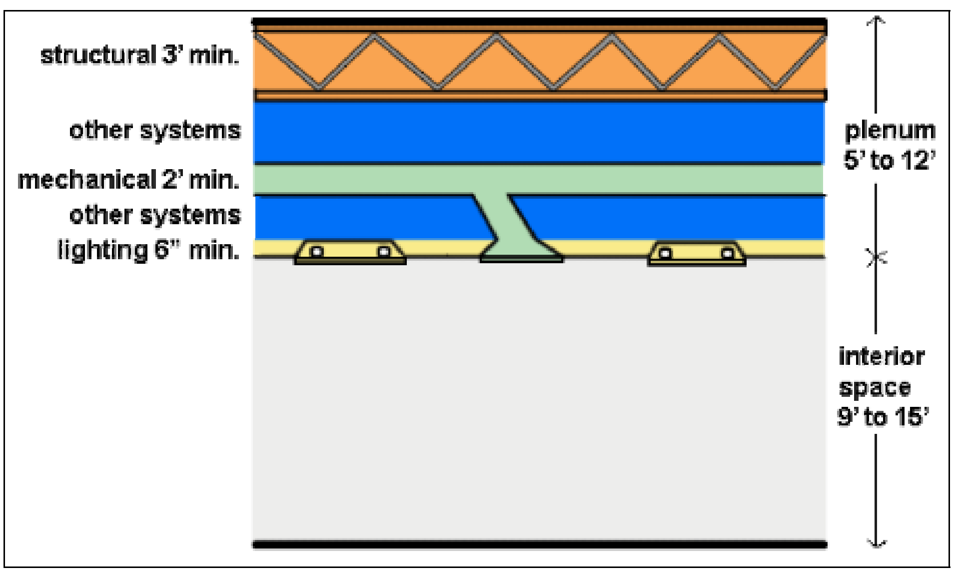

Figure 13. Typical vertical spacing of systems installed within the plenum.

The range of spacing and dimensions for the plenum and ceiling systems varies considerably according to the system used, but for the building types considered in this guideline, they will typically be within the ranges illustrated in Figure 13 and Figure 14 (HMGa, 2003).

Coordination Strategies during the Design Phase

It is essential for a designer to inform the project team members that skylights are to be installed in the project as soon as possible. The early warning allows each design specialty to make allowances in their preliminary design to accommodate for the modular skylight well placement.

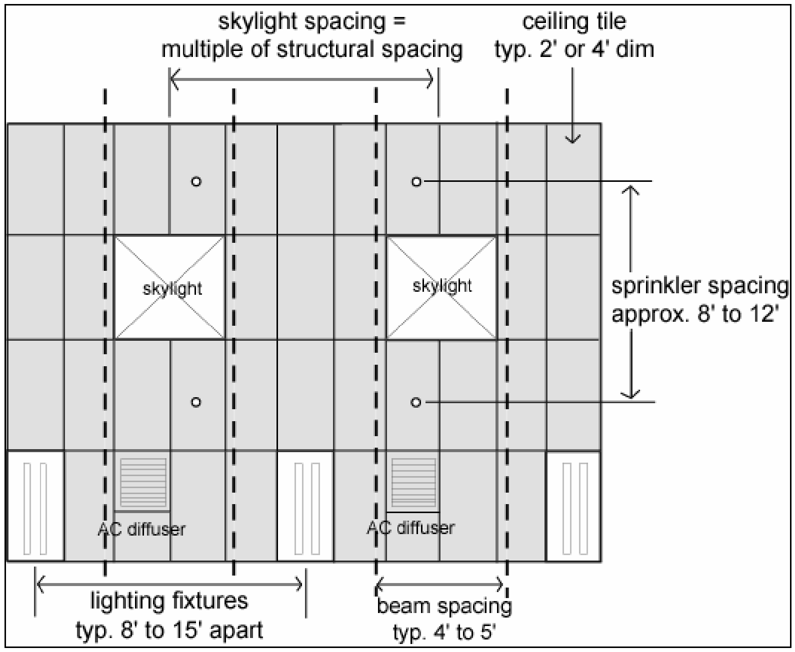

Figure 14. Typical horizontal spacing of systems installed on the ceiling.

1. Designation of the Exclusion Zone

To set aside space for the skylight, an exclusion zone should be established early in the design process. The exclusion zone is the maximum penetration area of a skylight well. It will correspond to the volume being occupied by the skylight well on the roof, within the plenum space and on the ceiling. An exclusion zone communicates to the various professions and to the project designers that this zone is reserved for the light well. Any trespass into this area will require communication with the architect or designer in charge of coordination.

2. Notation of Exclusion Zone on drawings

Skylight notations should be done on the appropriate Computer Aided Design (CAD) drawing layer, according to guidelines set by the American Institute of Architects (AIA).

The skylight well exclusion zone should be clearly called out on both plans and sections, including the following drawing sheets (see Figure 15):

- Roof plan
- Reflected ceiling plan
- Structural plan
- Wall sections
- Mechanical plan
- Electrical plan
- Plumbing plan

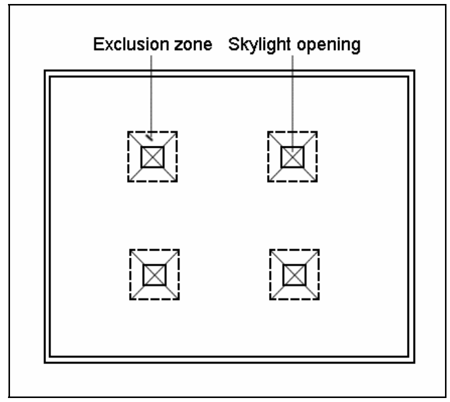

Figure 15. Exclusion zone marking in plans

3. Details

As with all other architectural systems, skylight wells require detail drawings to explain joints and connections. Figure 11 provides a starting point to think about which details need to be explicitly drawn in order to communicate the requirements of the project and the designer's quality expectations. Especially at any point where two construction trades will interface in making a connection between parts of the skylight well, such as a carpenter and a sheet metal worker, or an electrician and a ceiling installer, the designer is advised to provide explicit details about joining geometry, tolerances and connection methods.

4. Specification in Contract Documents

Skylight details and installation guidelines should be incorporated in the appropriate sections in specifications. The specifications should include description of materials, system, geometry installation methods and any performance criteria or warrantees.

Unit skylight assembly is addressed in the Construction Specifications Institute (CSI) Manual of Practice under section 08620. Skylight wells, on the other hand, do not yet have a fixed place in the specification system. If the light well is part of the skylight, as it is with tubular skylights (pre-manufactured single unit), it makes sense to list the light well under unit skylights (Section 08620). If the well is constructed of acoustic tile and it is anticipated that the ceiling installer will to be installing the light well, it should go under the section for suspended ceilings (Section 09120). If it is unclear who will install the light well, it should be treated as a specialty feature in the Section 10700s. This could potentially include Sections 10705 "exterior sun control devices" or 10730 "exterior wall panel: daylighting."

SYSTEM COORDINATION CHECKLIST

- ❑ Designate an exclusion zone that will reserve the volume for the light well and the splay during the design phase and during construction.
- ❑ Make sure that the skylight exclusion zone is properly designated on the following drawing sheets: roof plan, ceiling plan, sections, structural drawings, mechanical drawings, and electrical drawings.
- ❑ Incorporate skylight details and installation guidelines in the specification books to avoid skylight well coordination problems among the different trades on-site.
- ❑ Mark light well locations on-site to reserve space and to help coordinate with other building systems.

Coordination Strategies During the Construction Phase

The biggest challenge during construction is to avoid spatial conflicts with other trades and prevent damage to the skylight and well systems.

1. Marking of Light Well Location On-Site

During construction, the use of a “marker system” to block out the location of the throat and splay installation will prevent the encroachment of other building services system into the volume required for installation of the well system. This space reservation can be accomplished by incorporating ribbons or similar markers in the area of the throat and splay installation showing their approximate dimensions. Care should be taken to account not only for the size of the well, but also an allowance for worker access to the well for installation and assembly.

2. Proper Scheduling of Construction Activities

An alternative solution is to schedule construction activities to allow throat and splay work to be completed before other building services systems. This blocks out the space required for installation. The benefits of installing the well components early to define their space must be balanced against the risk of possible damage to the light well. See Appendix 7 for alternative scheduling solutions.

DESIGN PROCESS FOR SKYLIGHT WELLS

This section describes the process of designing the skylight well. The first part considers the steps involved in the process. The second part describes in detail considerations pertaining to skylight well sizing, geometry and photometric analysis. The design process for skylight wells can be broadly categorized into two phases: the schematic design phase and the design development phase. Each aspect of the flow chart is described in the following section. The next chapter explains this design process in detail through an example.

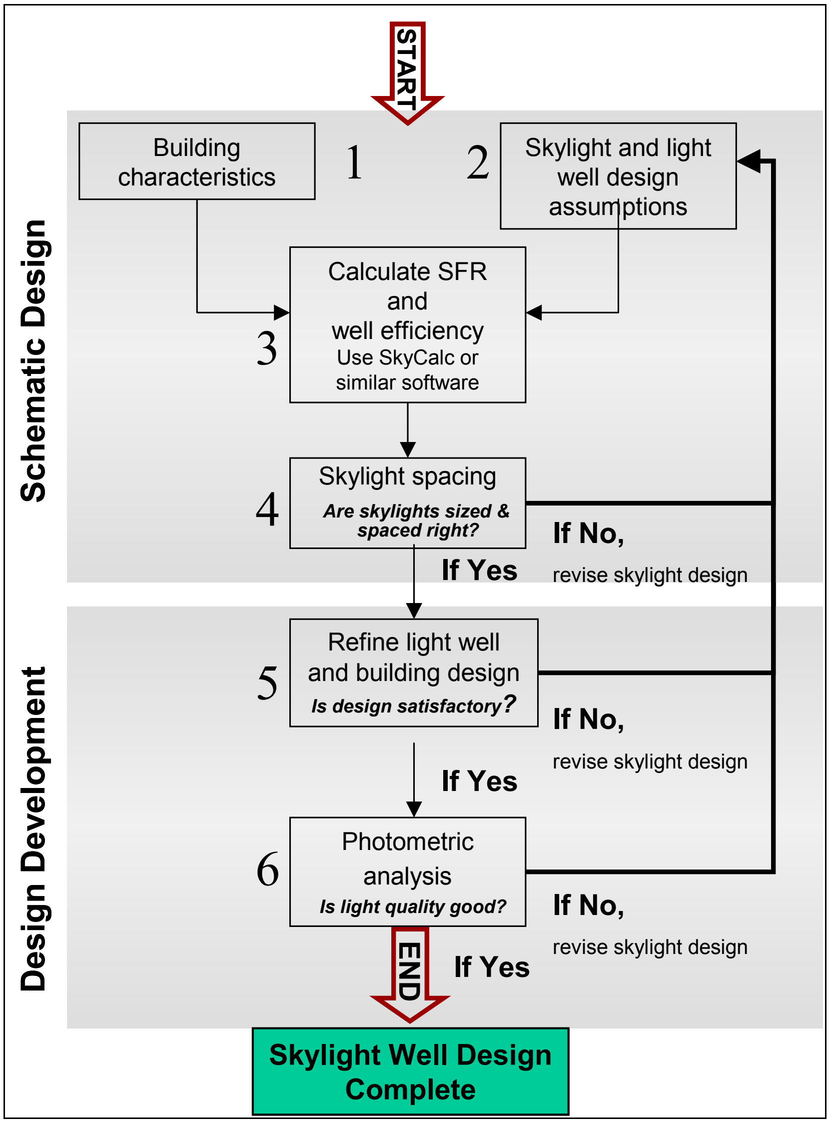

Figure 16. Flowchart showing design process for skylight wells.

Schematic Design Phase

Schematic design is the initial phase of a design project where the basic criteria and relationships of a building are established. For skylights, this means that the designer determines where skylights will be used, and roughly estimates their appropriate size and spacing. The key issue is establishing the appropriate amount of skylight area for the building type and location. Total skylight area is typically discussed in terms of the skylight to floor area ratio (SFR) that describes the percentage of the roof area which is devoted to openings for skylights.

These Guidelines focus only on the narrow issue of how to design a skylight well for spaces with suspended ceilings. There are, however, a number of other important resources available to help the designer make initial design decisions about skylighting. Three of these resources described below explicitly serve as companions to these Guidelines, by providing additional information and tools to support early design decisions about a skylighting system.

The *Advanced Lighting Guidelines* document *(NBI 2003)* is available in web, CD and paper versions. It provides information and guidance on the design and specification of all lighting systems, including both daylighting and electric lighting. It has a particularly good chapter on lighting controls and also discusses how to select lighting systems that are compatible with daylighting systems.

The *Skylighting Guidelines (HMGc 1999)*, available as an Internet download, provides an overview of the issues specific to skylit building for both architects and engineers. It includes discussions of solar geometry, specification of skylight materials and performance, integration of skylights with electric lighting systems, and optimization of designs for lighting quality and energy savings. In addition to text, charts and graphics explaining skylighting issues, the document also serves as the user manual for the SkyCalc® spreadsheet, used to analyze skylight performance for alternative designs.

SkyCalc®[4] is a simple Microsoft Excel spreadsheet application that uses sophisticated analysis to provide quick estimates of illumination levels and energy savings from various skylighting strategies. The program uses a handful of user inputs describing the building and its proposed skylighting system, and combines these with information about the local climate to estimate predicted illumination levels and energy savings from alternate skylight designs. The program conducts an hour-by-hour yearly analysis based on the DOE-2[5] computer program to generate simple graphs and reports that help the designer quickly see the impacts of different design decisions. It uses a large library of performance information to simplify inputs for the user, allowing quick defaults or specific user-defined properties.

The following data is entered in the SkyCalc® program:

- Building location, which determines which weather file is used
- Building details, such as building type, dimensions, heating system and energy costs
- Information about the lighting system, and most especially the control strategy to turn off the electric lights when sufficient daylight is present
- Skylight details, such as number and size of skylights and glazing type
- Skylight well details, such as depth and surface materials

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[4] A Microsoft Excel application by the Heschong Mahone Group (1999-2003) that provides lighting and energy analysis of skylight designs. Available for download in two versions. For 16 weather zones in California see www.energydesignresources.com; for 32 weather zones in the United States see www.h-m-g.com.

[5] DOE-2 is a building energy analysis software tool originally developed by the Department of Energy. For more information: www.eere.energy.gov/buildings/tools-directory or www.doe.com

SkyCalc then produces graphs showing the hourly interior daylight illumination level that can be expected from this design, and the yearly lighting, heating and cooling energy savings and energy cost savings that will be due to the combination of daylight and lighting controls. These graphs show the change in results as the total area of skylights are increased, ranging from 0% SFR up to 12% SFR. These graphs give the designer a quick way to assess the most appropriate and cost-effective SFR for the building, given the climate and building conditions. Comparing alternate designs also shows the lighting and energy impacts of different glazing materials, configurations or skylight well materials.

Since SFR is calculated by multiplying the surface area of an individual skylight by the total number of skylights, it is clear that for a given SFR a designer has a choice of a few large skylights or many smaller skylights. SkyCalc provides some guidance on the relationship between spacing and sizing of skylights, but this is an important decision that has many other inputs. These considerations are detailed in the Design Development Phase discussion below.

Design Development Phase

Once the basic skylight design parameters have been selected and the appropriate SFR identified, the skylight and well design are refined in the design development phase, with the following steps:

1. Revise schematic design assumptions and sequentially finalize the following aspects of the design. Methods for making these decisions are explained in more detail later in this section:
   - Finalize skylight details such as dimensions, number, spacing and light well reflectance
   - Coordinate the skylight spacing with spacing of structural elements, electric light fixtures, fire sprinklers and HVAC diffusers
   - Decide on photocontrol set points, together with the electric lighting layout, to achieve maximum energy savings potential through skylighting
   - Finalize the skylight glazing characteristics, such as number of glazings, transparent or translucent, color, etc. The optical properties of the glazing materials influence daylighting quality and lighting savings
   - Decide on light control devices, such as louvers, reflectors, or diffusers
2. After the skylight well properties and spacing are established, a photometric analysis is recommended in order to understand the quality of light and illumination patterns that will be produced. A guide to photometric analysis is given in a later section of this chapter.
3. The light well space should then be reserved by representing the skylight opening and well dimensions on the CAD drawings per the discussion earlier.
4. The final step in the design process is to specify component requirements, such as geometry, material specification, and minimum performance

standards for each skylight component. These requirements are described in detail in the next chapter, "Component Requirements."

Skylight Well Sizing and Geometry

The layout and spacing of skylights in a roof are important determinants for the uniform light distribution characteristics of the skylighting system. SkyCalc® calculates the SFR, which in turn helps in determining the size and number of skylights in a given space.

Some design aspects that drive the skylight spacing and sizing decisions include:

- Structural spacing
- Ceiling height
- Coordination with other building systems
- Daylight uniformity versus cost
- Splay geometry
- Throat geometry

Roof Structural Spacing

Typically, low-rise commercial buildings have either a wood or steel roof deck. In both conditions, the spacing of the secondary structural members limits the size and spacing of skylight units.

To avoid penetrations through structural elements, skylight dimensions should be chosen relative to the secondary or tertiary roof framing modules.

Figure 17 diagrams the relationship between skylight size and placement and the structural elements of the roof. To avoid breaking structural lines, or adding additional framing members, skylights are typically spaced in multiples of the framing modules. Thus, if the major framing elements are spaced based on a 4' x 8' plywood sheet, then the skylights might be spaced on 16' x 16' centers, or 12' x 24'. If there are major structural supports every 20', then it is easiest if the skylights are also spaced 20' apart. Likewise, skylight unit sizes are typically selected to fit within the opening between smallest structural modules, accounting for the width of the framing member along with some tolerance, thereby avoiding a requirement for additional framing. Thus, a skylight with a rough opening width of 34" might be selected to fit between two-inch nominal framing members spaced 36" on center. The length of the unit skylight can also be selected to be multiples of framing dimensions, although this can also become too constraining of a criterion.

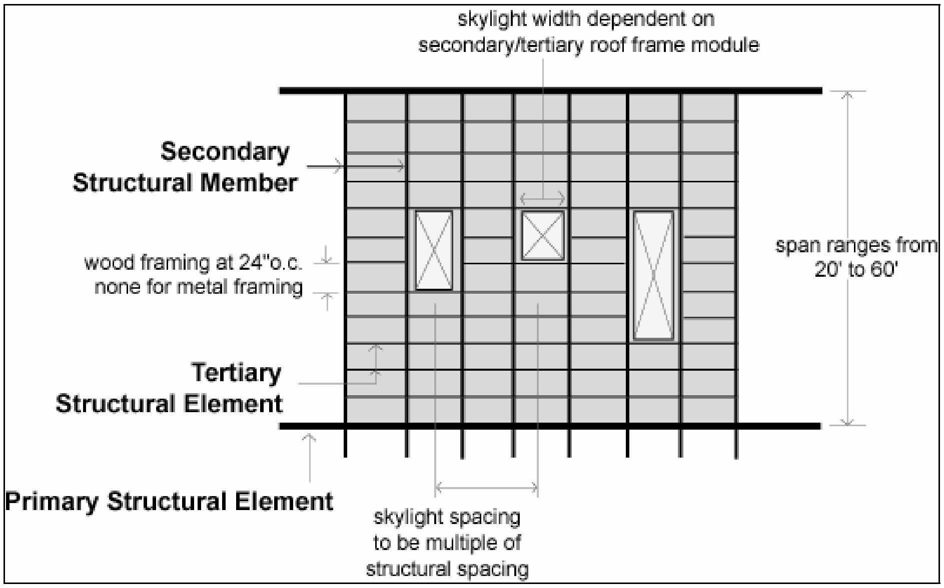


Figure 17. Plan showing primary and secondary structural members

Ceiling Height

Ceiling height is a major determinant of skylight spacing. Light distribution should be uniform on the work plane. The work plane is typically considered to be 30” above the finished floor. Too much distance between skylights results in dark spots on the work plane and should be avoided.

Rule of Thumb: Recommended maximum center-to-center spacing between two skylights should be no greater than the following equation:

$$\text{Skylight spacing} \leq (1.4\ x\ \text{ceiling height}) + (2\ x\ \text{splay width}) + \text{skylight width}$$

The splay width is how much a given side of the splay is offset horizontally from the edge of the skylight (see Figure 18). Skylight spacing can be determined for different ceiling heights based on the rule of thumb given above. Figure 18 shows spacing for skylights with splay, and Figure 19 shows spacing for skylights without splay. Note that skylights without splays need to be placed closer together than skylights with splays.

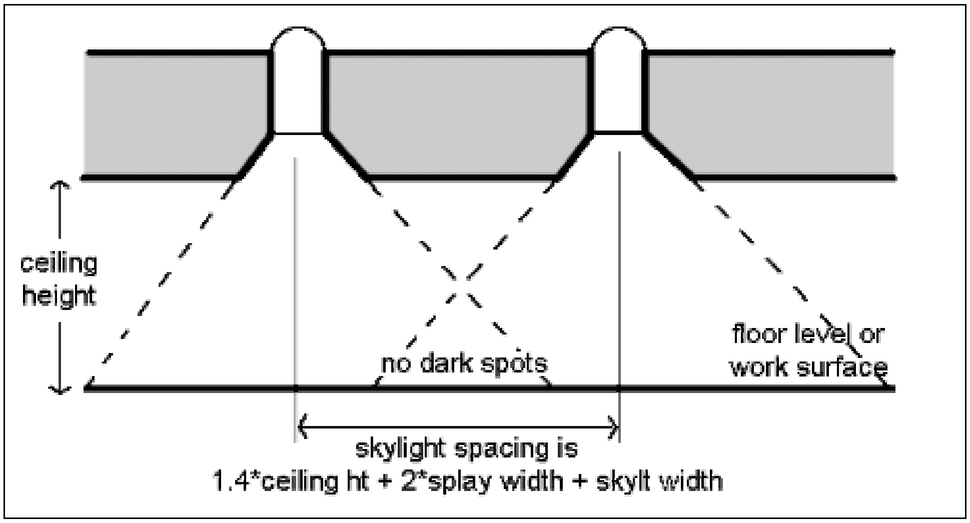


Figure 18. Skylight spacing with splay.

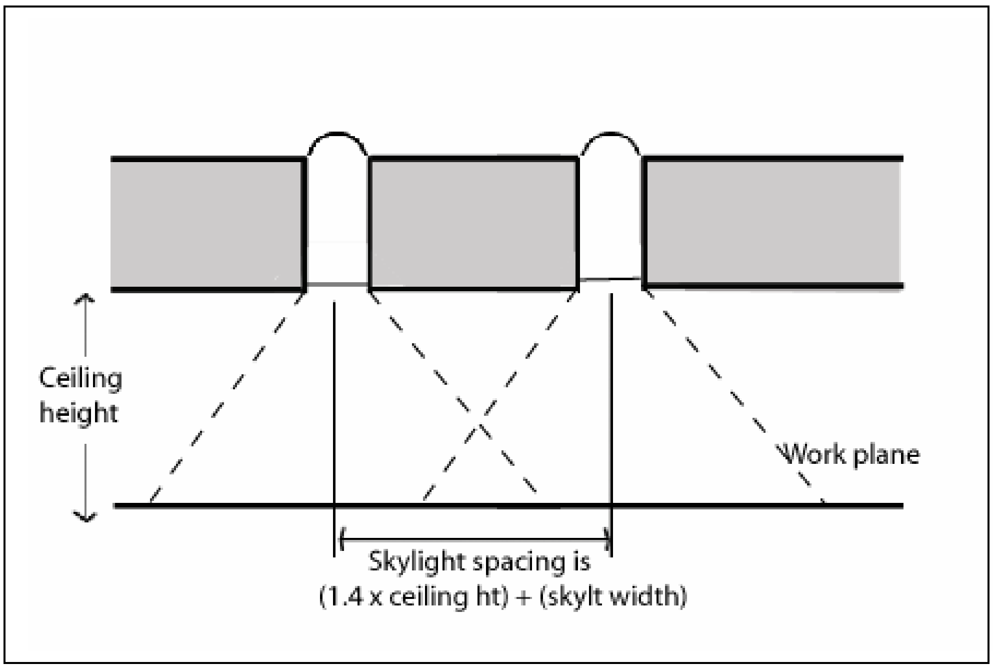


Figure 19. Skylight spacing without splay.

Coordination with Other Building Systems

Ideally, the skylight designer should keep in mind the spacing layout of the electric lighting with photocontrols, sprinklers, HVAC diffusers and ceiling tile dimensions in order to avoid site adjustments after construction. The photocontrol system should dim or switch light fixtures in areas with adequate daylight, while keeping the light fixtures in areas without daylight at the design output. Coordinating electric lighting with daylighting also makes controlling the electric lighting systems more effective.

Skylight Sizing

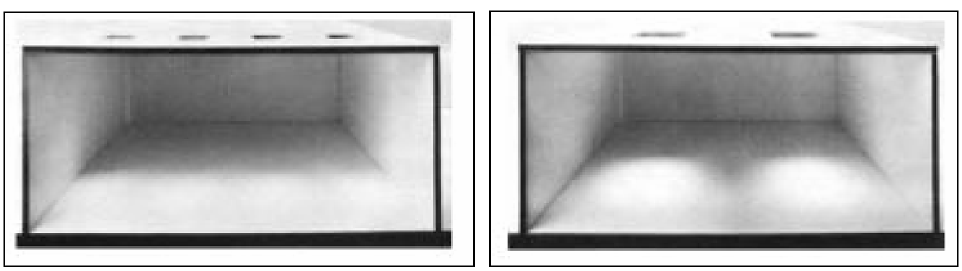
The amount of daylight in a space is a factor of the size of the skylight opening and the number of skylights. These two factors trade off each other to provide optimum lighting conditions according to the architectural limitations set by each project.

For a fixed percentage of the skylit roof area, designers could select anything from a single large skylight to many small skylights distributed uniformly across the roof. For the same total area, the tradeoff is typically between large skylights far apart versus smaller skylights arranged closely.

Listed below (Figure 20) are the advantages and disadvantages of small versus large (larger than 2' x 2') skylights. Figure 21 shows the light distribution pattern of a space with small skylights (image on left) and large skylights (image on right). Appendix 4 gives a calculated list of possible sizes of skylights and splays with their spacing, relative to ceiling height.

Small Skylights	Large Skylights
More costly to install	Usually most economical to install due to lower labor and material cost
More skylights required to provide an equivalent amount of daylight	Fewer skylights are required to provide an equivalent amount of daylight
More roof penetrations	Fewer penetrations, and therefore, less potential for leakage
More appropriate for lower ceilings	More appropriate for higher ceiling heights
Small, closely spaced skylights provide more uniform lighting	Larger skylights spaced farther apart may result in less lighting uniformity
A smaller light well is easier to locate within the plenum space	Larger light wells are more difficult to locate within the plenum space

Figure 20. Comparison of small vs. large skylights.



Many Small Skylights **Fewer Large Skylights**

Figure 21. Many small skylights versus fewer large skylights.

Figure 21 illustrates the difference in lighting uniformity between two skylight designs with the same SFR. The room on the left has four smaller skylights which produce very uniform illumination patterns. The room on the right has the same skylight area distributed into only two skylights spaced further apart. The resulting illumination pattern is les uniform, with greater contrast between bright areas under skylights and dark areas between skylights.

SYSTEM DESIGN CHECKLIST

- ❑ Define building and light well characteristics and assumptions
- ❑ Calculate SFR with SkyCalc or building energy software using skylight transmittance (Tvis) and well efficiency assumptions
- ❑ Calculate well efficiency of light well: well efficiency = WE throat x WE splay x Tvis diffuser
- ❑ Determine skylight spacing (on center)= <1.4 x ceiling ht + 2 x splay width + skylight width (keeping in mind lighting, sprinkler, HVAC spacing)
- ❑ Finalize building and light well dimensions, skylight spacing, sizing, light well characteristics.
- ❑ Coordinate with other building systems
- ❑ Perform a photometric analysis for uniformity and magnitude of light from skylights
- ❑ Reserve space by indicating skylight opening and well dimensions in roof & ceiling plans

Advantages of Splays in Light Wells

Skylight wells can either have splays in their design or not. The trade-offs involved in choosing between a splayed light well and a non-splayed (vertical) light well can be summarized as follows:

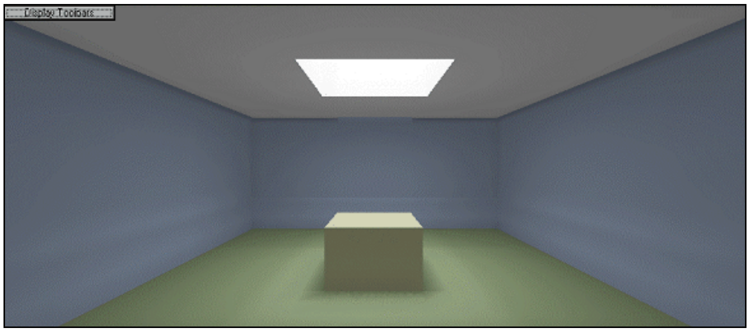
Cost: The cost of the splay itself is greater than a vertical light well. The splayed light well requires more light well material and is more difficult to install. As compared to a vertical light well with a bottom diffuser at the ceiling level, the splay requires more finish detail for the exposed surfaces. However, since splayed light wells result in a wider distribution of light (note the difference in distribution between Figure 22 and Figure 23), these skylighting systems can be spaced further apart than systems with vertical light wells while maintaining the same illuminance uniformity. Thus splayed light wells can be part of a skylighting design that uses fewer but larger skylights spaced further apart. Splays result in less roof penetrations, which reduces installation costs. Thus the relative incremental costs of the splay and roof penetrations will determine whether adding a splay will increase or decrease the overall cost of the skylighting system.

Aesthetics: The splayed light well creates a coffered look to the ceiling that many find attractive.

Visibility and Contrast: When the splay is compared to a vertical light well with a bottom diffuser, the splay acts as a cut-off louver that shields the observer from a near horizontal view of a diffuser. The splay has a luminance that is intermediate to that of the ceiling or the throat of the light well. This intermediate luminance reduces luminance contrast and discomfort glare.

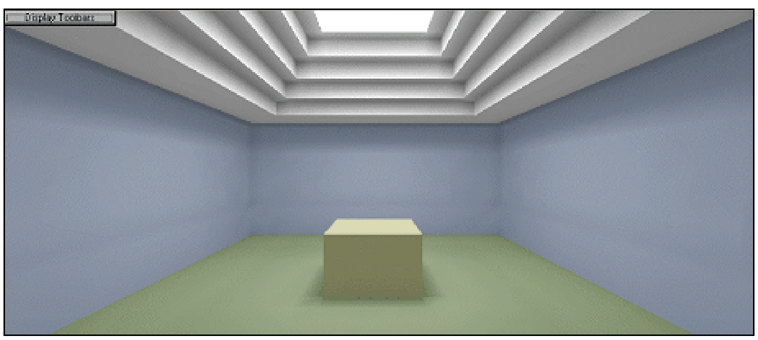
Physical size: Typically a splayed light well is significantly larger than a vertical light well and thus there is less room for other building systems without placing them in the splay. This can create a problem when the size of the splay is larger than the maximum spacing dimension for electric lights, sprinklers, HVAC diffusers etc.

Figure 22 and Figure 23 illustrate the difference in light distribution for a diffusing skylight with a straight well versus a splayed well. In Figure 22 daylight is channeled through a straight throat between roof and ceiling which results in a pool of light directly below the skylight. In Figure 23 a steeped splay allows wider distribution of the daylight, providing more uniform distribution of daylight in the room.



Source: Lighting Technologies

Figure 22. Skylight without splay.



Source: Lighting Technologies

Figure 23. Skylight with splay

From the discussion above, there are pros and cons associated with using splays but overall splays are desirable if mass-producing modular splays can sufficiently reduce their cost. Thus the following recommendations are how to design skylighting systems with splayed light wells.

Splay dimensions affect skylight spacing. Appendix 4 lists the appropriate spacing for various skylights of given dimensions, splay angles and splay dimensions. Wider splays produce wider light distribution and therefore allow a wider center-to-center spacing.

Photometric research has shown that making the skylight splay wider than 60° (splay angle less than 60°) has little impact on the distribution of light (Murdock et al 1989). This is because the spread of light from a diffusing skylight is predominantly within 30° from the nadir. Typical angles of splay are 45°–60° (see Figure 24).

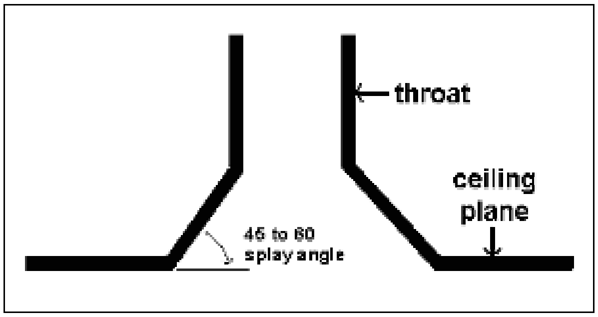


Figure 24. Splay angle.

Wider splays increase the well efficiency of a light well for a given reflectance (see section on "Well Efficiency "). This helps reduce the skylight area needed in a space.

Throat Geometry

The throat geometry also plays an important role in deciding the skylight spacing and sizing criteria:

- The shallower a light well is relative to its width, the less light is transmitted. This is an important consideration when determining throat height.
- Ideally the inside surface of the throat should be a highly reflective material, like white paint, which will enhance the light entering the light well. Specular materials provide excellent light transmission but must be shielded or have a bottom diffuser to minimize glare.
- A throat that has angle connectors or several offsets/wrinkles in its design (e.g., a tubular throat) may reduce the amount of light entering the light well. The angle connectors or adjusters should be designed to minimize light losses within the range of typical offset angles. (Also discussed in further detail in the "Component Requirements" section).

Well Efficiency of a Skylight System

The well efficiency is the ratio of the amount of visible light leaving the skylight well to the amount of visible light entering the skylight. The well efficiency of the skylight well can be calculated using the well cavity ratio equation as given by the 2005 Building Efficiency Standards. The chapter "COMPONENT REQUIREMENTS" describes a detailed calculation method for well efficiency. The well efficiency (WE) of a skylight well depends on the well cavity ratio (WCR), well dimensions and reflectance of the light well material. When designing skylights it is important to keep in mind how the well efficiency affects the quality of daylighting in a space:

- When the ratio of depth to width is high in a light well, well efficiency drops.
- Higher well surface reflectance results in higher well efficiency.
- Well efficiency drops for taller light wells.

More details on well efficiency can be also found in the *Skylighting Guidelines* (HMGc 1999) under the "Well factor" section.

Room Specifications

When daylight penetrates past the glazing, light well and shading devices, it interacts with the interior of the building. As a result, the lighting quality of the skylight system is also dependent on room geometry and on surface reflectances of walls, floors, ceilings and furnishings. Light-colored surfaces with high reflectance will help distribute brightness around the space and reduce glare potential.

Light Control Devices

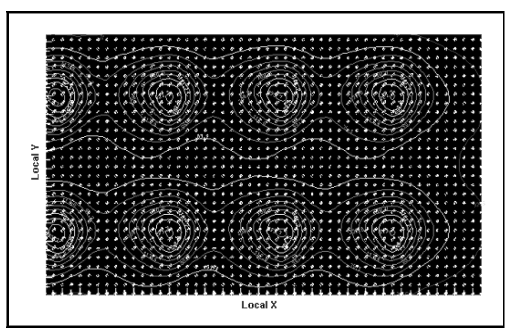
Light controlling devices like diffusers, louvers, reflectors or clouds enhance the quality of light reaching the work surface (See details in the next chapter).

Photometric Analysis

Almost every electric lighting luminaire sold in the US has a photometric report and photometric data in IESNA LM-63 format. The photometric report describes the distribution of light leaving the luminaire both in terms of a candela polar plot and a zonal lumens summary. This information gives the designer information about the width of the "spread" of light from a fixture as well as its likelihood of creating glare. The photometric report also provides a "spacing criterion," or a recommended maximum spacing distance to maintain illuminance uniformity.

Photometric data files are used in conjunction with lighting software to predict the lighting patterns resulting from a lighting design using that luminaire. Typical methods of displaying this information include calculations of uniformity ratios (min:max illuminance ratios), iso-footcandle (iso-lux) contour plots and visualizations of the lighting design. The iso-footcandle contours (see Figure 25) provide a simple way of recognizing the patterns of light on a given work surface. Many programs also allow one to plot iso-footcandle contours on vertical surfaces such as shelves. This can be used to evaluate whether the design is providing the required uniformity or highlighting. Visualizations of a lighting design are very helpful in that it allows one to recognize if a given design is creating the look that one desires (Figure 26)

Until recently, photometric files and reports based upon testing of skylights did not exist. In response to this lack of critical performance information for skylights the California Energy Commission PIER (Public Interest Energy Research) program had commissioned a study to develop a photometric test method for skylights and to perform tests on a sample of representative skylights used on commercial buildings. (Domigan et al 2002). As a result, the CEC PIER program has published photometric files for sixteen skylight and light well combinations under a range of sky conditions and solar positions. This data can be freely downloaded from either of the following Internet websites: www.newbuildings.org/pier or www.h-m-g.com.



Source: Lighting technologies

Figure 25. Isolux contour.

Source:http://radsite.lbl.gov/radiance

Figure 26. Detailed skylight visualization using Radiance simulation software

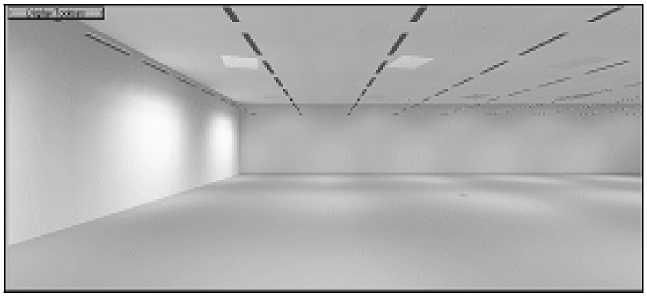
Usually, initial skylight well spacing decisions are based on rules of thumb (such as the photometric report spacing criteria times the ceiling height) and the spacing of structural elements and electric lighting spacing. Once an initial skylighting and electric lighting design has been conceptualized, the photometric analysis can be performed using electric lighting design software and photometric files for both the skylights and electric lights (McHugh et al. 2002). If the space has a significant amount of obstructions (such as partitions or shelves) these should be modeled, as an empty space will overstate the uniformity of illuminance. It is important to identify the effects of objects blocking light and creating shadows.

In evaluating a design there are three primary light conditions to evaluate:

1. Under full sun on a summer day with the lights turned off
2. At night with all lights completely on
3. On a cloudy day with lights partially dimmed or the first bank of lights switched off

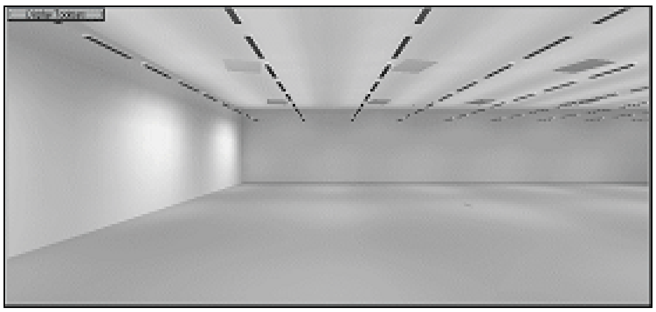
Modeling the skylights with the electric lighting turned off allows one to evaluate the characteristics of the daylight design in isolation from electric lighting. For optimal energy savings, the skylighting system should be able to provide excellent illumination during peak daylight hours. As a rule of thumb in moderate climates, the peak daylight average illuminance in a space should be about twice the design light level for the electric lighting system. For spaces where illuminance uniformity is desirable, a maximum: average illuminance ratio no greater than 3:1 is appropriate (IESNA 2001). If higher uniformity is desired, one can space the skylights closer together or increase the height of the splay in the light well.

The photometric analyses in Figure 27 show the difference in lighting effects due to the use of electric lighting. One important fact to keep in mind is that the use of electric lighting will reduce the energy savings potential of daylighting with skylights. In the first image, electric lights are switched off with the skylights, while in the second image the skylights are present with electric lights on.



Source: Lighting Technologies

With electric lights

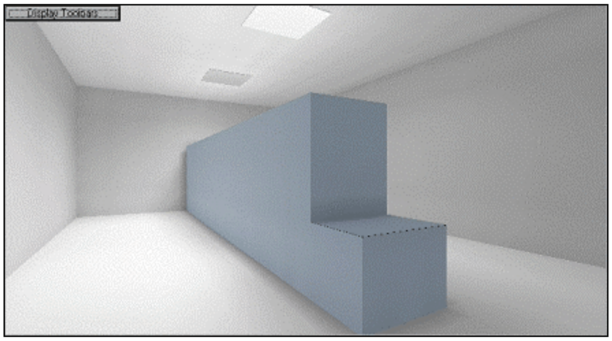


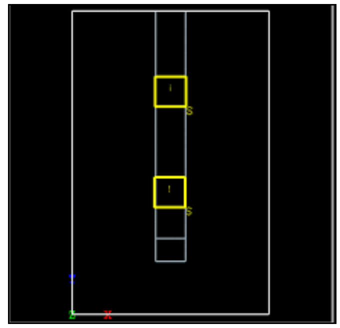
Without electric lights

Figure 27. Photometric analysis of uniformity due to skylights and electric lights

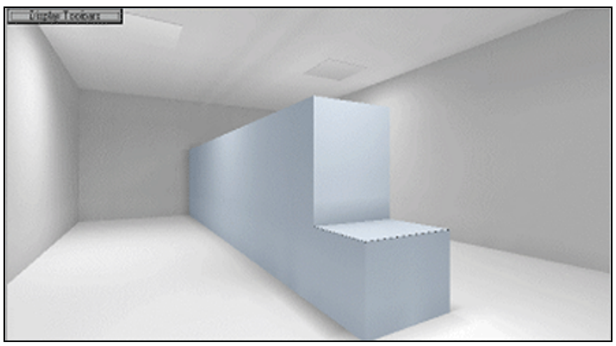
Uniformity is not always desired in a space. Figure 28 shows a hypothetical retail store, where skylights are used to highlight certain products on the shelves. The visualization results show the effects of skylight placement on the visibility of a retail display. Option 1 shows two skylights in a linear arrangement directly above the shelving. However, since it is desired to bring light onto the vertical surfaces of the shelving and to bring extra light on the ends of the shelves, Option 2 shows three skylights in a staggered arrangement, which gives a better distribution of light.

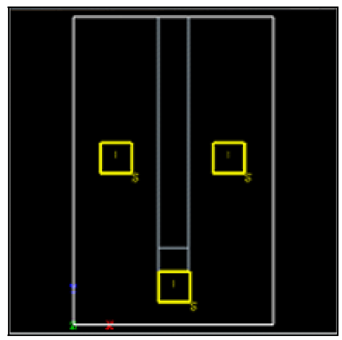
Option 1





Option 2





(source: Lighting Technologies)

Figure 28. Using photometrics to evaluate appropriate luminance levels.

Described below is a photometric analysis of two light well conditions: One with splay and one without splay. The analysis was performed on a 4'x4' skylight (double glazed white acrylic dome, 59% VLT) with a 10'x10' splay (throat height 3' and splay height 3') in a 60' x 72' room with a 11' ceiling height. The splayed system had a prismatic diffuser where the bottom of the throat and the top of the splay met. The system without a splay had a prismatic diffuser at the bottom of the light well at the ceiling plane.

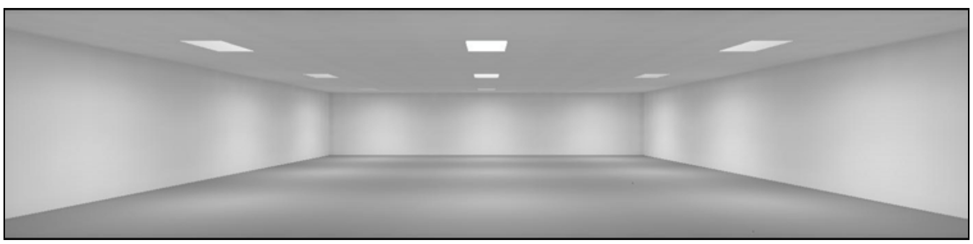
The results of the "light well with splay" design show acceptable room light levels under clear sky conditions. At least 63% of the room is 50 footcandles or more. The *max:min* ratio is 5:1, indicating that the space has reasonable uniformity.

The results of the light well without splay are marginally acceptable. At least 63% of the room is 36 footcandles or more. The *max:min* ratio is 7.5:1, indicating that the space has marginal uniformity.

The lighting software also provided a rendering of both the splayed system and the system without a splay. Figure 29 shows a fairly uniform light distribution for a light well with splay. However, the walls are not well illuminated by the skylights. Modifications by changing the spacing of skylights more towards walls or adding appropriate electric lighting to illuminate the walls may help resolve this situation. Figure 30 shows light distribution of the skylights without splay, which indicates that the light is not as uniform as with the case of light well with splay. In Figure 29, the light well opening is not as bright as the unsplayed opening in Figure 30. This is because the diffuser in Figure 29 is above the splay and the splay provides some shielding of the diffuser. The light levels on the floor in both figures reflect the difference in illuminance uniformity. However, the vertical light well with the bottom diffuser does a better job at illuminating the walls of the space. As mentioned earlier there are trade offs involved in choosing between a splayed and non-splayed light well. It is finally the decision of designers as to how they want their space to be illuminated.

Source: Benya Lighting Design

Figure 29. Photometric results for light well with splay (cloudy conditions)



Source: Benya Lighting Design

Figure 30. Photometric results for light well without splay (cloudy condition)

Conceptual Examples

This section includes an overview discussion of four conceptual modular light well systems and then a detailed description of the step-by-step design process for one example. The four systems are:

- System 1— Pivoting Threaded Rod (Fixed Splay) System
- System 2— Fixed Metal Throat (Adjustable Splay) System
- System 3— Tubular Adjustable Throat (Fixed Splay) System
- System 4— Fixed Throat Flexible Connector (Fixed Splay) System

These four systems each provide a possible solution to one of the central challenges of a skylight well placed in a suspended ceiling system—that of accommodating the dimensional shifts between skylight opening and well opening. Although in the best of all worlds, skylight wells would always be located precisely underneath the skylight opening, in reality there are many reasons why there will be some degree of offset between the skylight and the well opening, including:

- Roof decks at a slope for water drainage while ceilings are truly horizontal
- Actual ceiling installed (or retrofitted) at a slightly different height than specified
- Well opening located at two foot modules of ceiling grid, while skylight openings are located on structural modules with a three foot or five foot intervals
- Skylights placed in original shell construction by owner, while ceilings are installed (or retrofitted) much later by tenant
- Other major building element (such as beam, column, duct, pipe, light fixture) must occupy preferred location for skylight well, so well location must shift to accommodate

In addition, each system addresses other construction realities. They differ in how they indicate to other trades the space which must be reserved for the skylight well, how they protect important finish surfaces during construction, such as the light reflective surfaces of the throat, and how they stage construction so that all parts and systems are accessible when needed for installation or maintenance.

It is hoped that the conceptual diagrams and descriptions of these example systems provide inspiration for innovation by both designers and manufacturers to create new solutions and products to meet the needs of skylight buildings.

SYSTEMS DESCRIPTIONS

System 1: Pivoting Threaded Rod (Fixed Splay) System

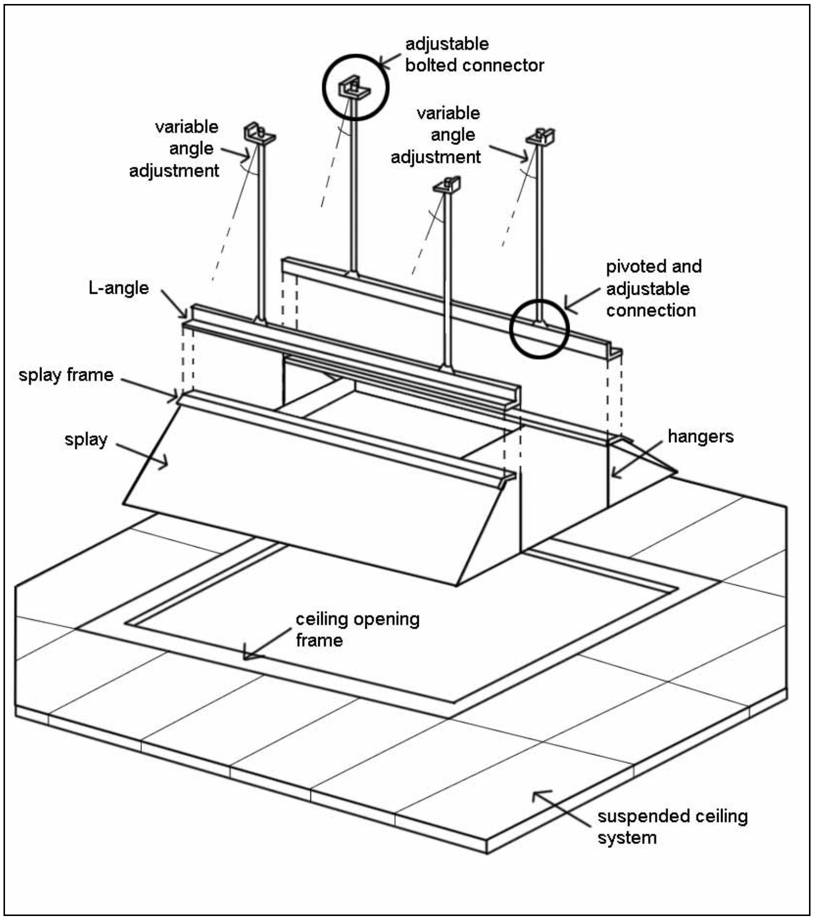


Figure 31. Conceptual diagram of Pivoting Threaded Rod (Fixed Splay) System.

The design of this conceptual skylight well system consists of a flexible throat and a fixed splay. The flexibility in the throat is provided by pivoting threaded rods that form the four corners of the throat. Following is a brief description of each component:

- **Pivoted Rods**: Threaded rods can be screwed up or down from angle irons bolted to the skylight curb or roof deck for vertical adjustment in the length in the throat. Within their holder, the rods can pivot in three dimensions, allowing angular adjustments to the throat position. The rods form the corners of the throat, providing structural support for the throat surface material. They can be installed early in construction, before the installation of the throat surface, in order to delineate the volume reserved for the skylight well.
- **Connectors**: The connectors at the top of the throat attach the threaded rod to the curb or roof deck, and allow three dimensional movement of the rods according to the throat configuration. The bottom connectors are angle irons bolted to the bottom of the rods, providing a horizontal

attachment structure for the splay. The angle iron can be fitted with slots every 3”– 6” to allow for multiple attachment locations.

- **Splay:** A fixed-dimension splay can be attached to the angle iron and the ceiling system, since all location adjustments between roof and ceiling can be accommodated with the throat system. A fixed dimension splay allows the use of prefabricated parts. A limited set of parts could be manufacturer for splays with openings on a two foot module and with 45 degree or 60 degree slopes. Some examples of the resulting dimensions are given in the chart in Appendix 4.

  The splay is constructed by hanging two trapezoidal surfaces on either side of the well, supported between the angle iron and the ceiling. Once in place, the secondary rectangular surfaces are added to the other two sides, leaning against the edges of the trapezoids and once again supported by the angle irons. There is no need to create a compound angle at the inner joint of the splay, since the secondary surfaces can simply “pass” by the joint.

- **Throat material:** Once the throat and splay have been fixed in position, the throat surface can be added around the rods. This surface could potentially be constructed of almost any lightweight planar material such as sheet metal, duct board, ceiling tiles, fabric or reflector coated plastic. (Of course, any material chosen needs to meet all functional requirements of the plenum, including fire and smoke resistance.)

- **Construction scheduling:** In the construction phase, the scheduling of activities should follow this sequence: the placement of the pivoted rods and angle iron before installation of ducts and plumbing the in plenum, final adjustment of the throat location when the splay support locations are finalized during installation of the ceiling. The final sheathing of the throat can occur just before the ceiling tiles are placed to close off the plenum.

System 2: Fixed Metal Throat (Adjustable Splay) System

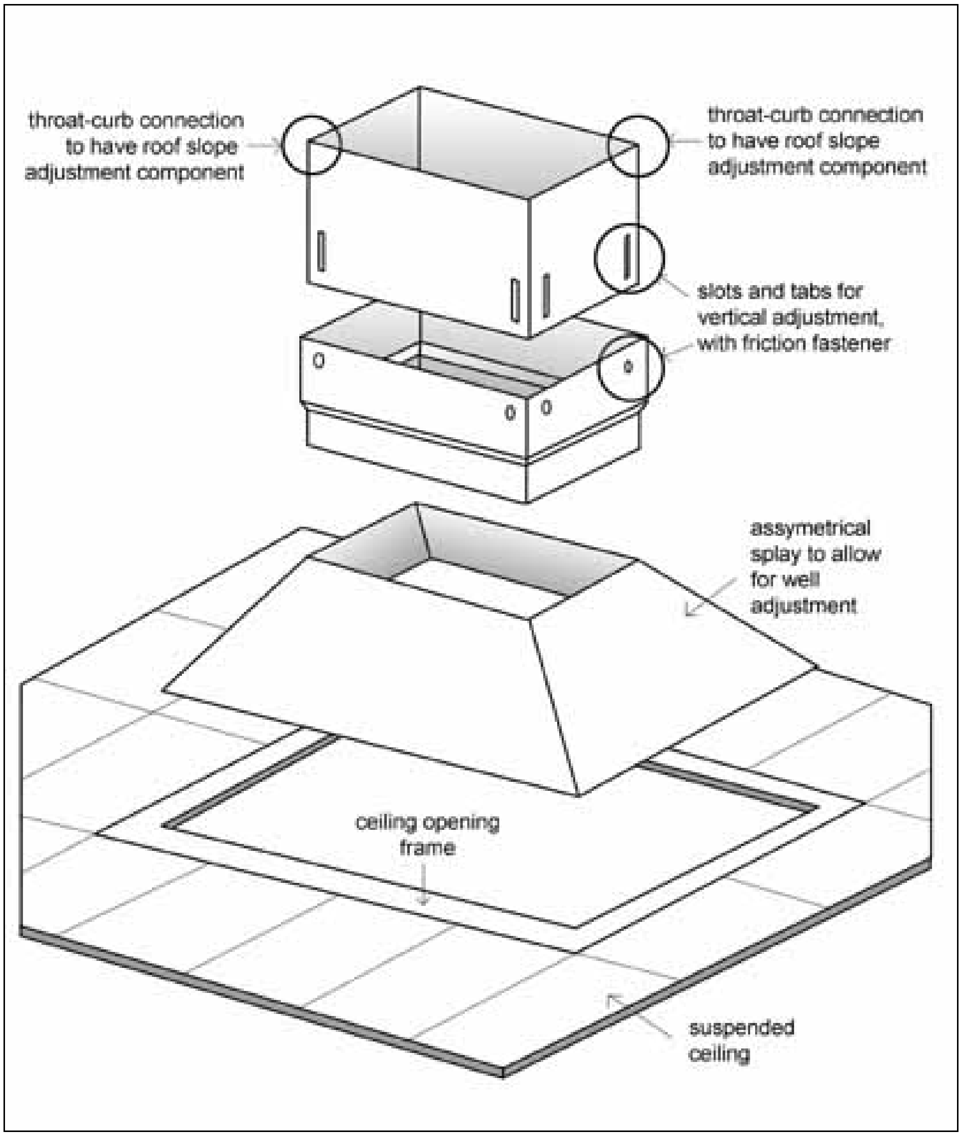


Figure 32. Conceptual diagram of Fixed Metal Throat (Adjustable Splay) System.

In this approach, the throat is a rigid sheet metal assembly placed early in construction. Vertical and angular adjustments are accommodated in the throat system, while horizontal adjustments are accommodated with an assymetrical splay.

In this example, the first stage of this system is the placement of the throat and its connection to the curb or roof deck. The throat would best be located with sides plumbed to vertical so that the bottom rectangular opening is also maintained horizontal. This implies that the connection between roof and throat needs to correct for any slope in the roof deck or curb. Once placed, the throat reserves the skylight well space in the plenum during the installation of other plenum system. It needs to be either durable enough to resist damage or protected from abuse during this phase. The splay is constructed during the installation of the ceiling, taking up any horizontal adjustment necessitated by offsets between the roof and ceiling grids with asymmetrical slopes of the walls of the splay. Final vertical adjustments of the sheet metal throat, via sliding slot and tab connections, would be done at this time to meet the final height of the splay.

The splay can be constructed of any material that meets the needs of the project. The most likely material would be the same ceiling tiles and runners used in the ceiling system. If an asymmetrical splay is required, then the ceiling tiles and runners would have to be specially cut on site.

System 3: Adjustable Tubular Throat (Fixed Splay) System

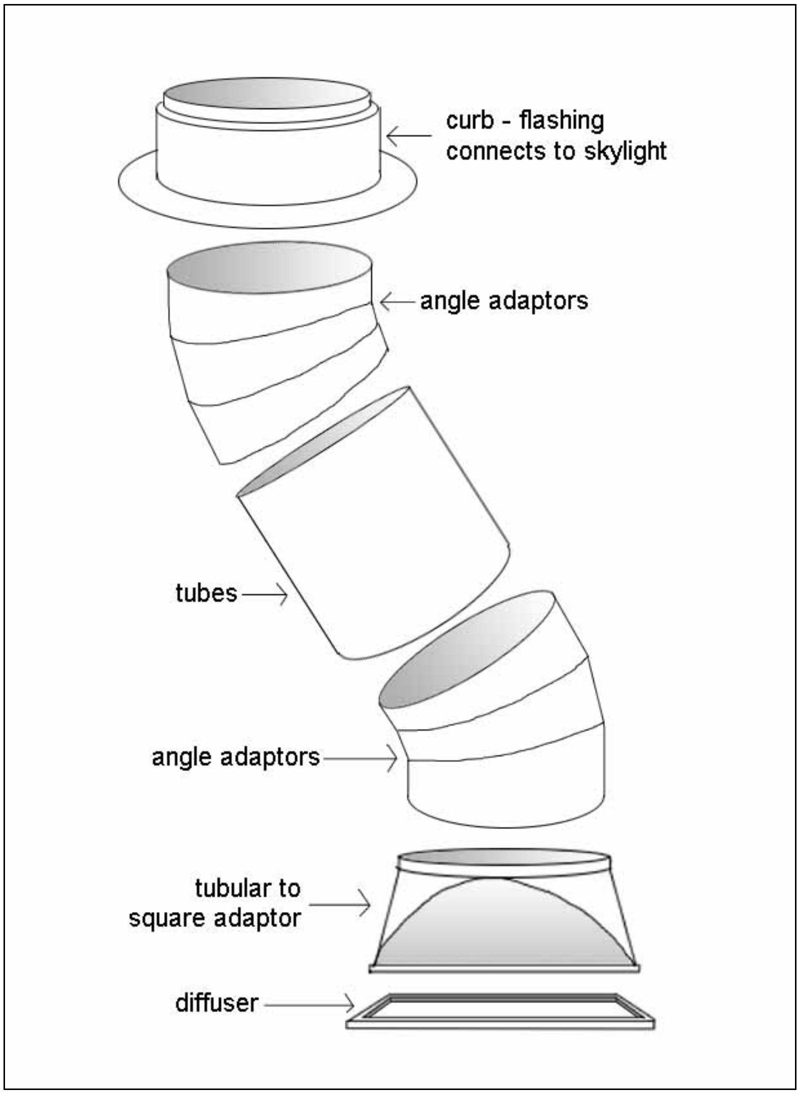


Figure 33. Conceptual diagram of Adjustable Tubular Throat (Fixed Splay) System.

This concept consists of a tubular sheet metal throat that can accommodate angular, horizontal and vertical offsets. Similar to angle adaptors used in plumbing and HVAC ductwork, the circular angle adaptors are twisted to create an appropriate angle offset. To create a horizontal offset and return the shaft to vertical, two complementary angle adaptors are used, as illustrated in Figure 33. Vertical adjustments are created by adding shaft members of different lengths, and some latitude for slippage in the shaft joints.

Figure 33 illustrates a commonly manufactured tubular skylight system that terminates in a plastic diffuser mounted at the ceiling plane. In order to make the transition from the circular cross section of the skylight well to the square shape of the ceiling diffuser a shape adaptor is mounted at the bottom of the shaft. It is also possible that the square diffuser could be mounted at the top of a splay, following the techniques discussed in either system example one or two.

System 4: Fixed Throat–Flexible Connector (Fixed Splay) System

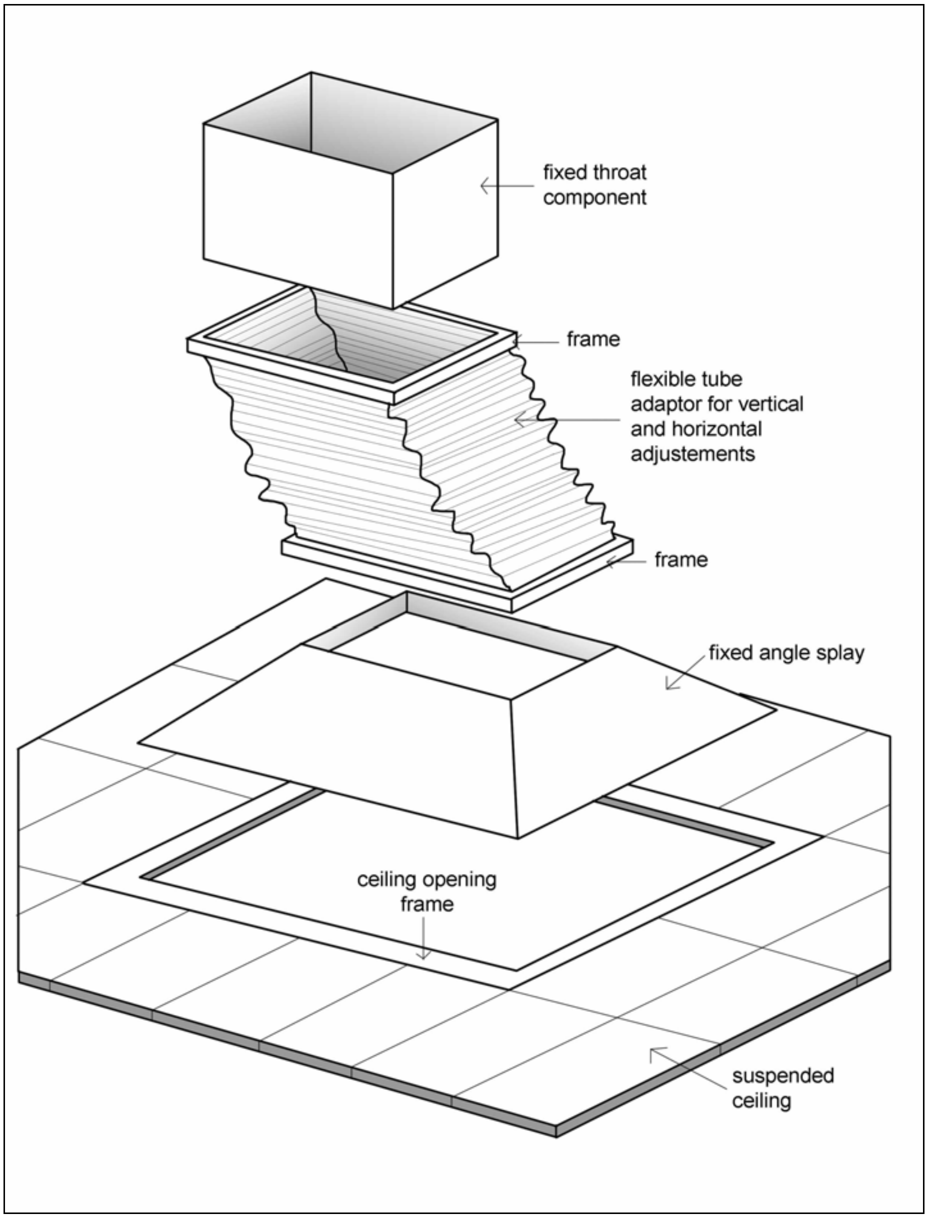


Figure 34. Conceptual diagram of Fixed Throat–Flexible Connector (Fixed Splay) System.

This concept uses a flexible throat-splay connector to take up all of the angular, vertical and horizontal adjustments, while allowing use of a fixed-angle splay system that could be prefabricated. Such a flexible connector could potentially be rectangular or circular or even amorphous in section. It is possible that the flexible element could create the entire throat, or be just a joint between a fixed throat and splay. Possible materials include a flexible tube, in the nature of HVAC "flexi-duct" or a stretchable fabric or elastic membrane.

In addition to identifying a construction material that meets requirements for elasticity, light reflection, and all fire and safety codes, other challenges to this system include avoiding joints or wrinkles that will reduce light transmittance, reserving the skylight well space during construction, and protecting the throat material during construction. It is possible that the flexible material would be the final element to be installed in the skylight well, creating a light-tight seal between a previously installed throat and splay.

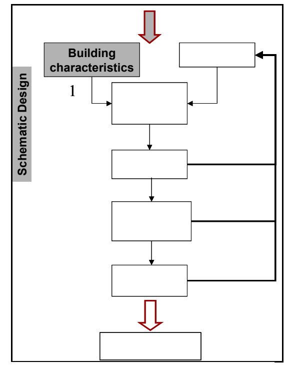
SAMPLE PROJECT

This section describes a step-by-step approach to the design of an example skylighting system that includes modular light wells. This example includes initial sizing and spacing of skylights and wells, energy and lighting calculations to optimize the design, and sample specifications. The broad outline of the design process is summarized by these six points:

1. **Building information**: The occupancy and the geometry of the space are key determining factors for estimating how much daylight is needed to enter the space.
2. **Early estimates**: SkyCalc or other simulation programs can combine the above information with climatic information, thermal and light transmittance details of the light well system and the electric lighting control strategy to estimate the energy savings for a range of total skylight areas. One can then choose the total skylight area that optimizes energy savings. The total skylight area is often normalized in relation to the floor area in the skylight-to-floor area ratio (SFR).
3. **Coordinate spacing**: In order to achieve uniform illumination patterns, the total skylight area has to be distributed evenly across the roof. Thus a regular spacing pattern needs to be defined. This spacing pattern will be primarily influenced by criteria for uniformity and coordination with the spacing of the building's structural grid. The secondary influences will be coordination with other building components, most especially electric lighting, but also fire sprinklers and HVAC diffusers.
4. **Refine design**: The size of an individual skylight can be calculated from the total skylight area and the spacing dimensions desired. The size of the skylight typically determines the throat and splay dimensions, and thus impacts the efficiency of the skylight well, which in turn may influence choice of skylight size. Thus, optimizing all of these parameters usually follows an iterative calculation of the ideal size, properties and spacing of the skylighting system.
5. **Test for lighting quality**: Once a skylight system design has been somewhat finalized, it can be tested for illuminance uniformity using photometric analysis. Steps four and five are typically performed during the design development phase.
6. **Specify system and construction process**: Coordination of the skylight placement and systems needs to be continued during both the construction document phase and the construction phase.

Schematic Design

In the schematic design stage the building and skylight details are entered into the SkyCalc software (or similar analysis program) to determine an appropriate SFR and well efficiency, based on desired illumination levels and energy savings from the system. Once these two criteria are established, the size and spacing of skylights can be determined. The various inputs and outputs of the SkyCalc analysis are outlined below and further detailed in the many tables and graphs in this chapter.



Stage 1.

Stage 1: Example Building Characteristics

- Occupancy type and location: An office space in Sacramento, California
- Room dimensions and reflectances: An open office space 60' x 72', with a roof height of 17', ceiling height of 11', and a 6' high plenum. The room surfaces have typical floor reflectance of 20%, wall reflectance 80% and ceiling reflectance 80%
- Spacing of fire sprinklers: approximately 100 sf area per head
- Electric lighting system: fluorescent T5 or T8, direct or direct/indirect, 50 footcandles target illuminance, layout to be determined, automatic photosensor controls with dimming or multi-level switching
- Structural system: Wood deck with primary structural members spaced 20' on center, secondary members 8' on center, and tertiary members 2' on center
- Partition dimensions: 8' x 8' office cubicles, with 5' high partitions

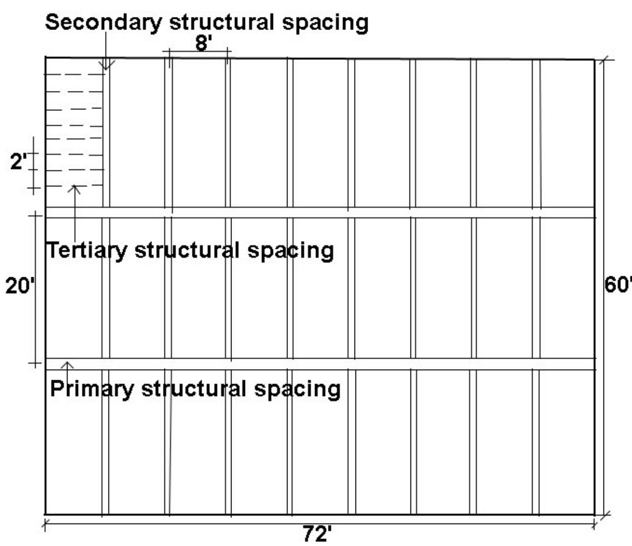
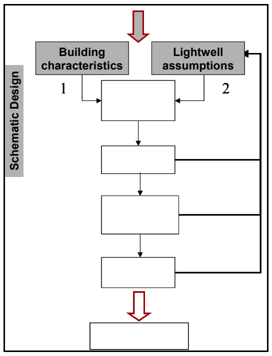


Figure 35: Approximate spacing of structural components in the office space.

Figure 35 shows the spacing of the primary, secondary and tertiary structural components in the office space. Ideally, the skylight spacing will work with these dimensions to minimize special conditions or a need for additional framing. It is also possible, however, that the architect might inform the structural engineer that a different spacing might be more optimum for the skylight design.



Stage 2.

Stage 2: Skylight and Light Well Design Assumptions

At this stage, some assumptions are made about the number and dimensions of the skylights and light wells, along with a target for the SFR (which must be no more than 5%, based on the current energy codes). Based on the discussion earlier in this document, the skylight well is designed with a throat and splay as shown in Figure 36. (The specifics of this example were chosen for simplicity rather than optimum performance.)

The assumptions for the skylight and light well are:

- Skylight size: 4' x 4'
- Number of skylights: 9
- SFR: 3.3%
- Skylight type: double glazed acrylic dome, white pigmented upper layer, 59% visible light transmittance
- Skylight well height: 6'
- Throat height: 3'
- Splay height: 3'
- Splay angle: 45°
- Diffuser: At base of throat (visible light transmittance of 80%)
- Splay and throat reflectance: 80%
- Ceiling reflectance: 80%
- Floor reflectance: 20%
- Wall reflectance: 70%

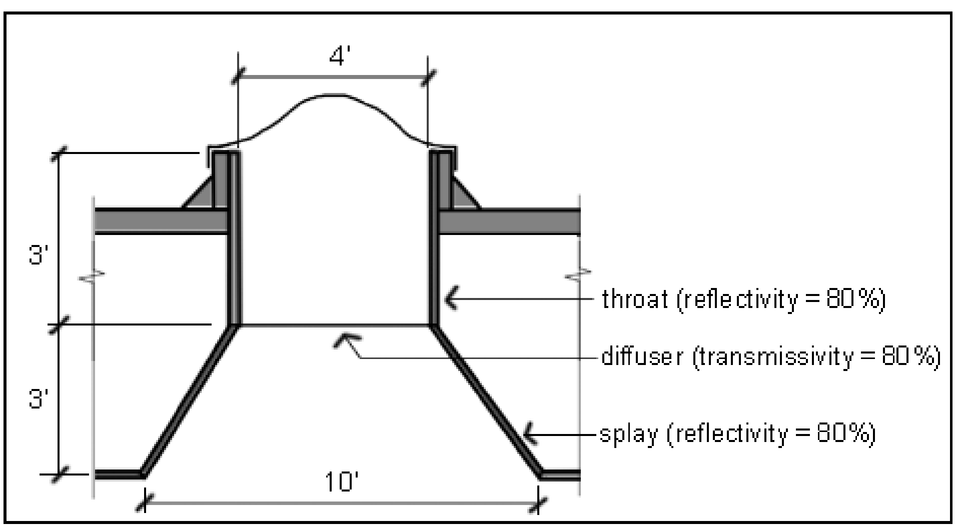


Figure 36. Section of the example skylight well.

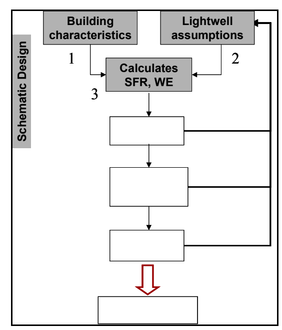
Stage 3: Determine SRF and Well Efficiency

The SkyCalc simulation then calculates the well efficiency of the light well, and the total annual energy savings for that particular SFR and skylight design. The following sections give a step-by-step explanation of the SkyCalc calculation process.

1. Skylight to Floor Ratio (SFR) depends on the area and number of skylights relative to a fixed floor area.

SFR= Area of skylights x number of skylights

Thus, for a given SFR (in this case 3.3%) there are other sizing and spacing alternatives available. For example, alternative solutions for this design could be 9 skylights (4' x 4' dimension), 12 skylights (3' x 4') or 36 skylights (2' x 2') all of which achieve the same SFR and average illumination levels. The choice of which alternative to select should be determined by minimizing cost of purchase, installation and number of roof penetrations while optimizing for lighting uniformity and coordination of spacing with other building elements. In general, for the same well height and configuration, fewer larger skylights will be more efficient and cost less to install, while more smaller skylights will produce better lighting uniformity.



Stage 3.

2. Well Efficiency (a.k.a. Well Factor)

For a light well with a throat and a splay, the well efficiency must be calculated in a two or three step procedure. First the well efficiency for each component is calculated, then all components are combined into a net value. This can be done either using SkyCalc® or hand calculations. The hand calculation procedure is shown in Appendix 8. The SkyCalc® method is illustrated here.

First, calculate well efficiency of the throat (WE_{throat}), specifying the skylight and well dimensions of 4' x 4' and a well height of 3' with a surface reflectance of 80%. The resulting WE_{throat} is shown as 68% in Figure 37 (see highlighted box in the figure).

Skylights	Default	User Revisions	Design Input
Visible transmittance	59%		59%
Solar heat gain coefficient	53%		53%
Curb type	Wood	Default	Wood
Frame type	Metal w/ thermal brk	Default	Metal w/ thermal brk
Unit U-value (Btu/h·°F·ft^2)	0.653		0.653
Dirt light loss factor	70%		70%
Screen or safety grate factor	100%		100%
Light well reflectance	80%		80%
Well factor (WF)	68%		68%
Bottom of light well:			
Width (ft)	4.00		4.00
Length (ft)	4.00		4.00
Diffuser on bottom of well?	No	◉ Yes ○ No	Yes

Figure 37. Part of SkyCalc inputs showing well efficiency of throat.

Next, well efficiency for the splay (WE_{splay}) is calculated by running SkyCalc® again, changing the bottom of the splay area to 10' x 10' (this value is input in the "user revisions" column on the "Optional Inputs" tab—see circled area in Figure 38) while the skylight dimensions, well height and reflectance remain the same based on the design described above. WE_{splay} was calculated as 87% (highlighted box).

Skylights	Default	User Revisions	Design Input
Visible transmittance	59%		59%
Solar heat gain coefficient	53%		53%
Curb type	Wood	Default	Wood
Frame type	Metal w/ thermal brk	Default	Metal w/ thermal brk
Unit U-value (Btu/h·°F·ft²)	0.653		0.653
Dirt light loss factor	70%		70%
Screen or safety grate factor	100%		100%
Light well reflectance	80%		80%
Well factor (WF)	87%		87%
Bottom of light well:			
Width (ft)	4.00	10.00	10.00
Length (ft)	4.00	10.00	10.00
Diffuser on bottom of well?	No	◉ Yes ○ No	Yes

Figure 38. Part of SkyCalc inputs showing well efficiency of splay.

Finally, the WE of throat and splay are multiplied together with the VLT of the diffuser included in the throat to obtain a net well efficiency for this design.

$WE_{lightwell}$ = WE_{throat} x WE_{splay} x T_{vis} of diffuser

= 0.68 x 0.87 x 0.80 = 47%

Now that the net well efficiency of the compound light well has been determined to be 47%, this value should be used for all subsequent calculations. This can be done in SkyCalc by entering 47% in the "user revisions" column for "Well Factor" to override default values.

Stage 4: Skylight Spacing

Skylight spacing can then be estimated using the rule of thumb equation for spacing between skylights discussed in the System Design Section of this Guide.

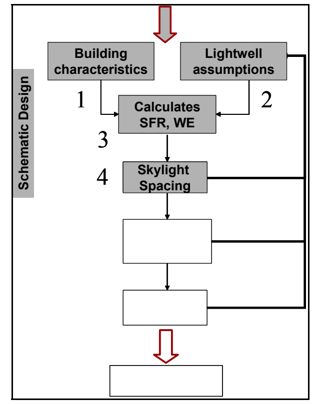
Rule of thumb: The distance between skylights (on center) should be no greater than:

$$\text{Skylight spacing} \leq (1.4\ x \text{ ceiling height}) + (2\ x \text{ splay width}) + \text{skylight width}$$

$$< (1.4\,x\,11) + (2\,x\,3) + 4$$

Thus, the distance between skylights with splay (on center) should be no more than 25.4'.

Figure 39 shows one solution to the proposed design of (9) 4'x4' skylights spaced no more than 25' apart: skylights placed on a 20' x 24' grid.



Stage 4.

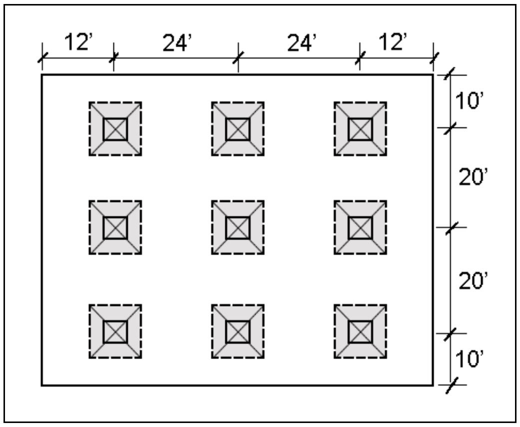


Figure 39. Spacing layout of light well with splay.

Figure 40 shows how this skylight spacing could work with the proposed structural grid. In one direction, both the skylights and the primary structural members are spaced every 20'. In the other direction, the 8' secondary structural spacing works well with a 24' skylight spacing, with skylights placed every third bay. The 2' tertiary structure and 4'x4' skylight allow easy framing of the skylight opening. However, if the skylight opening and structure conflicted, the architect and structural engineer would need to reconsider the skylight spacing or structural spacing.

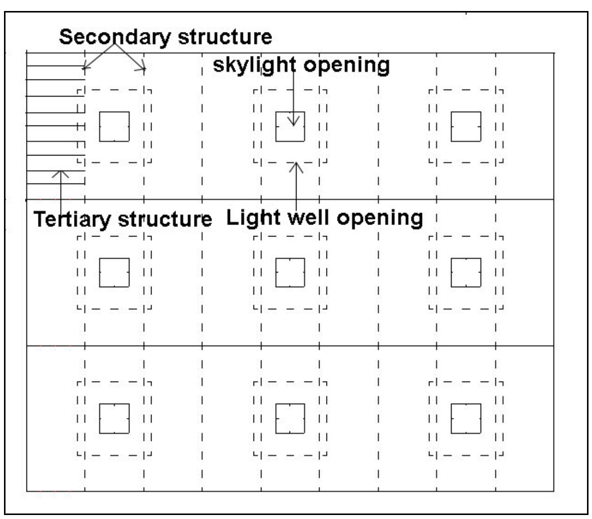
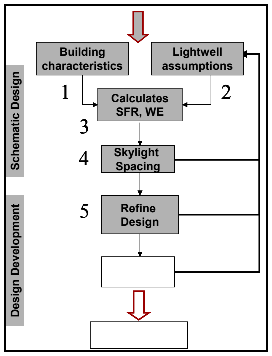


Figure 40: Overlay of structural spacing with skylight spacing.

Design Development



Stage 5.

Stage 5: Refining Design

The next step, usually undertaken during design development, is to coordinate the skylight system design and spacing with other building systems and refine the well design.

Ceiling Grid: A 2' x 4' ceiling grid could potentially be laid out in a number of relationships to the skylight grid. Each possibility should be considered relative to its impact on the placement of other systems, especially the electric lighting layout. One ceiling grid arrangement with skylights is shown in Figure 43. Since the light well opening is 10' x 10' while the 2' x4' tiles can only be laid out in a 10' x 12' pattern, ceiling tiles will have to be cut on at least one side of the opening. A one foot tile on either side of the splay allows for symmetrical arrangement of tiles around the splay, while a 2' tile on one end of the splay would allow for placement of 2' wide diffusers or troffers in that area.

Often, however, the ceiling grid and skylight opening do not properly align. In such a case, there are other possibilities for adjustments to resolve the issue: the ceiling grid can be shifted within the room; the tiles can be cut to match the splay location; or the throat or splay opening can be shifted horizontally to better align with the ceiling grid. Sometimes, all three of these adjustment methods may be used to resolve the two systems.

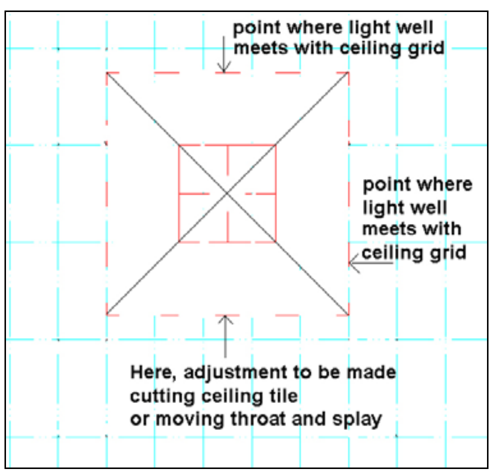


Figure 41: Partial plan showing ceiling grid with one skylight well.

Another option of laying the ceiling tiles is shown in Figure 42 where the grid has been adjusted to avoid cutting ceiling tiles on both sides of the skylight well.

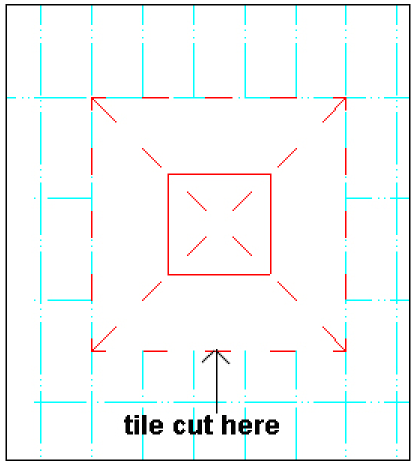


Figure 42: Ceiling grid layout option 2.

Electric lighting: It is easiest to lay out the electric lighting system when the skylights are located on a direct multiple of the light fixture spacing dimension or vice versa. Ideally, the splay opening should not be larger than the maximum spacing of electric lights. This is especially important with the use of recessed direct lighting systems. The use of pendant mounted direct/indirect fixtures allows the skylight grid and electric grid to be somewhat independent of each other, since pendant fixtures can be mounted directly underneath the splay area. Below are three examples that illustrate alternative strategies for lighting system design and also incorporate the sprinkler grid.

Figure 43 shows the layout of indirect/direct fixtures with the skylight spacing of the example building. This design is based on the use of very wide distribution 30% down / 70% up light fixtures mounted 18" below the ceiling plan with one T5HO lamp per 4' section on single circuit dimming controls. The lighting designer found that by keeping the luminaires a minimum of 3' from the edge of the skylight well, system efficiency and uniformity were optimized, since the reflection of light off of the horizontal ceiling plane was maximized. The irregular spacing of the pendant fixtures is unusual, but produces acceptable uniformity ratios of less than 1:4 in an open plan room.

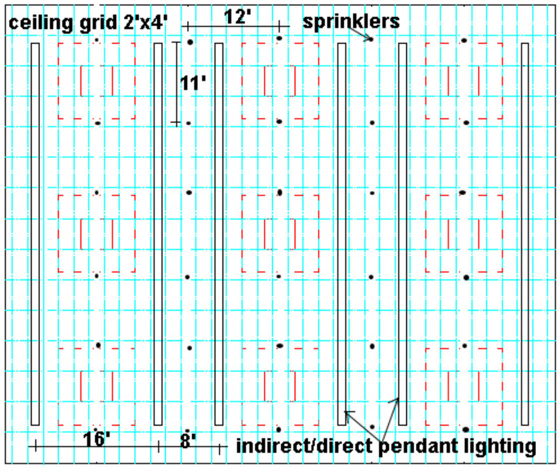


Figure 43. Plan showing 16' and 8' space for pendant lighting (and sprinkler spacing).

Figure 44 shows another layout with the same pendant fixture spaced a uniform 12' apart, with one fixture centered below the skylight and one in between skylights. This approach allows the use of a two-circuit control system that could switch or dim the row of fixtures under the skylights sooner than those between the skylights. The ability to turn off the row of lights underneath the skylights more often may produce higher energy savings in some climates. However, these savings needs to be counterbalanced with the loss of efficiency of the system from the greater proportion of electric light which will escape up the skylight throat.

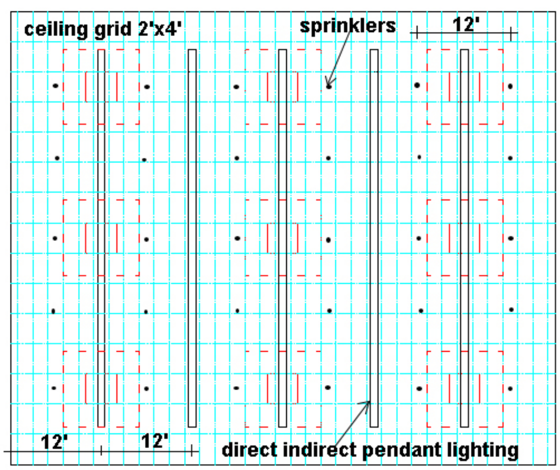


Figure 44: Plan showing 12' spacing for pendant lighting (and sprinkler spacing).

In both pendant lighting examples above, the sprinkler positions are located to avoid interference between the water throw pattern of the sprinklers and the pendant light fixture locations. The sprinkler grid may not be uniform throughout the layout as a result.

Figure 45 shows a possible layout of 2' x 4' recessed troffers around the skylight openings. The troffers are spaced on an approximate grid of 8' x 10', however the pattern actually alternates between 8' x 8' and 8' x 12' in order to keep the luminaire spacing in line with the skylight well openings. The troffers can be fitted with parabolic louvers which will direct most of the electric light downwards, minimizing the illumination on walls and ceiling. This may be an appropriate choice if computer tasks dominate and it is important to shield computer monitors from reflections from the light fixtures. However, if the illumination level of the walls is the most important, as might be true in a classroom where computer tasks do not dominate, then selection of a prismatic lensed troffer with a wide distribution might be more appropriate. Sprinkler spacing for recessed troffers is less critical, as the recessed lights will not interfere with the water throw pattern of the sprinkler heads. The sprinkler heads can even be located underneath the skylight well.

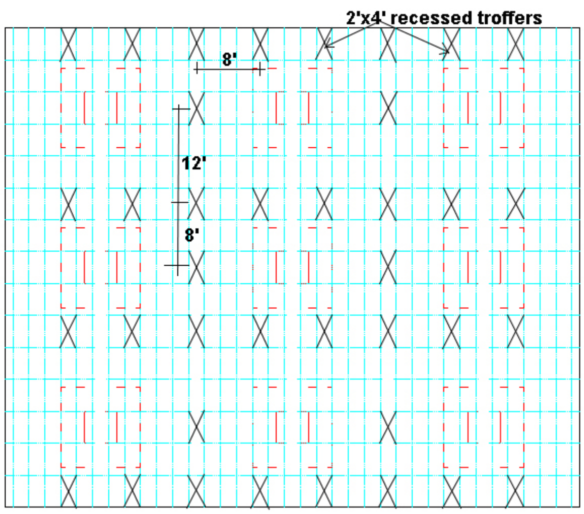


Figure 45. Plan showing 2' x 4' recessed troffers.

HVAC diffusers: The location of diffusers (not shown in the figures) should be based on the ceiling grid spacing. Diffusers can be typically placed as 2'x2' within the ceiling grid or linear diffusers, also in multiples of 2'. The duct layout within the plenum space needs to avoid the vertical skylight wells and allow for working room on both systems. The pivoted rods in the throat region help reserve the light well space. These rods also allow adjustments to be made to the throat, if the HVAC ducts overlap with the light well space.

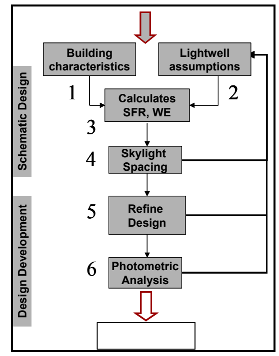
Photocontrols: Decide on photocontrol type, logic and set points. Consider the circuitry layout of the electric lighting system to optimize energy savings.

Glazing: Finalize the skylight glazing type: Double-glazing with clear prismatic lens was chosen for this example. Double glazing on a skylight is the minimum requirement according to energy code. The prismatic lens helps in better distribution of daylight in the room through the light well.

Light control device: Decide on any additional light control devices for the skylight system

Reserve space: Represent the skylight openings and well exclusion zones on the architectural plans and sections (see list of CAD drawings in section "System Coordination") to make sure other professions and trades are aware of skylight and well locations.

Stage 6: Photometric Analysis



Stage 6.

The photometric analysis (using Lumen Micro 2000 software program) was done for various conditions of the light well (4'x 4' size) with splay: with and without electric light; a clear and cloudy day; peak daytime light conditions. An open room (no shelves) and a room with shelves were also considered for analysis. This light well was also compared with a light well without splay to analyze the advantages of having splays in light wells. Some broad conclusions were made based on this photometric analysis.

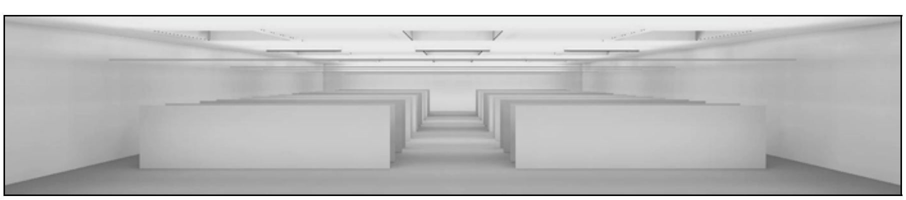
Two conditions of the effect of furniture on the spacing and sizing of skylights is given below:

- Open space with minimum furniture (like a classroom): The size of the skylight (4' x 4') for an open space with the given ceiling height produced a reasonable uniformity of light in the space. Figure 46 shows that even though there is uniformity in the room, the walls are not that well illuminated and the skylights may need to be spaced more towards the walls.

Source: Benya Lighting Design

Figure 46. Photometric results for light well with splay (cloudy conditions).

- Room with significant shadowing from furniture (like a retail space with display shelves or open plan office with partitions): Partitions add shadows in the room and as a result are more demanding in terms of uniformity in light (shown in figure below). A room with partitions would require smaller skylights and more in number in order to get the same uniformity as that of an open space. Increasing this dimension of skylight (4'x 4') might not be a good design in this room condition unless the ceiling height is increased to 15—16'. Smaller skylights like 2' x 4' or 2' x 2' and more in number would result in a more uniform distribution of light for this given room specification.

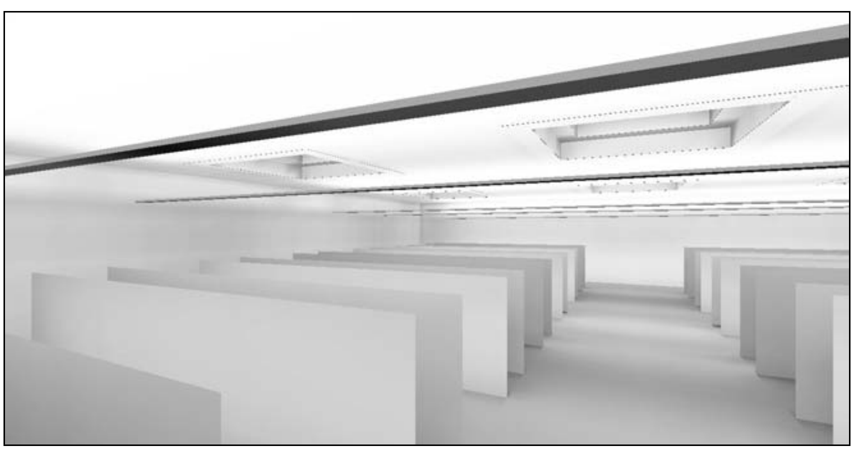


Source: Benya Lighting Design

Figure 47. Effect of skylights on a room with shelves.

Photometric analysis on compatible electric lighting design was conducted for the following conditions:

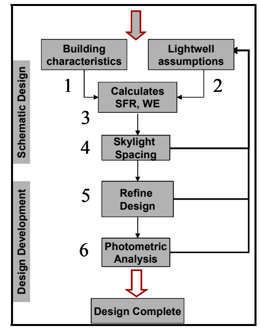
- Room with skylights and all electric lights on during night time (open space). Here the lighting system (indirect luminaries) provides all the lighting needs at night. This analysis resulted in a uniform light distribution with max:min ratio of 3.2:1 with average light levels of 47 fc and lighting power density of 0.76 w/sf.
- Room with skylights and all electric lights on during night time (room with shelves in Figure 48). Here, an indirect electric lighting system was analyzed. The aisles and shelves show even illumination with typical aisle lighting of 50-70 fc at work plane and 30 fc average on shelves.
- Room with partial sun and lights partially dimmed. This indicates that the lighting system is designed to complement the skylighting system. The focus of this analysis is that the electric lights provides efficient light between skylights. Thus the analysis is looking at the spatial patterns of illuminance in iso footcandle contours and is reflected in the uniformity metric of max to min illuminance. On a cloudy day with electric lights (direct luminaries) dimmed to 50%, the room with shelves showed even illumination as a result of even pattern of direct lighting.
- Room with full sun and electric lights dimmed or turned off. This analysis is focused on the quality of light from skylights. It helps identify if the design must be altered to maintain uniformity, provide adequate luminances on walls or other surfaces and minimize glare. In some cases, it might be found that some electric lights must be left on to provide adequate visual quality. Ideally, this is not the case and electric light is required only for times when solar availability is low.



Source: Benya Lighting Design

Figure 48. Room view with partitions and indirect lighting.

Example Outline Specifications



Skylight Design Process

The component specifications given below are based on the example building and the conceptual skylight well “System 1” and would vary depending on the actual light well system and other details of the building. These may serve as a building block for designers to start the process of specifying their light well components.

Scope of Work

1. Contractor shall provide all materials and labor necessary to install the whole skylight well system, including the unit skylight, throat, splay, diffusers, component interconnectors and other structural supports required to attach skylight well to the structure.
2. Other work sections related to skylight well installation includes electrical, fire protection and the suspended ceiling system.

Quality Assurance

1. Contractor shall provide documentation of product evaluation reports, such as those issued by ICC-ES or Underwriters Laboratories (UL) listing.
2. Contractor shall provide product performance evaluation reports, such as photometric reports.
3. Contractor shall submit a sample of the product or material to be installed for owner approval.

Materials

Skylight

1. Skylight shall be placed upon a curb projecting at least 4” above the surface of the roof.
2. Skylight product shall be compliant with the ICC Acceptance Criteria for skylights.
3. Opening should be fitted with burglar bars or fall protection bars, according to OSHA standards.
4. Skylight frame shall be self-flashing, insulated and have an integrated condensation gutter. If the skylight frame is metal it shall have a thermal break with a thermal conductivity no greater than 3.6 Btu-inch/hr·sf·°F.
5. Glazing shall be double-glazed. If it is glass, it shall have a low-e coating on the inside surface of the outer glazing layer and shall comply with ANSI-Z97.1. If it is plastic, it shall be classified as CC2 or CC1 material.
6. Skylight glazing will withstand a pressure test according to ASTM E-330-97 with a safety factor of 3 applied.
7. No water penetration shall occur when the system is tested in accordance with ASTM E331 using a differential pressure of 20% of the inward design load pressure but no less than 12 psf.

8. Glazing material or diffusing interlayer should have a minimum haze of 90%.

Throat

1. Throat material to have reflectivity of at least 80%.
2. Throat material shall have a flame spread index no greater than 25 and a smoke developed index no greater than 50 when tested according to NFPA 255 or ASTM E84.
3. Material should have accommodations for sprinkler head penetration.
4. Interconnectors should be of a non corrosive material.
5. Connector of light well to structure should allow for isolated movements of the light well independent from the structure.

Splay

1. Splay material shall have a flame spread index no greater than 25 and a smoke developed index no greater than 50 when tested according to NFPA 255 or ASTM E84.
2. Splay material shall have a reflectivity of at least 80%.
3. Connectors shall be made of a non-corrosive material, properly concealed and finished on the light well interior.
4. Throat-splay connector shall have attachments for a diffuser.
5. Splay-ceiling connector shall be compatible with the ceiling grid system.

Light Control Devices

1. Diffuser should have a light transmittance of at least 80%.
2. Diffuser should have a haze value of at least 90%.
3. Diffuser attachment should allow access to the throat of the light well.

Photocontrols

1. Dimming controls for office spaces shall comply with section 118 of Title 24.
2. Location of dimming controls to be decided at a spot with minimum light level for photosensor placement.
3. Dimming controls to be compatible with electric light ballasts.

Fabrication

1. All assemblies shall be finished, fabricated and shop-prepared under the responsibility of one or more manufacturer, depending on the light well system.
2. Assemblies to allow thermal movement of materials when subject to a temperature differential from -30°F to 180°F.

Installation

1. Worker shall be protected during installation according to OSHA 1910.23. Installing fall protection bars in the skylight opening immediately after framing in the opening will partially meet this requirement.
2. Skylights shall be installed according to the National Roofing Contractors Association (NRCA) Roofing and Waterproofing Manual.
3. Installation shall be coordinated with installers of related systems, such as suspended ceiling, fire protection, electrical, mechanical and structural.
4. Installation procedure shall be in compliance with seismic requirements.
5. Throat and splay shall be installed according to manufacturer's installation instructions.
6. Light well space shall be reserved during construction to prevent the trespass of other building services. Construction ribbons or tape shall be hung from the bottom of the throat to the ceiling level.

Commissioning

1. Upon installation, skylights shall be tested for water tightness. All repairs to be done before installation of throat, splay and ceiling.
2. Photocontrols to be commissioned according to manufacturer's instructions.

Component Requirements

This chapter discusses in detail the geometric and physical properties required of each skylight well component to satisfy the minimum performance requirements goals for illumination and energy performance, fire safety, structural integrity and assembly sequence along with design options.

SKYLIGHT

A skylight is a glazed opening in a roof which admits light. Its main function is to transmit daylight while preventing people from falling through the roof penetration into the interior space. In addition there are many secondary functions that must be satisfied. A skylight must be firmly attached to the building structure so it cannot blow away under storm conditions. The skylight should maximize the amount of daylight and direct sunlight transmitted to the space below, while simultaneously helping to diffuse the light for optimum light distribution. The skylight system should reduce heat flows in and out of the building to reduce heating and cooling costs. The skylight should also be designed to prevent problems from the moisture that will occasionally condense on cold glazing and frame surfaces.

A skylight encompasses the frame, condensation gutters, glazing and associated connectors to the curb (Figure 49). These components are directly attached to a rooftop curb assembly.

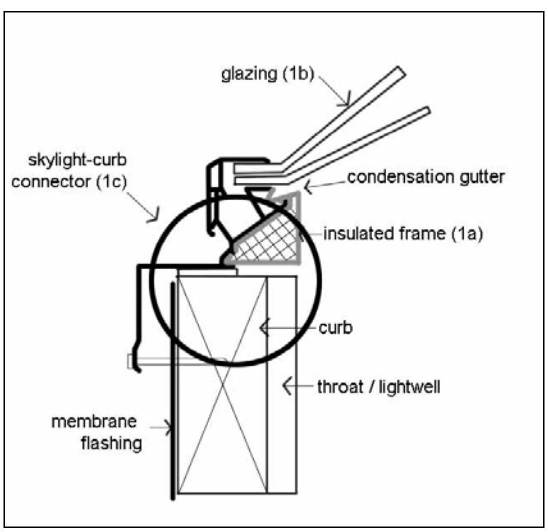


Figure 49. Details of a skylight.

Minimum Performance Requirements

The following are necessary for a skylight to perform the minimum functions listed above:

- Frames should be thermally broken to mitigate extreme temperature differences between the exterior and interior, thereby reducing heat flow between inside and outside and reducing condensation in colder climates
- Frames should incorporate a condensation gutter to control water penetration
- Glazing should diffuse sunlight to collect small amounts of moisture from condensation on the glazing surface
- Skylight glazing and diffuser should be compliant with section 2409 and section 2603.8 of Uniform Building Code

The skylight frame should be properly attached to the curb, as follows:

- Appropriate counter flashing should be included if the frame is not self-flashing
- Roof membranes should be installed over the curb and the frames should be installed over it
- To minimize leakage problems, fasteners should not penetrate membrane flashing
- Skylights should be installed according to the National Roofing Contractors Association (NRCA) Roofing and Waterproofing Manual
- Rails or burglar bars for fall protection and safety should be incorporated according to OSHA 1910.23
- Test for water leakage should be made in accordance with AAMA 501.2: Field Check of Metal Curtain Walls for Water Leakage

Design Options

Glazing

The type and shape of glazing used in skylights is an important determinant of the efficiency of the skylight system. Key options include the degree of visible light transmittance of the glazing material, the thermal properties of the glazing, clear versus diffusing glazing, glass versus various plastics, and the three dimensional shape of the skylight. Most of these issues are discussed in depth in the *Skylighting Guidelines*, and the reader is referred to that document for additional guidance. However, there have also been a number of new developments in glazing materials available for skylights since the *Skylighting Guidelines* was written in 1999. This document cannot provide detailed technical information about all of these developments, but does try to provide an overview on the key glazing choices facing the designer.

Since the primary function of a skylight is to provide illumination in the space below, the amount of visible light it lets through is a key determinant of its efficiency. In general, skylight glazing materials with the highest possible visible light transmittance typically have the best energy balance, allowing the greatest reduction in electric lighting energy use with the least penalties on the heating and cooling system. This is because glazing materials with a high visible light transmittance (VLT) allow the use of smaller skylight openings. Smaller openings mean less heat loss and heat gain. SkyCalc®, described earlier, allows comparison of the energy balance of various glazing options in different climates. In general, high visible light transmittance glazing is the most important characteristic to improve the efficiency of a skylighting system. The solar heat gain coefficient (SHGC) and the heat loss factor (U-factor) are secondary and tertiary concerns. Their relative importance varies with climatic conditions. Overall, a glazing material that provides high visible light transmittance while reducing solar heat gain (low SHGC) and minimizing heat flow (low U-factor) will give the best whole building energy performance.

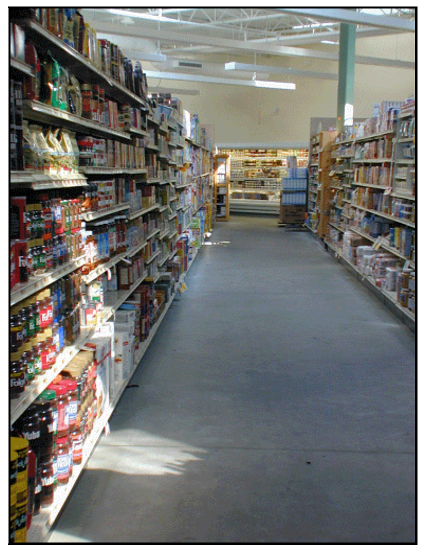


Figure 50. Clear skylight with "hot spot."

Figure 51: Diffused skylight with uniform daylight.

Many designers and building owners initially favor the concept of using clear glazing for the skylight material, primarily to allow a view of the sky and increase light transmission. However, a diffusing glazing material is typically the preferred choice for skylights in commercial buildings for a number of reasons. A clear glazing material allows direct beam sunlight to enter the skylight and potentially penetrate down to the interior space. Direct beam sunlight is too intense and will cause intense pools of light, called "hot spots," which are visually glaring and make the rest of the space appear dark in comparison. In addition to increasing the visual contrast within the space, these "hot spots" also raise local temperatures, making people uncomfortable. If a clear glazing is used in a skylight, a diffusing element should be located somewhere else in the skylight well system in order to avoid these problems. Using a diffusing glazing in the skylight scatters sunlight at the upper end of the well and avoids the problems of direct beam sunlight.

Figure 50 shows a grocery store with clear skylights. This store had problems with chocolate cookies melting and an ice glaze forming over frozen goods that came underneath the hot spot. The bright spots of sunlight also interfered with the optical scanners at the checkout counters.

A similar grocery store, but with a diffusing glazing in skylights (Figure 51), has daylight distribution that is vastly more uniform and has no local overheating problems.

There are a number of methods to create a glazing material that diffuses light. This can be done with pigments located within or on the glazing, composite materials such as fiberglass, optical surfaces such as prismatic or fresnel lenses, or micro-optical surfaces such as holographic films. The key issue is how well the light is scattered. Diffusion is best measured with photometric testing that describes the pattern of how light passing through the material is scattered. A simpler metric, called "haze," gives an approximate metric of diffusion..

Designers are also faced with a basic choice of glass versus a variety of plastic skylight glazing materials. Plastic materials have many advantages, such as the ease of creating three-dimensional shapes and incorporating optical surfaces, while glass has other advantages such as durability and low-e coatings. Multiple glazing layers are available in both glass and plastic. There have been many recent innovations in glazing materials, involving technical issues beyond the scope of these Guidelines, thus the reader is advised to consult additional current sources regarding the selection of the best glazing material.

The following lists summarize some of the key issues in the choice between plastic and glass skylight glazing materials.

Plastics

- Can have three dimensional shapes
- Lighter in weight
- Optical surfaces can aid in distribution of light
- Stability of glazing varies by plastic formulation
- Optical surfaces can aid in distribution of light
- Shaped edges can rely more on gravity than sealants to shed water
- Low-e options not commonly available

Glass

- Can only have straight surface configurations
- Heavier in weight
- Requires secondary light control devices to achieve a diffused light distribution
- More durable and stable material but relies on sealant for water-tightness at joints
- Requires slanting skylight or curbs to shed water
- High performance glass options like low-e glazing provide better ratio of visible light transmission to heat gain and heat loss

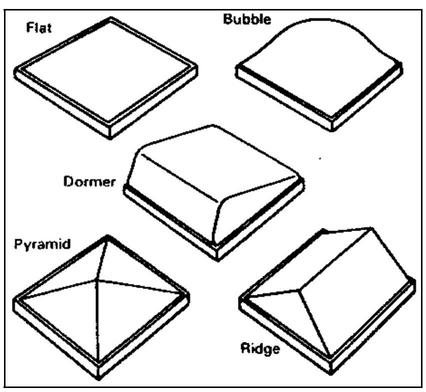


Figure 52. Different skylight shapes for plastic glazing.[6]

Figure 53. Glass skylight[7]

The shape of the skylight glazing can also affect the efficiency of a skylight system. Three-dimensional shapes, such as domes and pyramids, capture more low-angle sunlight in the early morning and late afternoon, thereby extending the number of hours with effective daylighting in the space below. Flat surfaces can have high reflectance angles, rejecting more sunlight when it is most useful. Photometric reports (HMGc 2003) are available on various skylight shapes that compare performance at different sun angles over the course of a day and season.

[6] Source: Home Energy Magazine 1993

[7] Source: Unique Commercial Applications of Light Pipes, Ensar Group, Inc.

Figure 52 and Figure 53 illustrate some of the shape options available for skylight glazings. In general, a shape and a glazing material that increases light transmittance at low sun angles and reduces sunlight transmittance at high sun angles will improve the efficiency of the system.

THROAT

The throat is the element of a light well that conveys light from the skylight to the interior space. By providing a reflective surface, it reduces the loss of daylight in the volume between the roof and ceiling. Since the location of the skylight on the roof may be determined by the structural grid, while the placement of the skylight well opening in the ceiling may be determined by a different ceiling grid, the throat should also allow for slight displacements between the top and bottom openings of the system. In addition, even in flat roofed buildings, the roof plane is typically at a slight slope to shed water while the ceiling surface is purely horizontal. Furthermore, since there are many other building systems competing for space in the plenum, sometimes there is a need to move the skylight well out of the way of a structural column or a water pipe. All of this implies the throat should have an ability to redirect light to some degree and have an adjustment mechanism to accommodate construction tolerances.

Throats may serve other secondary purposes, such as protecting the plenum from fire and smoke spread or reducing the transmission of noise between the plenum and interior space. They also need to accommodate the requirements of other building systems and codes. For example, some jurisdictions require that fire sprinkler heads be placed at certain intervals inside the skylight well. Throats may also serve as attachments and supports for other skylight well elements, such as light control devices, diffusers, or electric lights.

As explained in the "Nomenclature and Functions" section, the throat has two components: the structure and the surface. Structure refers to the components giving support and shape to the throat, such as frames, braces or hangers. The throat surface is the base material and interior finished surface providing the reflective and aesthetic properties of the light well, such as sheet metal, painted gypsum board or acoustic tile.

In a splayed light well, the throat connects the top of the roof curb to the top of the splay. In a non-splayed light well, it connects the skylight directly to the ceiling. A throat also includes a support system, such as bracings or hangers, which satisfy structural and seismic requirements.

The throat interconnectors are elements that connect two throat surfaces. They can be simple rigid members or flexible members that will allow the throat to have horizontal, vertical and angular displacements.

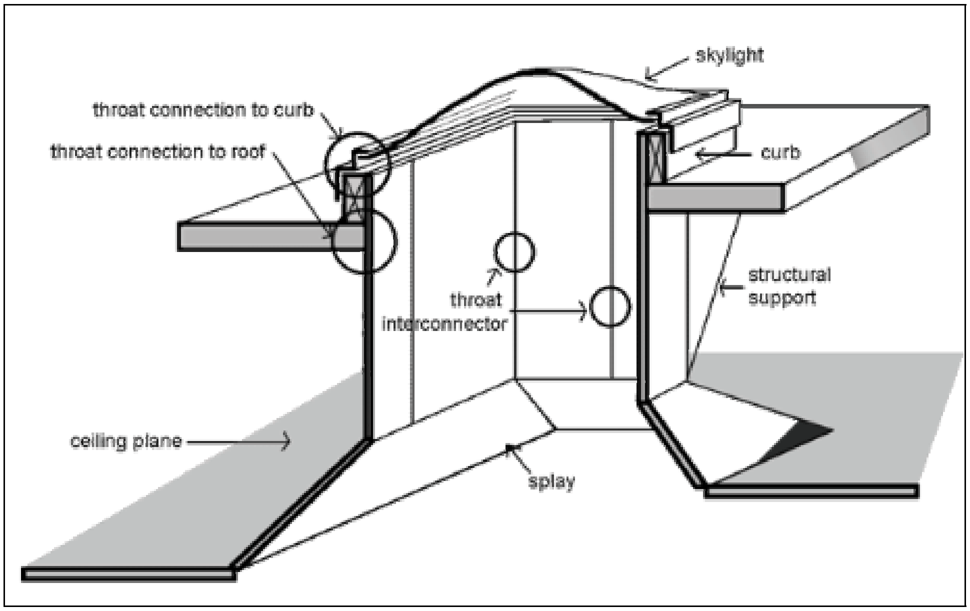


Figure 54. Cut section of throat.

Minimum Performance Requirements

The following are necessary for a throat to perform its minimum functions:

- The diffuse reflectance of the throat should be greater than 80%, and the specular reflectance should be greater than 90% (ASTM 2003)
- The throat should allow for angular vertical and horizontal adjustments repeated in the design
- The throat material should allow for easy penetration of sprinkler heads, if required by the Fire Code and/or the Fire Marshall having jurisdiction
- The throat materials should be relatively fire resistant. Throats in return-air plenums should have a maximum flame spread index of 25 and a maximum smoke developed of 50
- The throat and its supports should have sufficient strength to support a light control device and its associated components, if required by design
- The throat should allow for easy attachment of light control devices such as louvers or photosensors, and penetration of related electrical elements, if required by design
- For rigid throats, their connection to the building structure should be provided with an isolating mechanism to absorb differential movements of the light well and the building
- Throat interconnectors (see Figure 54) should be properly concealed or finished
- The throat should be able to withstand physical abuse during installation or maintenance of other building systems located in the plenum

Figure 55. Light well made of sheet metal.

- Depending on building design, the throat might need to reduce heat loss to the plenum

Design Options

The design options for a throat depend on its shape and the properties of the construction materials chosen. Properties of four commonly used throat materials are described below:

Sheet Metal

- Overall high reflectivity and specularity
- Thin and relatively lightweight
- Typical rectangular cross section, compatible with rectangular skylights and T-bar grids
- Will require concealment of the well through the use of a diffuser
- With use of angle adapters, can easily navigate building systems within the plenum
- Connectors can be factory fabricated
- Can be shop manufactured

Source: Solatube

Figure 56. Tubular light well.

Adjustable Metallic Tube

- More flexible than a sheet metal system and can more easily navigate building systems within the plenum
- Circular shape reduces joints
- Multiple bends greatly reduce light transmittance
- Works best with a circular skylight
- Requires a transitional element from circular throat to rectangular ceiling grid
- Connectors can be factory-fabricated
- Will require concealment between interior space and throat through the use of a diffuser

Acoustic Tile

- Easier to install than gypsum board systems

- Consistent with appearance of T-bar ceiling
- Inflexible and difficult to manipulate within plenum
- Has to be built on-site
- More labor intensive, but lower in cost than gypsum board construction
- Requires flat surfaces
- Angled joints and location adjustments difficult to make

Source: Williams + Paddon office

Figure 57. Light well made of acoustic tiles.

Gypsum Board

- Inflexible and difficult to manipulate within plenum
- Seamless corner joints
- Requires finishing of interior surface, if left exposed to interior
- Will result in a heavier well system, requiring more structural support
- Has to be built on-site
- Most labor-intensive system
- Can be exposed to interior without diffuser as a concealment if throat and skylight provide adequate diffusive qualities

Figure 58. Gypsum board light well

SPLAY

The splay is the tilted bottom transitional component of a light well. It serves as a visual transition between the much brighter throat and the relatively darker ceiling to reduce glare effects from the skylight (Figure 59). Its main function is to improve light distribution in the interior space. At the same time, it can be used as a transitional element to change the light well's location, allowing it to avoid building components within the plenum or adjust its opening location to match the ceiling tile pattern.

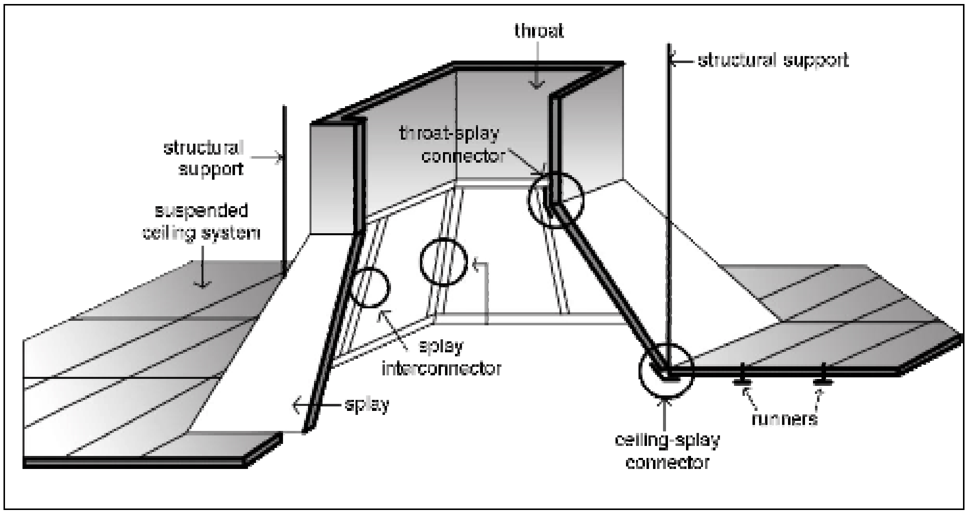


Figure 59. Cut section of splay.

A splay is directly connected to the throat and the ceiling system. It will also be connected to a network of support systems, such as bracing, or hanger wires, as required by structural and seismic conditions, and therefore it should fit into standard suspension grid dimensions (typically multiples of two feet).

Minimum Performance Requirements

The splay should have the following properties:

- Components should be easy to replace with off-the-shelf materials, preferably in pre-cut or cut-to-size sections
- Connection of structural support to surface members should be quick and easy, using pre-drilled holes, clips or tabs
- The splay should allow for sprinkler head penetration, should the design necessitate this
- The splay materials should be relatively fire resistant. Splays that are in return-air plenums should have a maximum flame spread index of 25 and a maximum smoke developed of 50
- If the splay is made of acoustic tiles, it should have a bottom opening dimension that is a multiple of the ceiling tile dimension. In most cases, this will be two feet or four feet
- The splay should have a minimum diffuse reflectance of 80%

An interconnector should have the following properties:

- It should have the necessary locking mechanism to prevent movement of attached splay surfaces
- It should be able to receive hangers or other structural support members
- For fixed angle splays, the connector should also have a fixed angle.
- Splay edges should be properly concealed for a clean, seamless finish

- Connections should be quick and easy, using predrilled holes, mechanical locks, slots or tabs

The throat and splay connection refers to the interface between the two components of the light well: the throat and the splay. This connector should have the following properties:

- Geometry of the connection should be such that the top surface of the connector (5a in Figure 11) is parallel to the throat and the bottom surface is parallel to the splay
- There should be proper concealment of the joint between the splay and the throat
- Connection to the throat should be quick and easy, using pre-drilled holes, mechanical locks, slots, or tabs
- The connection should allow for the attachment and removal of a diffuser, if one is required by design
- It should incorporate the necessary receivers for supplementary structural support (5c in Figure 11)
- Tolerances or adjustments shall be defined in horizontal offsets, vertical offsets and acceptance angle adjustment

Design Options

Design options for splays depend on the properties of the splay materials. The predominant splay materials commonly used are gypsum board and acoustic tile, as described below. Other splay materials can be sheet metal and fabric which are not described here.

Acoustic Tile

- Easier to install than gypsum board systems
- Has to be built on-site
- More labor intensive, but lower in cost than gypsum board construction
- Inflexible and difficult to manipulate within plenum
- Requires on-site bending of connectors

Figure 60. Acoustic tile splay in a classroom.

Figure 61. Gypsum board splay.

Gypsum Board

- Nice seamless connections
- Requires finishing of interior surface, if left exposed to interior
- Will result in a heavier well system
- Has to be built on-site
- Most labor-intensive system solution
- Can be exposed to interior without diffuser as a concealment if throat and skylight provide adequate diffusive qualities
- Inflexible and difficult to manipulate within plenum

SUSPENDED CEILING SYSTEM

The basic function of a suspended ceiling is to provide concealment for the array of building systems installed within the plenum and create a more uniform ceiling plane that could be more aesthetically pleasing within the interior space. The supporting grid for a modular ceiling system, typically made of T-shaped metal "runners." provides support for ceiling tiles, along with support and attachment for all of the other equipment that must be placed in a ceiling, including the light fixtures, the HVAC diffusers, fire sprinkler heads, and acoustic system speakers. The support grid must meet all structural and seismic support requirements. The ceiling tiles also serve a number of functions, including engineered light reflectance and sound absorption. In addition the ceiling tiles may serve an insulating or fire suppression function.

The suspended ceiling system is connected directly to the splay or light well opening. The splay-ceiling connector joins the ceiling system to the splay. It can incorporate a frame that provides concealment of the joints between the splay and ceiling.

Minimum Performance Requirements

The splay-ceiling connector should have the following characteristics:

- The top surface supporting the splay should be parallel to the splay
- Surface supporting the ceiling tiles should be horizontal, in line with the ceiling plane
- The connector should have the necessary attachments or details for connection to the hanger wires or other structural support system and to the ceiling grid
- Connection to splay and ceiling system should be quick and easy
- The edge interface should have a clean, seamless finish

LIGHT CONTROL DEVICES

Light control devices typically modulate or redirect the daylight entering the skylight before it enters the interior space. Light control devices include diffusers, louvers or shutters, baffles, reflectors and their associated attachments and control systems.

There are many possible functions for light control devices, including:

- Redirecting the daylight to create a wider distribution of light
- Redirecting daylight to certain surfaces, such as the ceiling or a wall
- Reducing the apparent brightness of skylight well surfaces to prevent glare
- Reducing the amount of daylight entering the space
- Providing blackout capability in the space
- Reducing the amount of light escaping back outside at night

Light control devices may also be designed to interact with the electric lighting system. For example, a reflector located underneath a skylight well might redirect both daylight from above and electric light from below, or an operable louver system might reduce daylight penetration at midday while also serving to minimize electric light escaping at night. In addition, light control devices might have secondary functions related to heat flow or fire safety. Diffusers can create an air tight layer to prevent warm room air from stratifying up into the skylight well, which has the potential added advantage of also reducing condensation from moist warm room air on cold skylight surfaces. Operable louvers or black out shutters can be designed with an insulting layer that not only provides the ability to reduce the amount of light (and unnecessary heat gain) entering the skylight during the day, but also can be closed to reduce heat loss at night.

The need for and function of light control devices is highly variable, depending on the design requirements of the building. It is possible to design skylights and modular wells with no light control devices at all. Since additional light control devices will inevitably add to the cost of a skylight system, it is a good idea for them to be as simple as possible while also providing the greatest possible utility.

Minimum Performance Requirements

Properties that are required of all light control devices are:

- They should help improve the efficiency of the skylight system by maximizing the useful distribution of daylight according to the needs of the space
- They should be easily attached to the throat-splay assembly
- Devices should allow access to the upper areas of the well for maintenance purposes
- Attachment should allow for tolerances in throat or splay construction
- Separate structural support and/or bracing is likely to be required for fire and seismic safety

- Any material placed inside of a skylight well should meet all applicable smoke and fire ratings

Design Options

Figure 63. Diffusers (without splay).

Source: PJHM Architects

Figure 62. Diffuser in skylit classroom.

The four main types of light control devices that designers can choose from to control light levels from skylights are described below. These are diffusers, reflectors, louvers or shutters and baffles. If any operable systems are used, designers must also specify whether they will be manual or automatic.

Diffuser

A diffuser is typically made of a thin plastic material with optical properties that scatter or redirect light. They can be flat or shaped, and are most likely to be located at the top of the splay, and thus the bottom of the throat. This location allows the greatest spread of light out from the restricted throat area, while helping to keep the bright diffuser surface from becoming a glare source.

Currently, the most common type of diffuser is prismatic acrylic sheets, similar to those used in 2' x 4' troffers. Figure 63 shows a diffuser at the bottom of a skylight well without a splay. In this photograph the skylight well diffusers seem indistinguishable from the similarly sized electric light fixture diffuser. However, in reality the skylight well diffusers will often be either much brighter or dimmer than the electric light diffusers, and will inevitably have a slightly different color appearance as the color of daylight changes over the course of the day (as shown in Figure 63).

Other diffuser solutions include fresnel lenses, high tech micro-optic surfaces like holographic films, or the more traditional milky glass or plastic. The primary goal of the diffuser should be to provide the best possible light distribution from the skylight, while avoiding the creation of glare sources. Diffusers with high visible light transmittance will create the most efficient skylight systems.

Advantage of diffusers include:

- As a fixed element, does not require controls

- Can serve as a concealment for wells, therefore well structures above diffuser need not be finished
- Allows the use of clear skylights
- May allow the use of larger skylights and wider spacing
- Relatively inexpensive
- Lightweight
- Many existing products are readily available with pre-existing attachment systems
- Can provide an additional membrane in light well to control the flow of heat and moisture

Reflector

A reflector is a device to re-direct light via reflection. A reflector can be opaque or translucent, flat or shaped, static or operable. Typically a reflector surface will be specular in order to maximize directional control of the light, although diffusing or matte-surfaced reflectors are also possible. They can be made of almost any construction material, including metal, plastic, glass, wood or fabric. Skylight well reflectors are typically placed either up inside the splay area, or hung down below the ceiling plane. As a separate element, they may require additional structural support and bracing.

Source: http:// www.kimbellart.org

Figure 64. Reflectors.

Reflectors have been used above or directly inside of skylights in order to selectively capture and redirect sunlight down the skylight well. However, these Guidelines will focus only on the use of reflectors at the bottom of the skylight system to redirect light in the interior space. Reflectors at the bottom of the skylight well can be used to redirect the daylight onto additional room surfaces, most commonly the splay or ceiling. Skylight well reflectors have sometimes been termed "clouds" since they are devices floating in space that help to diffuse and redirect daylight, much as real clouds do for sunlight.

Currently, the most common skylight well reflector material is probably perforated metal, a relatively light weight material that allows the reflector to take a curved shape, provides a specular inner surface, and allows a proportion of the light to pass directly through. Since perforated metal is also currently used for many high-end pendant light fixtures, there is an existing industry providing such light control products.

An important consideration in the selection of reflector material is the balance of brightness created between the underside of the reflector and the surface that it is illuminating. A translucent reflector that lets too much light through may become a glare source by being too bright itself, while an opaque reflector can create contrast glare between its dark underside and the bright surfaces above. This need for visual balance is additionally complicated by the fact that the intensity of daylight is constantly changing. One solution is to have the underside of the reflector illuminated by electric lights. Another challenge of skylight well reflector design is that the direction of the effective light source may change as the sun moves through the sky and different areas of the skylight well become brighter or darker. Given these complexities, the design of a reflector system requires careful study with either detailed photometric analysis or full scale mock-ups.

Advantage of reflectors include:

- As a fixed element, does not require controls
- Redistributes light to room surfaces, thus potentially creating more uniform appearance and reducing glare
- Can conceal the throat installation
- May allow the use of larger skylights and wider spacing
- Can be designed as an “architectural element,” adding visual interest to the space

Figure 65. Louver at the top of a skylight.

Louvers and Shutters

Louvers and shutters are typically opaque, operable devices that can be opened or closed to control the flow or light and/or heat in a skylight well. The louvers can be opaque or translucent, rigid or flexible, insulating or not, and either manually or electrically operated. If electrically operated, they can be under the control of various automatic sensing devices, such as photosensors, timers, or thermostats.

An example of rigid metal louvers at the top of a skylight well is illustrated in Figure 65. A small photosensor and motor can be seen in the lower right corner than controls the angle of the louvers, which are mounted on an east—west axis to provide maximum sun control at midday. This system is designed to partially close the louvers during the hottest times of the day to reduce excessive solar gain while still allowing sufficient daylight in. Such automatic louvers can also be programmed to close at night or have a manual override switch that allows an occupant to cut out all daylight to darken the room. Louver systems have also been made out of mini-tests-blinds supported on a horizontal track or HVAC damper systems.

Many shutter designs are possible, including roller blinds, hinged rigid shutters, folding or sliding shutters. Flexible shutters can be made of plastic meshes, foil faced mylar, or insulating fabrics, and they are typically supported on wire tracks. Rigid shutters are frequently made of lightweight rigid board material, such as faced fiberglass or Styrofoam, and either lowered from a hinged support or slid horizontally across the light well.

Other issues to consider in the selection of a louver or shutter material are weight, spanning strength, durability of the operating mechanism and ease of maintenance. A good rule of thumb is that any moving or electrical part will need to be replaced at some point in its life.

Advantage of louvers or shutters include:

- Allows control of daylighting illumination levels for different space needs or by time of the day
- Can selectively reduce heat gain or heat loss according to climatic needs
- Can provide black-out capability
- Can be used to redirect sunlight, acting as a reflector or baffle system
- Translucent louvers or shutters can be used as a diffusing system
- Can be controlled by user or automatic sensors

Baffles

Baffles are light control elements that are primarily designed to reduce glare by preventing the view of bright skylight well surfaces and by helping to diffuse or redirect daylight. They are typically stationary vertical surfaces hung inside or below the splay in a linear, grid or circular configuration. They can be opaque or translucent, rigid or flexible, and are most often made of lightweight fabric, painted sheet metal, perforated metal or wood. Baffle systems can also include decorative banners or sculptural elements which provide an attractive artistic element highlighted by the skylight.

Figure 66. Baffles in skylights in a classroom.

The use of baffles should be considered in relationship to the directionality of light exiting the skylight well. While baffles can create additional diffusing surfaces, they tend to concentrate the light from a skylight well downwards. If they thus reduce the wider distribution of daylight, they may increase the need for more skylights spaced closer together in order to maintain illumination uniformity.

Any baffle system is going to require an additional structural support system that may require additional bracing for fire and seismic safety. In addition, a method for removing the baffles for cleaning and maintenance should always be considered.

OTHER ACCESSORIES

In addition to the major light well components discussed above, there are other elements that may be incorporated into a skylight well based on the needs of the building. These include photosensors, sprinkler heads, an electric lighting system, HVAC diffusers or grills, smoke detectors, security cameras and other devices. The most common accessories are fire protection sprinkler heads and photosensors

The proper selection, design and control logic of photocontrol systems is beyond the scope of this document. The reader is referred to the *Skylighting Guidelines*, the *Advanced Lighting Guidelines*, the HMG report on photocontrols (HMGd, 2003) and manufacturer's literature in order gain more guidance on the use of photosensors and photocontrols with modular skylight wells. A few key issues in photocontrol design relative to modular skylight wells are discussed below. The other accessories found in skylight wells are more idiosyncratic, and will be discussed only in general.

Sprinkler Heads

Sprinkler heads are part of the fire protection system within a building. They are required within the throat and splay for some skylight wells exceeding certain dimensions, as determined by the local jurisdiction or the National Fire Protection Association (NFPA). Specifications for their physical location, output and direction of spray should be reviewed by the local code official.

Electric Lighting

Figure 67: Linear fluorescent lighting system with skylights in a grocery store.

Figure 68: Pendant fluorescent lighting system in an office.

A number of designers have considered placing electric lights within the skylight well in order to use the skylight well as a continuous light source during the day and night. In general, this concept is discouraged for a number of reasons. First, if placed inside the skylight well, the lamps, reflectors and other equipment needed to provide good electric light distribution will typically block some of the daylight, making the skylight system substantially less efficient. Second, the optimum optical controls for highly variable daylight and static electric light are different and difficult to combine for optimum performance of either system. Third, the intensity of daylight and electric light sources are typically very different, and thus suggest very different spacing criteria. Most commonly, electric light fixtures are spaced at a multiple of two to four times the spacing of skylights. Instead, the designer is encouraged to carefully consider the optimum spacing of the electric light fixtures in relationship to the skylight spacing, per the discussion in the Section on System Coordination above, and select an electric lighting system that coordinates successfully with the skylight spacing and well details.

Figure 67 shows a linear fluorescent system located at the edges of each skylight well in a grocery store, such that the spacing of the luminaires is two times the spacing of the skylights. Linear pendant luminaires are especially easy to coordinate with skylight well spacing, since the linear luminaire can span across a skylight well and thus be spaced independently of the well spacing. Figure 68 shows a pendant fluorescent system in an office application.

HVAC Grills

Occasionally, HVAC return or supply grills have been located in skylight wells. In general, this practice is discouraged, as it greatly complicates construction coordination issues and may also interfere with the proper functioning of the HVAC system. The air distribution pattern from a supply register placed in a skylight well will be very different than that of a register placed horizontally on the ceiling. A return air register place in the skylight well may pick up more heat from warm air stratifying in the well.

Other devices may be placed in the skylight well, as in any other part of the ceiling system. The designer should be aware of access and maintenance for that device along with similar needs for all other systems in the skylight well. The designer should also consider that temperatures in the well are likely to be considerably higher than elsewhere in the interior space, due to both warm air stratification and additional heat gain from sunlight entering the skylight.

Photocontrol Minimum Performance Requirements

Photosensors are electronic components that detect the presence of visible light. Information from these sensors is transmitted to a photocontrol system that dims or switches off the electric lighting system in order to save energy. The use of automatic photocontrols to reduce electric lighting energy use when the skylights provide sufficient daylight illumination is an essential component of a skylighting system designed to save energy.When using photocontrols with skylights, the following should be considered:

- The photosensor location should receive light levels representative of the space
- The photosensor should not be installed in an area where it can be blocked, shaded, easily dirtied or damaged
- Electric lighting circuitry should be coordinated with daylight illumination levels within the space—with separate control zones for lights nearest skylights—in order to maximize energy savings from a switching or dimming system
- The photocontrol system must be properly calibrated and commissioned. This is best done after the space is occupied so that partitions and finish surface materials are in place
- Occupants should have the capability to temporarily override automatic switching features of the photocontrol
- The photosensor location should be easily identifiable and accessible for maintenance
- The photocontrol logic must be coordinated with the needs of the electric lighting system to maximize lamp life and minimize annoyance to occupants

Design Options

A few of the design options available for photocontrols include the choice of dimming versus step switching, and the choice of open or closed loop control logic (described in next section). Open and closed loop logic determine the placement of the photosensor in the space. An open loop system (Figure 69) responds only to the daylight illumination levels, while a closed loop system (Figure 70) senses both combined daylight and electric light levels. Since it is responding to the system that it is also controlling it is called a closed loop feedback system. Some of the major differences and issues to consider in choice of step switching versus dimming, and open versus closed loop systems, are highlighted below. A step switching system (Figure 71) turns off some of the lamps or light fixtures when there is sufficient daylight to illuminate the space. It creates discrete jumps in illumination levels as lights are turned on or off. In order to minimize disruption to the occupants, it is recommended that at least three levels of electric illumination be provided. A dimming system (Figure 72) responds to changing daylight illumination levels with a continuous response, and thus is less perceptible.

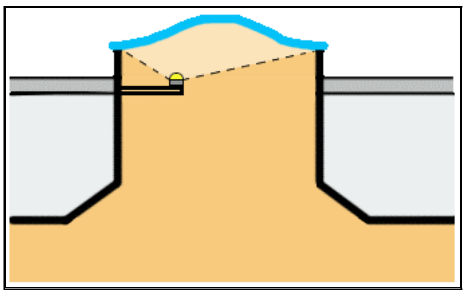


Figure 69. Open loop control scheme.

Open Loop

- Sensor mounted so it "sees" only daylight and not changes to electric light levels
- Sensor best located in the light well "looking" up to underside of skylight
- Wide sensor acceptance angle so it measures average brightness of entire underside of skylight
- Better system to use with skylights and switching controls
- Less concern about excessive lamp cycling
- Avoids problems associated with changing reflectances in work space

Closed Loop

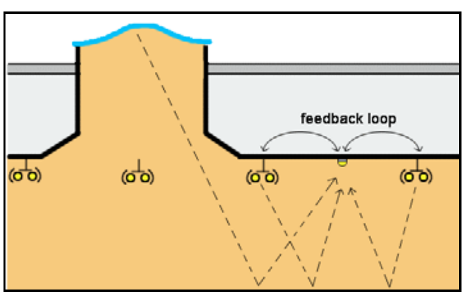


Figure 70. Closed loop control scheme.

- Sensor receives light from both daylight and interior lights and adjusts light levels accordingly
- False responses can be triggered by temporary reflectance changes within the space
- Sensor best located within the space, "looking" at a wall or on a task surface where reflectance will not likely change
- Better system to use with skylights and dimming ballasts

- Control must have offset (light level when lamps at full brightness) adjustment and sensitivity (amount the lamps should dim in response to higher light levels) adjustment

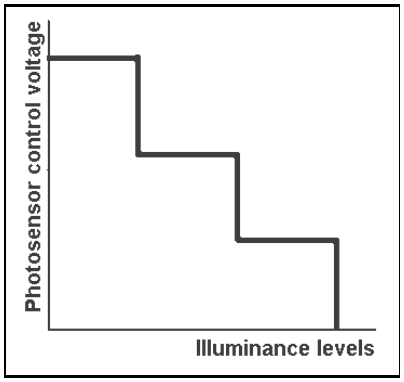


Figure 71. Stepped switching diagram.

Stepped Switching

- Illumination levels are switched off or reduced to a minimum light level in a series of discrete steps
- Switching can be done by fixture, by individual lamps within a fixture, or with a step-ballast that controls the light output of each lamp
- Common switching options include: 100% on / 100% off, 100% on / 50% on, 100% on / 50% on / 100% off, and 100% on / 70% on / 30% on / 100% off
- Stepped switching is generally less expensive than dimming to install, and can offer greater energy savings in some climates, especially those with less variable cloud conditions
- Turning lamps completely off can extend their service life, especially if they are not too frequently switched (fluorescent lamp life is typically predicted based on three-hour burn times)

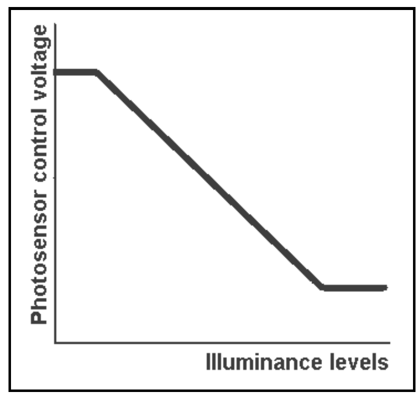


Figure 72. Continuous dimming diagram.

Continuous Dimming

- Lights are continually dimmed responding to available daylight levels in the space
- Common dimming options include continuous dimming to 20%, 10% or 5% light output, or continuous dimming to a certain point where the lamps are then turned completely off.
- When correctly calibrated, dimming systems are often imperceptible and least likely to cause annoyance to occupants
- Dimming systems, especially those that turn the lamps completely off at full daylight levels, can save substantial energy, especially in climates with variable cloud conditions
- Dimming is best done with electronic dimming ballasts, which currently cost considerably more than static or step electronic ballasts
- Compatibility between lamps and dimming ballasts, and stability of lamps over time under various dimming regimes, must be carefully considered
- Energy consumption in dimmed fluorescent lamps is relatively proportional to light output. High intensity discharge (HID) become substantially less efficient as they are dimmed. HID lamps may consume up to 60% of power at 25% light output and may also become less stable in light color

- Dimming often requires separate wiring in addition to power circuiting

Product Evaluation and Approval

This chapter describes the process of product approval for a modular skylight well system. Buildings are subject to plan review by building officials prior to permitting. Part of that review is evaluating whether products have suitable properties for compliance with building codes according to standardized tests. These approval processes are necessary to assure that the product will not adversely affect the comfort and safety of building occupants.

CODE BODIES

Various code bodies are responsible for approving the building products, including the Building Officials and Code Administrators International (BOCA), International Conference of Building Officials (ICBO) and Southern Building Code Congress International (SBCCI). The code body required to approve a product may differ from state to state. In California, for example, educational buildings come under the jurisdiction of the Division of State Architects (DSA), based on the California Building Code requirements. However, in February 2003, the three major code bodies mentioned above were consolidated into the International Code Council (ICC).

PRODUCT EVALUATION

Product evaluation services previously offered by these code bodies, including the ICBO Evaluation Services (ICBO ES), are now consolidated into the International Code Council Evaluation Services (ICC-ES).

Products undergoing ICC-ES evaluation will be evaluated against the most recent version of the International Building Code (IBC). Since existing building codes in the United States, including the state of California, are still based on the Uniform Building Code (UBC), evaluations for compliance with the UBC may be made for an additional fee.[8] It is recommended that

[8] Based on phone interview with Nic Horezcko of the International Code Council Evaluation Services, on April 28, 2003.

manufacturers interested in marketing to states with building codes based on the UBC avail themselves of this additional evaluation service.

Each product will be evaluated according to Acceptance Criteria (AC) developed specifically for the product type. The Acceptance Criteria lists the relevant code sections and the ASTM International tests required for evaluation of the product. Acceptance Criteria relevant to the modular skylights are:

- AC 16 for plastic skylights
- AC 17 for glass skylights
- AC 78 for skylights with plastic frames

See Appendix 5 for a list of code requirements listed in the AC 16 and AC 17 documents. Evaluation Reports of existing modular skylight well products indicate that the performance of the unit skylight is the overwhelming criteria for product approval. Both ICC and ICBO acceptance criteria specifically for light wells are needed. The criteria would vary depending on the classification of light well, such as whether it is located in a fire-rated or non-fire-rated assemblies or plenum return. (see section "Fire Ratings" below).

CODE REQUIREMENTS

This section deals with the fire and seismic code issues to be kept in mind when designing skylight well systems, along with applicable tests associated with skylights. More information on various fire and seismic codes based on California Building Code (CBC) requirements can be found in the research report titled "Modular Skylight Well for Suspended Ceilings Research" (HMGa, 2003).

Fire Ratings

Based on the requirements to meet the fire code, three scenarios of buildings with skylight wells have been presented below. The designers can decide what category their building belongs to based on the criteria stated. All the conditions given have to comply with Section 2409, 2001 CBC that specifies the allowable skylight glazing and framing.

1. **Buildings with fire-rated roof/ceiling assemblies**. A fire-rated ceiling/roof assembly is required for certain noncombustible building types (CBC 2001). Most areas in most of the buildings in the scope of these Guidelines (low-rise offices, schools and retail) likely do not have to meet this most rigorous classification of roof. This fire-rated construction is also required over some egress corridors of non-fire-rated assemblies as well. The Building Code requires penetrations through a fire resistive ceiling/roof assembly, including skylight wells, to be dealt with in two ways:

   - Manufacturing a skylight well system of equivalent performance to a fire-rated shaft. Refer to Section 711 of CBC, "Shaft Enclosures," for more details.

- Using non-fire-rated materials and methods for the skylight well that are either contained in, or integrated within, a fire-rated shaft enclosure.

2. **Buildings with non-fire-rated roof/ceiling assembly, but with plenum returns**. Many commercial buildings use plenum above the ceiling rather than return air ducts to return air back to the HVAC system. In this case, according to Section 602 of the 2003 Uniform Mechanical Code (UMC), "Materials exposed within ducts or plenums shall have flame spread of not more than 25 and smoke developed not more than 50 when tested as a composite product according to ASTM E84 or ANSI/UL 723." This code requirement might limit the materials used in light wells.
3. **All other buildings with non-fire-rated roof/ceiling assembly and no plenum return systems but lesser fire ratings.** Light wells in these buildings would still have to comply with fire rating for interior finishes and unit skylights. Section 2409, 2001 CBC, specifies allowable skylight glazing and framing. Chapter 8, 2001 CBC, deals with fire rating of interior finishes.

Insulation Location

Another aspect to keep in mind when dealing with skylight well penetrations is the code requirements for insulation. Three scenarios may be possible:

1. When insulation is located on top of the roof deck, a skylight well placed in the plenum space need not be insulated, and all light well surfaces exposed to the interior of the room may comply with fire ratings for interior finishes (Chapter 8, 2001 CBC).
2. When there is no insulation installed at the roof, as is often the case when the ceiling is insulated, the sides of the light well must be insulated.
3. The proposed 2005 California Energy Code (Title 24) states that buildings with suspended ceilings will be required to have insulation at the roof deck and not at the ceiling level (HMGe, 2003).

Seismic Rating

Addition of skylight openings disrupts the seismic diaphragm of the roof. Often the solution is to increase the strength of the diaphragm connections via extra nailing, screwing or welding. The light well attachment to the roof and ceiling must be designed so that it is not rigid. This would transfer movement of the roof to the ceiling. There are a few things to keep in mind for seismic loads:

- Extra bracing is to be considered at the suspension grid supporting the acoustic tiles. Seismic requirements, according to the CBC, relate to the installation and performance of grid systems with regard to grid strength [what is this sentence saying?]. ASTM E580 and UBC-25-2 are applicable common standards for "suspended acoustic ceiling systems." The testing and standards relate to the compression and tension strength of grid connections. There are no seismic ratings or requirements for ceiling panels.

- While calculating roof structural loads in their design, designers and structural engineers need to take into consideration the opening in the roof for skylights. Section 2409.5 (design loads for glass) of the CBC deals with resistance to wind load, tributary loads and maximum allowable glass area required. Section 2603.7 (plastic skylights) of the CBC deals with design loads for plastic skylights and Section 2603.8 of the CBC deals with design loads for light diffusing systems. If skylight curbs and throats are properly braced back to the roof, they are unlikely to be a problem. Wind loads need to be calculated by structural engineers based on type of building and seismic zone. In current practices for skylights, the extra bracing is generally provided at the throat and the splay.

Applicable Tests

As part of compliance with the code requirements and for ICC evaluation, the skylight product has to undergo various tests. Test evaluations should be conducted by a third-party test lab complying with ICBO ES Acceptance Criteria 85 (AC 85) and accredited by the International Accreditation Service (IAS) or by an accreditation body that is a signatory to the International Laboratory Accreditation Cooperation Mutual Recognition Arrangement.

For a list of testing standards required by code and ICC evaluation, see Appendix 6.

FUTURE EVALUATION STANDARDS

Currently the only skylight well products that have an evaluation report are tubular skylights. These evaluation reports did not evaluate the well components, but only code required performance of the skylight and its curb. Hence, specific evaluation criteria are needed for the light well and to provide a rating for the three categories described in the fire rating section above (fire rated assemblies, non-fire rated assemblies but with plenum returns, non fire-rated, no plenum return).

In these design guidelines, some future evaluation standards pertaining specifically to skylight wells are proposed. With the development of systems having bigger skylight wells, and heavier and more complex components, there is a need for more comprehensive evaluation criteria to ensure that skylight wells perform in a safe manner.

Some important safety issues pertaining to fire and seismic codes that should be addressed in future evaluations of skylight wells include:

Seismic

- The evaluation process should include specific seismic code requirements for skylight wells.
- Well connection to structure and internal integrity should be properly designed to prevent separation or disassembly during seismic events
- Well construction to structure should allow for independent movement of the roof and ceiling

- Well connections to building structure and other lateral supports should be of adequate strength to ensure that the light well will not fall and cause injury to occupants

Fire Safety

- Compatibility and ease of installation of fire protection requirements, such as sprinkler head installations and smoke detection equipment in skylight wells, should be addressed
- An evaluation criterion for skylight wells should be developed for different classes of light wells depending upon their fire resistant rating (as mentioned in section on Fire Ratings)
- Materials should be evaluated for longevity and weathering effects

References

American Institute of Architects. 1997. *AIA CAD Layer Guidelines*. American Institute of Architects.

ANSI S12.60-2002 Acoustical Performance Criteria, Design Requirements and Guidelines for Schools.

Brooks, Martha. 2002. *California Electricity Outlook: Commercial Building Systems*. Presentation at PIER Buildings Program HVAC Diagnostics Meeting, Oakland, CA on April 16.

CEC, 2003. *2005 Building Energy Efficiency Standards*, Standards for residential and Nonresidential buildings, Express Terms 45-Day Language Commission Proposed Standards, California Energy Commission, July 2003, P400-01-023.

Ching, Francis D.K. 1991. *Building Construction Illustrated, 2nd Ed.* New York: Van Nostrand Reinhold.

CISCA, Ceiling Systems Handbook, Ceilings & Interior Systems Construction Association, St. Charles 1l.

Coldham Architects. 2000. *Beauty, Productivity, Energy Savings*. Accessed from the World Wide Web: http://www.coldhamarchitects.com/greenbuilding/beauty.htm.

Designlights Consortium. 2000. *KnowHow*. Lexington, Massachusetts: Northeast Energy Efficiency Partnerships, Inc. Accessed from the World Wide Web: http://www.designlights.org/guides.

Domigan, J, Lewin, I, O'Farrell, J. and McHugh, J. 2002 "Photometric Test System for Skylights and Luminaires," *2002 IESNA Annual Conference Proceedings*.

Energy Information Administration (EIA). 1999. *Commercial Buildings Energy Consumption Survey: Building Characteristics Table*. Accessed from the World Wide Web: http://www.eia.doe.gov/emeu/cbecs/set3.html.

Heschong Mahone Group, Inc. 1998. *Skylighting Guidelines*, web-based publication providing guidance on general skylighting design issues. Supported by Southern California Edison and the American Architectural Manufacturing Association (AAMA). Available for free download from www.energydesignresources.com.

Heschong Mahone Group, Inc. (a). 1999. *Daylighting in Schools*, a Pacific Gas and Electric Company sponsored study for its Third Party Market Transformation Program. 1999. Accessed from the World Wide Web: www.h-m-g.com.

Heschong Mahone Group, Inc. (b). 1999. *Skylighting and Retail Sales*. An investigation into the relationship between daylight and human performance Detailed Report for Pacific Gas and Electric Company. Fair Oaks, CA.. http://www.energydesignresources.com.

Heschong Mahone Group, Inc. 2001. *Re-Analysis Report: Daylighting in Schools, Additional Analysis*. A report on behalf of California Energy Commission Public Interest Energy Research Program. Access through the World Wide Web: http://www.newbuildings.org.

Heschong Mahone Group, Inc. (a) 2003. *Modular Skylight Wells for Suspended Ceilings Research*. A report on. Access through the World Wide Web: http://www.newbuildings.org.

Heschong Mahone Group, Inc. (b) 2003. *Daylight and Retail Sales*. A report on behalf of California Energy Commission Public Interest Energy Research Program. Access through the World Wide Web: http://www.newbuildings.org.

Heschong Mahone Group, Inc. (c) 2003. *Skylight Photometric Testing*. A report on behalf of California Energy Commission Public Interest Energy Research Program. Report to be completed in late 2003 and available at http://www.newbuildings.org.

Heschong Mahone Group, Inc. (d) 2003. *Photocontrol Systems: Design Guidelines*. A report on behalf of Southern California Edison.

Heschong Mahone Group, Inc. (e) 2003. *Effectiveness of Lay in Insulation*. A report on behalf of California Energy Commission Public Interest Energy Research Program. Access through the World Wide Web: http://www.newbuildings.org.

ICC Evaluation Service, Inc. 1991. *AC 17: Acceptance Criteria for Sloped Glass Glazing in Solariums, Patio Covers and Prefabricated Skylights*. Whittier, California: ICC Evaluation Service, Inc.

ICC Evaluation Service, Inc. 1994. *Acceptance Criteria 79: Acceptance Criteria for Skylights with Plastic Frames*. Whittier, California: ICC Evaluation Service, Inc.

ICC Evaluation Service, Inc. 1997. *AC 16: Acceptance Criteria for Plastic Skylights*. Whittier, California: ICC Evaluation Service, Inc.

ICC Evaluation Service, Inc. 2003. *Rules of Procedure for Evaluation Reports*. Whittier, California: ICC Evaluation Service, Inc.

ICC Evaluation Service, Inc. *AC85: Test Reports and Product Sampling*. Whittier, California: ICC Evaluation Service, Inc.

IESNA 2001. *Lighting Handbook, Reference & Application*. Ninth Edition. Illuminating Engineering Society of North America. Page:10-5.

Demonstration and Evaluation of Lighting Technologies and Application, (DELTA Portfolio) Vol. 2 Issue 2, Lighting Case Studies, Lighting Research Center. 1996 http://www.lrc.rpi.edu/programs/DELTA/publications/pdf/SMUD.pdf

McHugh , J., Lewin, I and Domigan, J. 2002 " Skylights as Luminaires: PIER Skylight Photometric Test Results," *2002 IESNA Annual Conference Proceedings*.

Murdock J.B, Parent M.D. 1989. *Skylight Dome Well System Analysis from Intensity Distribution Data*. Volume 21, No 3, 1989. Pages 111-123. Lighting Research &Technology. Chartered Institution of Building Science Engineers.

New Buildings Institute, Inc. 2003. *Advanced Lighting Guidelines*. White Salmon, Washington: New Buildings Institute, Inc. Can be accessed from the World Wide Web: http://www.newbuildings.org/lighting.htm.

NRCA, 2001, *The NRCA Roofing and Waterproofing Manual, Fifth Edition*, National Roofing Contractors Association, Rosemont, IL.

Nittler, Ken and Mattinson, Bill. 2003. *Proposed 2005 Title 24 Standards*. Presentation at the Annual CABEC Conference in Tahoe, Nevada on May 16, 2003.

Pierson, John 1995. *Letting the Sun Shine is Good for Business*, The Wall Street Journal, November 20, 1995, page B1.

PG&E. 1999. *Daylighting Initiative: Retail Applications Ralph's Grocery*. Accessed from the World Wide Web: http://www.pge.com/003_save_energy/003c_edu_train/pec/daylight/di_pubs/1487Rahs_repaginated.pdf.

Warner, Jeffrey. 1993. "Sizing Up Skylights". *Home Energy Magazine*. Accessed from the World Wide Web: http://hem.dis.anl.gov/eehem/93/931109.html.

Glossary

Coefficient of Utilization

The Coefficient of Utilization is an indication of a fixture's efficiency. In other words, how well the fixture gets the lamp lumens onto the horizontal surface to be lit. It is expressed as a percentage of the total light produced by the lamp.

Effective Aperture

Effective aperture is a measure of light-transmitting ability of a fenestration system. It is a product of the skylight-to-floor ration (SFR), the visible transmittance (Tvis) and the well factor. Value ranges from 0 to 1.0, with most practical skylights at less than 0.1.

Isolux / Isofootcandle Contour

An isolux contour is a line graph of a space showing equivalent illuminance values in lux or footcandles.

Luminance

Luminance is the amount of visible light leaving a point on a surface in a given direction. This "surface" can be a physical surface or an imaginary plane, and the light leaving the surface can be due to reflection, transmission, and/or emission.

Photocontrols

Photocontrols is a lighting control system that adjusts the electric lighting power in response to the amount of interior light or ambient daylight available.

Photometrics

Photometrics, a description of the magnitude and direction of light distribution from a source, is the basis of predicting how that light source will light a space.

Photometry

Photometry is the science of measuring visible light in units that are weighted according to the sensitivity of the human eye.

Photosensor

A photosensor is an electronic component that detects the presence of visible light.

Plenum

The plenum is the space between the suspended ceiling and the floor or roof above. A plenum may also be under a raised floor.

Prescriptive Measure

Non-residential buildings can comply with the Energy Code by using either of two approaches: prescriptive or performance approach. Prescriptive measures become the base case upon which buildings that use the performance method will be compared against.

Skylight-to-Floor Ratio (SFR)

SFR is the ratio of the gross skylight opening area to the daylit floor area.

Solar Heat Gain Coefficient (SHGC)

SHGC is the fraction of solar radiation admitted through a glazing assembly. It is the sum of the transmitted solar energy plus that portion of the absorbed solar energy which flows inward. It measures how well a product blocks heat caused by sunlight. It is expressed as a number between 0 and 1. The lower the number, the less heat is transmitted.

Uniformity

Uniformity refers to the even distribution of light levels in a space. Uniformity is often quantified as the ratio of maximum to minimum or maximum to average illuminance in a space.

Visible Transmittance (Tvis)

Visible transmittance is the fraction of visible light energy that passes through a material. Light that is not transmitted is either reflected or absorbed by the material.

Well Cavity Ratio (WCR)

The well cavity ratio is a measure of the geometric shape of the well and is used to determine the light well efficiency.

Well Efficiency (WE)

The well efficiency is the ratio of the amount of visible light leaving the skylight well to the amount of visible light entering the skylight. Well efficiency is sometimes called the well factor.

Appendix

APPENDIX 1: ACRONYMS

AAMA	American Architectural Manufacturers Association
ASTM	American Society for Testing and Materials International
BOCA	Building Officials and Code Administrators International
CBC	California Building Code
CBECS	Commercial Building Energy Consumption Survey
CEC	California Energy Commission
CISCA	Ceilings & Interior Systems Construction Association
CMC	California Mechanical Code
HMG	Heschong Mahone Group
ICBO	International Conference of Building Officials
ICC	International Code Council
ICC-ES	International Code Council Evaluation Service
NBI	New Buildings Institute
NFPA	National Fire Protection Association
NRCA	National Roofing Contractors Association
PG&E	Pacific Gas and Electric Company
PIER	Public Interest Energy Research
SBCCI	Southern Building Code Congress International
SFR	Square Foot Ratio (see Glossary for definition)
SHGC	Solar Heat Gain Coefficient (see Glossary for definition)
TAG	Technical Advisory Group
UBC	Uniform Building Code
WE	Well efficiency (see Glossary for definition)

APPENDIX 2: AVERAGE ANNUAL CONSTRUCTION

Building Activity	1990 to 1999 (in M sq. ft.)	Annual Construction (in M sq. ft.)
Education	1,239	1234
Mercantile	2,030	203
Office	1,830	183
Food Sales	355	36
Food Service	Q	Q
Health Care	473	47
Lodging	716	72
Public Assembly	736	74
Public Order and Safety	227	23
Religious Worship	357	36
Service	336	34
Warehouse and Storage	2,079	208
Other	367	37
Vacant	Q	Q
TOTAL	**11,094**	**1,109**

Figure 73. U.S. annual national construction by building type.

This table describes the breakup of US annual construction for educational, retail (mercantile) and office spaces as 509.9 million sf. This is discussed in the section "Skylight Market Potential" in the first chapter. The square footage is equivalent to 49% of the total annual construction volume. Calculations are done based on Table B9 CBECS database (EIA 199). See figure below for percentages.

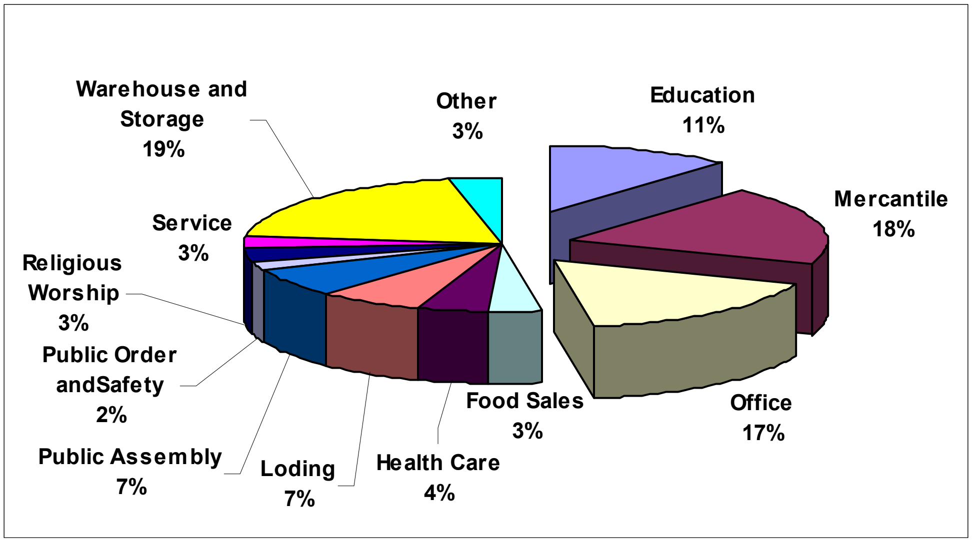


Figure 74. Percentage of floor area for new construction/retrofit in U.S.

Applying the percentage of floor areas with suspended ceilings and skylights by building types reveals that there should be approximately 121 million sf of commercial space built per year at the national level that could potentially integrate skylights with suspended ceilings, and 16.5 million sf in California alone (see Figure 4).

Occupancy	Annual New/retrofit construction M sf	Under Roof	T-bar Ceiling	Feasible	Total Million SF/yr	$/SF-yr	Annual Savings ($Millions)
Office	183	35%	45%	50%	14.4	$ 0.15	$ 2.1
Education	124	60%	68%	75%	37.9	$ 0.16	$ 5.9
Merchantile	203	80%	46%	75%	56.0	$ 0.23	$ 12.9
Food sale.....	36	100%	46%	75%	12.4	$ 0.23	$ 2.9
Totals	**546.0**				**120.8**		**$ 23.8**

Figure 75. Energy cost savings potential from one year's new/retrofit construction for five selected building types in US.

APPENDIX 3: MARKET POTENTIAL FOR SUSPENDED CEILING SYSTEMS IN SPLAY APPLICATIONS

The discussion and calculation below is based on the section "Why use Suspended Ceilings" in the first chapter. This summarizes that even if the presence of skylights with splay result in the loss of ceiling tiles due to the area cut out for skylights, but the skylight splays are made of acoustic tiles, then the ceiling tile manufacturer actually gains by the use of skylights.

Assumptions

Floor and ceiling area: 40,000 sf

Skylight-to-Floor Ratio (SFR): 4%

Skylight size: 4' x 4' = 16 sf

Splay angle: 45° on all sides

Well opening size: 12' x 12' = 144 sf

Calculations

How many skylights do we need?

At 4% SFR,

40,000 sf * 0.04 = 1,600 sf of skylight area

1,600 sf of skylight area / 16 sf = 100 skylights

144 sf of ceiling opening * 100 skylights = 14,400 sf

What is the area of splays in the building?

Area per splay = (4' x 5.66') * 2 = 45.28 sf

Splay area per skylight = 45.28 sf * 4 splays = 181.12 sf per skylight

Total splay area in building = 181.12 sf * 100 skylights = 18,112 sf

Summary

Total ceiling area with remaining horizontal suspended ceiling = 25,600 sf (40,000-14,000)

Total suspended ceiling area lost due to skylights and splayed wells= 14,400 sf = 36% of ceiling area

Total area of splay installation = 18,112 sf = 45% of ceiling area

Net Increase in acoustic tile installation = 45% - 36% = 9% more than typical building without skylights

APPENDIX 4: SKYLIGHT SIZING CHART

The chart below compares the number of skylights required as a function of splay sizes and angles. The sample below assumes the following conditions:

SFR 4%

Skylight size 2' x 4'

The table below calculates the splay dimensions, and number of skylights required for a particular skylight dimension (SFR=4%). If larger skylights with splays are used, fewer skylights are required.

Ceiling Height	Splay width	Splay Angle	Splay Height	Splay Diagonal	Skylight Spacing	Spacing other direction	Relative # skylights	Skylight Width	Skylight Length	Opening Width (bottom of splay)	Opening Length (bottom of splay)
10	0	0	-	-	12	17	100%	2	4	2	4
10	1.5	45	1.50	2.12	16	19	67%	3	3	6	6
10	2	45	2.00	2.83	16	21	61%	2	4	6	8
10	2.5	45	2.50	3.54	20	23	44%	3	5	8	10
10	4	45	4.00	5.66	24	27	31%	4	6	12	14
10	1.5	60	2.60	3.00	16	19	67%	3	3	6	6
10	2	60	3.46	4.00	16	21	61%	2	4	6	8
10	2.5	60	4.33	5.00	20	22	46%	4	4	9	9
10	4	60	6.93	8.00	24	27	31%	4	6	12	14
12	0	0	-	-	16	19	100%	3	4	3	4
12	1.5	45	1.50	2.12	20	23	66%	3	5	6	8
12	2	45	2.00	2.83	20	23	66%	4	4	8	8
12	2.5	45	2.50	3.54	20	25	61%	3	5	8	10
12	4	45	4.00	5.66	24	29	44%	4	6	12	14
12	1.5	60	2.60	3.00	20	23	66%	3	5	6	8
12	2	60	3.46	4.00	20	23	66%	4	4	8	8
12	2.5	60	4.33	5.00	24	25	51%	5	5	10	10
12	4	60	6.93	8.00	24	29	44%	4	6	12	14
14	0	0	-	-	20	22	100%	4	4	4	4
14	1.5	45	1.50	2.12	24	26	71%	5	5	8	8
14	2	45	2.00	2.83	24	28	65%	4	6	8	10
14	2.5	45	2.50	3.54	28	28	56%	5	5	10	10
14	4	45	4.00	5.66	28	34	46%	4	8	12	16
14	1.5	60	2.60	3.00	24	26	71%	5	5	8	8
14	2	60	3.46	4.00	24	28	65%	4	6	8	10
14	2.5	60	4.33	5.00	28	28	56%	5	5	10	10
14	4	60	6.93	8.00	28	34	46%	4	8	12	16

Figure 76. Skylight Well dimensions for various ceiling heights, skylight opening, and splay angles.

The chart above indicates that for skylights of the same dimensions, splayed wells would require less skylight installations than an unsplayed one. For splayed skylights, skylights with wider and higher splays will also require fewer skylights.

The figures below illustrate the various sections of skylight wells with varying splay dimensions.

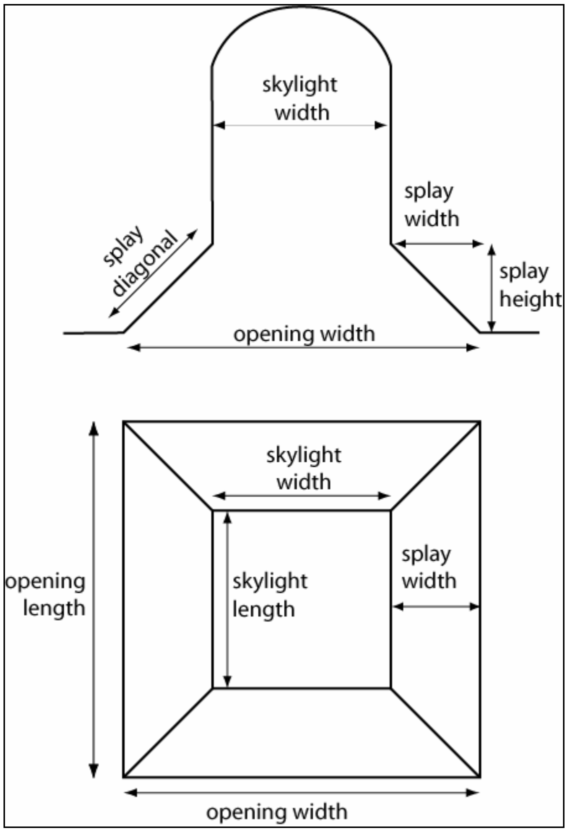


Figure 78. Section and plan of skylight with 45 angle and 2’ high splay.

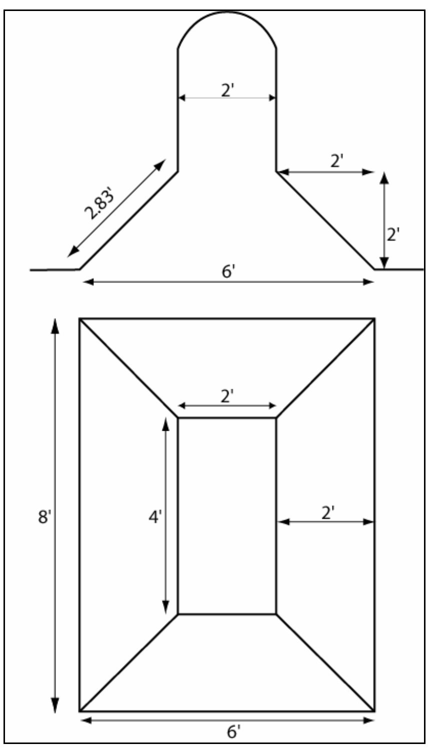


Figure 77. Diagram showing various parts of the light well based on the table above.

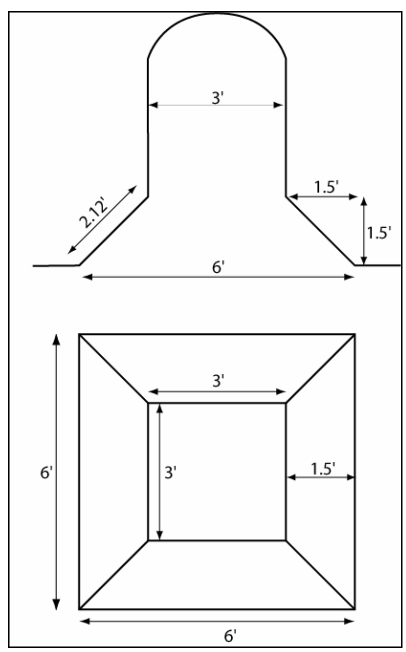


Figure 79. Section and plan of skylight with 45 angle and 1.5’ high splay.

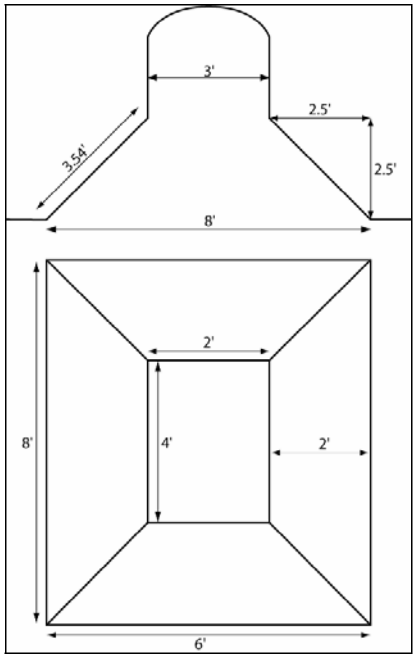


Figure 80. Section and plan of skylight with 45 deg. splay and 2.5’ splay height.

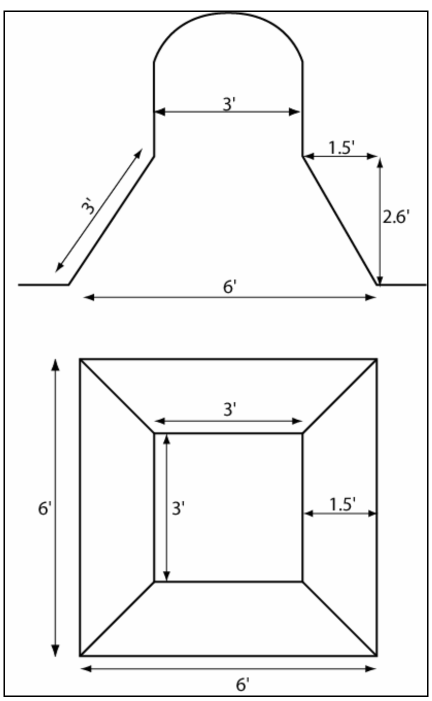


Figure 82. Section and plan of skylight with 60 deg. splay and 2.5’ splay height.

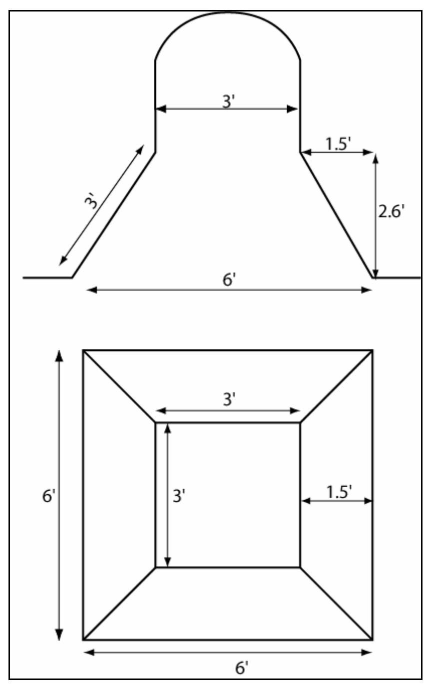


Figure 81. Section and plan of skylight with 60 deg. splay and 1.5’ splay height.

APPENDIX 5: CODE REQUIREMENTS

Following is a list of code requirements for both plastic and glass skylights mostly based on Uniform building code, Uniform Mechanical Code and the California Building Code. This list is not exhaustive and only provides assistance to certain broad issues related with code compliance for skylights.

- UBC Section 104.2.8
- IBC Section 104.11
- IRC Section R104.11
- UBC Sections 2409 and 2603
- IBC Sections 2405 and 2609
- ANSI Standard Z35.1 – 1972
- Aluminum Design Manual, October 1994
    - For IBC compliance, fasteners in contact with aluminum shall be in accordance with the Aluminum Design Manual Section 6.6.1 of Part 1-A or 1-B.
    - For UBC compliance, fasteners in contact with aluminum shall be in accordance with Sections 2004.2 and 2004.3.
    - Plastic material should comply with UBC Section 217 or IBC Section 2606.4.
- UBC Chapter 34
- For UBC compliance, fasteners in contact with aluminum shall be in accordance with Sections 2804.
- Labeling in accordance with UBC Section 5402
- UBC Section 2311 for wind uplift load
- Glass thickness to comply with UBC 54-1, Table No. 54-1
- Glass and glazing strength should be designed according to the 2001 California Building Code Section 2409 *Sloped Glazing and Skylights - Design Loads*.
- Acrylic plastic glazing should be compliant with the 2001 California Building Code Section 2603.7 *Plastics – Skylights*.
- The proper installation of gypsum board constructed throats should be according to the 2001 California Building Code Section 2511A – *Gypsum Wallboard*.
- Code requirement for plastic diffusers includes the 2001 California Building Standards Section 2603.8 on *Plastic applications in Light Diffusing Systems*.

APPENDIX 6: APPLICABLE TESTS

Following is a list of applicable tests required by codes for skylights. This list is not exhaustive and only provides assistance to certain broad issues related with the applicable tests for skylights.

Plastic Skylights

The following tests are required as per Acceptance Criteria 16 of the International Code Council Evaluation Services:

- ASTM D 618 *Method for Conditioning Plastics and Electrical Insulating Materials*
- ASTM D 635 *Test Method for Rate of Burning and/or Extent and Time of Burning of Self-supporting Plastics in a Horizontal Position*
- ASTM D 638 *Test Method for Tensile Properties of Plastics*
- ASTM D 790 *Test Methods for Flexural Properties of Unreinforced and Reinforced Plastics and Electrical Insulating Materials*
- ASTM D 1929 *Test Method for Ignition Properties of Plastics*
- ASTM D 2565 *Practice for Operating Xenon Arc-Type Light Exposure Apparatus With and Without Water for Exposure of Plastics*
- ASTM D 2843 *Test Method for Density of Smoke from the Burning or Decomposition of Plastics*
- ASTM E 84 *Standard Test Method for Surface Burning Characteristics of Building Materials*
- ASTM E 108 *Standard Test Method for Fire Tests of Roof Coverings*
- ASTM E 330 *Standard Test Method for Structural Performance of Exterior Windows, Doors, Skylights and Curtain Walls by Uniform Static Air Pressure Difference.*
- ASTM E 331 *Standard Test Method for Water Penetration of Exterior Windows, Skylights, Doors, and Curtain Walls by Uniform Static Air Pressure Difference*
- UL 790 *Test Method for Fire Resistance of Roof Covering Materials*

Glass Skylights

The following tests are required as per Acceptance Criteria 17 of the International Code Council Evaluation Services:

- If insulating glass glazing is used, it should comply with ASTM E774 *Specification for Sealed Insulating Glass* with a minimum Class C rating when tested in accordance with ASTM E 773 *Test Method for Seal Durability of Sealed Insulating Glass Units*
- ASTM E 331 *Standard Test Method for Water Penetration of Exterior Windows, Skylights, Doors, and Curtain Walls by Uniform Static Air Pressure Difference*

- No water infiltration into the interior should occur when tested in accordance with ASTM E331 *Standard Test Method for Water Penetration of Exterior Windows, Skylights, Doors, and Curtain Walls by Uniform Static Air Pressure Difference* and AAMA Standard 501-83 *The Methods of Test for Metal Curtain Walls*.

Skylights with Plastic Frames

The following tests are required as per Acceptance Criteria 79 of the International Code Council Evaluation Services:

- ASTM D 1929-96 *Standard Test Method for Determining Ignition Temperature of Plastics*
- ASTM D 635-74 *Standard Test Method for Rate of Burning and/or Extent and Time of Burning of Plastics in a Horizontal Position*
- ASTM D 4226 *Standard Test Methods for Impact Resistance of Rigid Poly(Vinyl Chloride) (PVC) Building Products*
- ASTM D 638 *Standard Test Method for Tensile Properties of Plastics*
- One of the following weathering tests should be applied:
    - ASTM D 1499 *Standard Practice Filtered Open-Flame Carbon-Arc Type Exposures of Plastics*
    - ASTM D 2565 *Standard Practice for Xenon Arc Exposure of Plastics Intended for Outdoor Applications*
    - ASTM D 4364 *Standard Practice for Performing Outdoor Accelerated Weathering Tests of Plastics Using Concentrated Sunlight*
    - ASTM D 1435 *Standard Practice for Outdoor Weathering of Plastics*
    - ASTM D 4329 *Standard Practice for Fluorescent UV Exposure of Plastics*

Miscellaneous Tests

These tests are not required by the ICC-ES, but would be beneficial for testing the performance of skylight systems:

- Fire-rating requirements of materials should have a flame-spread index of 25 or better (Class A) when tested according to ASTM E84 *Standard Test Method for Surface Burning Characteristics of Building Materials*.
- Air infiltration of the skylight unit should be tested in accordance with ASTM E283 *Air leakage Through Exterior Windows, Curtain Walls and Door under Specified Pressure Differences Across the Specimen*.
- Gypsum board material strength should be compliant with ASTM C472 *Test Methods for Physical Testing of Gypsum, Gypsum Plasters, and Gypsum Concrete*.
- Joints between gypsum boards should be compliant with ASTM C474-02 *Standard Test Methods for Joint Treatment Materials for Gypsum Board*.

- Installation of gypsum board materials should be in accordance with ASTM C1002-01 *Standard Specification for Steel Self-Piercing Tapping Screws for the Application of Gypsum Panel Products or Metal Plaster Bases to Wood Studs or Steel Studs* and ASTM C475 *Specification for Joint Compound and Joint Tape for Finishing Gypsum Board*.
- Class-A suspended ceiling systems should be tested according to ASTM E84 *Standard Test Method for Surface Burning Characteristics of Building Materials* and ANSI/UL 263 – ASTM E119 and NFPA 251 *Fire-Resistance Rating of a Ceiling Assembly* for t-bar ceiling systems.
- Framing members for ceiling panels should comply with ASTM C645-00 *Standard Specification for Nonstructural Steel Framing Members,* while attachments should comply with ASTM C754-00 *Standard Specification for Installation of Steel Framing Members to Receive Screw-Attached Gypsum Panel Products*.

APPENDIX 7: WELL ASSEMBLY SCHEDULE

Commercial building types that are being targeted by this document have a variety of ownership/occupant and construction types. These factors affect the construction schedule. Recommendations for efficient construction schedules for buildings with skylight wells are discussed for four of the most common conditions below.

Condition A: Owner-Occupied New Construction Option 1

1. Roof framing and the skylight roof opening, including supplemental framing for the opening, and burglar bars are constructed at the same time.
2. A curb for the skylight is constructed on top of the opening and coordinated with the roof decking.
3. A cricket, if needed, is constructed at the uphill side of the curb to direct water flow on the roof to the sides and around the skylight curbs.
4. The roofing insulation, wherever applicable, is installed over the deck.
5. The roofing membrane is installed over the deck with appropriate cants and flashing on the curb.
6. The skylight is installed on the roof curb.
7. Throat material is attached onto the curb, including supplemental support and bracing system for the throat. The throat is adjusted to approximately the right position, including angular adjustments.
8. Markers are placed to reserve space for future splay installations.
9. Building systems, such as mechanical, plumbing, and sprinkler piping, are installed and the throat is protected from damage.
10. The suspension grid for the ceiling is laid out with opening for the splay.
11. The splay is framed.
12. Any adjustments to the throat or splay are made to make the two meet.
13. Diffuser is installed, if applicable.
14. Electric light fixtures are mounted.
15. Ceiling and play materials are installed along with the diffuser and any other accessories.

Condition B: Owner-Occupied New Construction Option 2

In some skylight designs, the splay may be used as a transitional component for adjusting the light well location or splay opening. In such cases, the construction schedule should be as follows:

1-9. Initial construction scheduling is as Steps 1 to 9 in Option 1.

10. The suspended ceiling system will be installed according to designed ceiling pattern.

11. The light well splay and its associated supports are installed to adapt to the positions of the throat and ceiling opening.
12. Diffuser is installed, if applicable.
13. Electric light fixtures are placed finally.

Condition C: Tenant-Occupied—Construction as Tenant Improvements

1. The shell and other building systems, including the skylight, will be installed prior to tenant improvements.
2. Throat is installed.
3. Splay is attached to throat.
4. Ceiling is installed and coordinated with splay location.
5. Diffuser is installed, if applicable.
6. Electric lighting is attached to or recessed in ceiling.

Condition D: Remodel of Existing Building

1. Locate skylight light well to avoid existing mechanical ducting and other building systems within the plenum when possible.
2. Roof deck and roofing membrane is cut out for the skylight opening. Rigid insulation is also cut out, if applicable.
3. Supplemental roof framing is installed to support new skylight opening curb.
4. A curb for the skylight is constructed/installed.
5. New roofing membrane is tied into the existing membrane and installed onto the new curb with appropriate flashing on the curb.
6. The skylight is installed atop the roof curb.
7. The existing ceiling is demolished to accommodate new skylight well.
8. Sprinkler piping, mechanical ducts, electrical components, lighting, etc. are modified to accommodate new opening, if required.
9. Electricity is provided to motorize louvers and connect to lighting control system, if applicable.
10. Throat is attached onto the curb, including supplemental support and bracing system for the throat.
11. The light well splay and its associated supports are installed
12. The finished ceiling is attached to the skylight well.
13. Sprinkler piping and head are installed into skylight well, if applicable.
14. Diffuser is installed, if applicable.
15. Electric light fixtures are installed in place.

APPENDIX 8: HAND CALCULATIONS FOR WELL EFFICIENCY

Calculation procedure for well efficiency of a light well using SkyCalc has been described in the main document. The well efficiency can be calculated using the equation as per the 2005 Building Efficiency Standards (CEC 2003):

$$\text{Well Cavity Ratio (WCR)} = \frac{[2.5 \times \text{well height} \times \text{well perimeter}]}{\{\text{Well area}\}}$$

WCR of throat (throat ht 3ft, 4x4 dimensions) = {2.5 x 3 x 16}/ {16} = 7.5

WCR of splay = {2.5 x 3 x 40}/ {100} = 3

Well efficiency (or well factor-WF) of a light well can be located based on the WCR and the reflectance of the light well surface as shown in Figure 83. In this case, the reflectances of the well surfaces are 80%.

Well efficiency for throat (WE_{throat}) = 66%

Well efficiency for splay WE_{splay} = 87%

Tvis diffuser = 80%

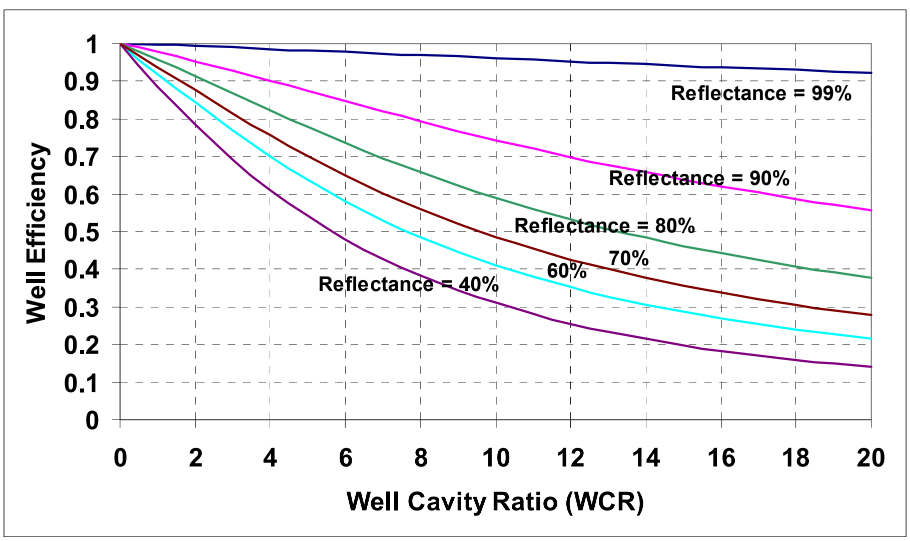


Figure 83: Well efficiency graph.

Well efficiency for the entire light well (Figure 83)

= WE1 (throat) x WE2 (splay) x Tvis of diffuser = 0.67 x 0.87 x 0.80

Well Efficiency for light well with splay = 45%