

DAYLIGHTING AND FENESTRATION DESIGN

Daylighting forms the cornerstone of sustainable, high performance design for schools. Affecting individuals on both conscious and subconscious levels, it provides light to see the work environment, a natural rhythm that determines the cycles of days and seasons, and biological stimulation for hormones that regulate body systems and moods. In addition, it offers opportunities for natural ventilation and, if properly integrated with the electric lighting system, can provide tremendous energy savings. These advantages of daylighting translate to higher performance in schools. Recent research has shown that children achieve significantly higher test scores in classrooms that are daylit than in those that are not,¹ making daylighting one of the best building-related investments for the learning environment.



Gentle, diffuse daylight permeates a classroom with both sidelight and toplight. Note that all surfaces are painted white to distribute light more efficiently and reduce contrast glare. Photo courtesy Barbara Erwine.

This chapter provides an overview of daylighting and fenestration design. It also presents eight daylighting guidelines for specific sidelighting and toplighting schemes. The on-line Appendix that supports the Best Practices Manual provides additional detailed information.

View Windows (Guideline **DL1**)

High Sidelighting—Clerestory (Guideline **DL2**)

High Sidelighting—Clerestory with Light Shelf or Louvers (Guideline **DL3**)

Classroom Daylighting—Wall Wash Toplighting (Guideline **DL4**)

Central Toplighting (Guideline **DL5**)

Patterned Toplighting (Guideline **DL6**)

Linear Toplighting (Guideline **DL7**)

Tubular Skylights (Guideline **DL8**)

To fully daylight most spaces, the guidelines should be combined with each other or repeated as a pattern across the space. For example, Wall Wash Toplighting (Guideline DL4) on an interior wall could be combined with High Clerestory Sidelighting (Guideline DL2) and View Windows (Guideline DL1) on an exterior wall to fully daylight a classroom. Since daylight is additive, the total amount of daylight in the

¹ Heschong Mahone Group, "Daylighting in Schools—An Investigation into the Relationship between Daylighting and Human Performance," prepared for Pacific Gas & Electric Company and funded by California utility customers, 1999. Heschong Mahone Group and New Buildings Institute, "Re-Analysis Summary: Daylighting in Schools, Additional Analysis." February, 2002.

space is the sum of the daylight available from each individual pattern. Each guideline represents a daylight delivery system with inherent advantages and disadvantages, which are summarized below in Table 1.



Guideline DL5: Central Toplighting from a sawtooth monitor with sun baffles is combined with DL1: View Windows to provide balanced illumination in a classroom. Photos courtesy Barbara Erwine.

Table 1 – Selection Criteria for Daylighting Strategies

Design Criteria	View Windows (DL1)	High Sidelight w/ Light Shelf (DL2 & DL3)	Wall Wash Toplighting (DL4)	Central & Patterned Toplighting (DL5 & DL6)	Linear Toplighting (DL7)	Tubular Skylights (DL8)
Uniform Light Distribution	○ ○	● / ○	●	● ●	○	○
Low Glare	○	●	●	●	●	● / ○
Reduced Energy Costs	○	●	●	● ●	●	●
Cost Effectiveness	●	●	●	●	●	● ●
Safety/Security Concerns	○	● / ○	●	●	●	● ●
Low Maintenance	○	●	●	●	●	●

●● Extremely good application ● Good application ○ Poor application ○○ Extremely poor application ●○ Depends on space layout and number and distribution of daylight apertures ●/○ Mixed benefits

Overview

Daylight can be provided via windows and glazed doors, as well as via skylights and other forms of toplighting. These glazed openings are collectively referred to as "fenestration." The placement, design, and selection of materials for fenestration are extremely important and can tip the balance between a high performance and low performance building. Fenestration impacts building energy efficiency by affecting cooling loads, heating loads, and lighting loads. Visual comfort is strongly affected by the window location, shading, and glazing materials. Well-designed windows can be a visual delight. But poorly designed windows can create a major source of glare. Thermal comfort can also be compromised by poor fenestration design. Poorly insulated windows add to a winter chill or summer sweat, while windows with low U-values keep glass surface temperatures closer to the interior air temperature, improving thermal comfort. In addition, east-west windows and unshaded south windows can cause excessive cooling loads. And although windows and skylights provide opportunities for natural ventilation, they must be designed to ensure a safe, secure, and easily maintained facility.

Benefits of Daylighting

There are several advantages to the use of daylight in schools:

Academic Performance

Studies indicate that well-designed daylighting is associated with enhanced student performance, evidenced by 13% to 26% higher scores on standardized tests, while poor daylighting design has been shown to correlate with reduced student performance.² It makes sense that students and teachers perform better in stimulating, well-lit environments. Daylighting can provide high quality light, stimulating views, and an important communication link between the classroom and adjacent spaces.

Energy Savings

Daylighting can save energy and reduce peak electricity demand if electric lights are turned off or dimmed when daylight is abundant. Nationally, K-12 schools spend more than \$6 billion a year on energy. For most school buildings, electric lights are the largest energy consumer. For instance, in California, about 40% of school building energy use is attributable to just electric lighting. Daylighting per se, however, saves no energy unless the electric lighting system is appropriately controlled. To be effective, daylighting must be thoughtfully designed, avoiding glare and overheating, and must include dimming or switching of the electric lighting system, preferably with automatic photocell control. The design of systems for supplementary electric lighting and controls is addressed in the chapter on electric lighting.

Better Light

Daylight provides the highest quality light source for visual tasks. It enhances the color and visual appearance of objects, and helps students to see small details better.

Connection to Nature

Daylight provides a connection to the natural world by supplying information on time of day, season, and weather conditions. In doing so, it enriches the learning environment and may also help to make lessons more memorable. The constant variety in the quality and quantity of daylight also helps keep students and staff more alert.

Improved Health

Views provided by windows contribute to eye health by providing frequent changes in focal distance, which helps to relax eye muscles. Daylight, whether associated with a view or not, may also reduce stress for both students and teachers. Research in Sweden showed that work in classrooms without daylight “may upset the basic hormone pattern, and this in turn may influence the children’s ability to concentrate or co-operate, and also eventually have an impact on annual body growth and sick leave.”³

² Ibid.

³ Kuller and Lindsten. 1992. *Journal of Environmental Psychology* 12:305-317.

Environmental Education

Windows and solar gain through windows can present opportunities to teach how the sun moves through the sky and how daylight can be controlled by carefully designed overhangs and other shading devices. These observations can form part of an experiential learning unit for environmental education as students plot the movement of the sun on a sundial or across a schoolyard wall. Control of electric light in response to daylight may also be one of the “treasures” found in the Energy Treasure Hunt, a pilot program (sponsored by the U.S. Department of Energy's Rebuild America, the U.S. Environmental Protection Agency, Pacific Gas & Electric Company, and others) in several Northern California schools to educate students about issues pertaining to energy and efficiency.

Basic Daylighting Principles

The following six principles, described in more detail below, provide fundamental guidance in designing daylit schools.

- [Prevent direct sunlight penetration](#) into space.
- [Provide gentle, uniform light](#) throughout space.
- [Avoid creating sources of glare](#).
- Allow teachers to [control the daylight](#) with operable louvers or blinds.
- [Design the electric lighting system to complement the daylighting design](#), and encourage maximum energy savings through the use of lighting controls
- [Plan the layout of interior spaces](#) to take advantage of daylight conditions.

1. Prevent Direct Sunlight Penetration

One of the delights of daylight is that it changes in quality throughout the day and with each season. The daily and seasonal path of the sun is the prime determinate of sunlight availability, while the presence of clouds and moisture in the air affect the quality and intensity of light from the sky. It is essential that designers understand the basic principles of solar orientation, climate conditions, and shading systems to design successful daylit buildings.

Sunlight Versus Daylight

Direct beam *sunlight* is an extremely strong source of light, providing up to 10,000 footcandles of illumination. It is so bright, and so hot, that it can create great visual and thermal discomfort. *Daylight*, on the other hand, which comes from the blue sky, from clouds, or from diffused or reflected sunlight, is much more gentle and can efficiently provide excellent illumination without the negative impacts of direct sunlight. Good daylighting design typically relies on maximizing the use of gentle, diffuse daylight, and minimizing the penetration of direct beam sunlight. In general, sunlight should only be



Cameron Park Library, Peter Wolfe Architect. A skylit library provides a stimulating yet peaceful environment. Colorful banners enliven the space while blocking glare from the skylights and helping to diffuse the daylight. Photo courtesy Lisa Hescong.

allowed to enter a space in small quantities, as dappled light, and only in areas where people are not required to do work.

The best daylighting designs are initiated early in the design process of new buildings. The first step in good daylighting design is the thoughtful orientation of the buildings on the site and orientation of the fenestration openings. A carefully oriented building design will allow maximum daylight while minimizing unwanted solar gains. It is easiest to provide excellent daylight conditions using north-facing windows, since the sun only strikes a north-facing window in early morning and late evening during midsummer. South-facing windows are the next best option because the high angle of the south sun can be easily shaded with a horizontal overhang. East- and west-facing windows are more problematic because when the sun is low in the sky, overhangs or other fixed shading devices are of limited utility. Any window orientation more than 15° off of true north or south requires careful assessment to avoid unwanted sun penetration.



North versus south windows. South windows are shaded from direct sun, but receive daylight reflected off of concrete walk and white painted overhangs. North windows are large and unshaded. Photo courtesy Lisa Heschang.

For sidelighting, carefully designed shading devices both inside and outside the building can limit direct sun penetration while allowing diffuse daylight. For toplighting, avoid direct sun by using glazing that diffuses the sunlight, or by reflecting it off baffles, louvers, or light well walls. The sections on [Sidelighting and Toplighting](#) below give strategies for the design of shading devices for optimum performance.

2. Provide Gentle, Uniform Illumination

Daylight is most successful when it provides gentle, even illumination throughout a space. Evenly diffused daylight will provide the most energy savings and the best visual quality. Achieving this balanced diffuse daylight throughout a space is one of the greatest achievements of a good daylight designer.

It is easiest to achieve uniform daylight illumination from toplighting strategies that distribute light evenly across a large area. The next best approach is to provide daylight from two sides of a space with a combination of view windows and high windows, preferably no more than 30 ft to 50 ft apart. Combinations of sidelighting with toplighting can also be successful in providing uniform illumination levels. The most challenging condition is a room with windows on only one side. There, daylight illumination levels will be very high right next to the window and drop off quickly. Various strategies to distribute light deeper into the space are available, but require more design skill and construction cost.

Daylight can most easily be used to provide a base level of illumination throughout a space, referred to as the ambient illumination, which is often on the order of 20 to 30 footcandles. Individual work areas can then be highlighted with electric task lights to bring the illumination levels in specific areas to higher task level requirements, such as 50 or 75 footcandles. Alternatively, if the daylighting fenestration area is increased to provide the higher task illumination for most of the day, the electric lighting energy

savings will be maximized while heating and cooling costs may increase. The best daylighting designs balance these energy costs with the desired lighting quality.

Walls, Ceilings And Other Reflective Surfaces

The arrangement of reflective surfaces that help to distribute the light are just as important as the arrangement of daylight openings for providing gentle, uniform illumination. Whenever possible, place daylight apertures next to a sloped or perpendicular surface so the daylight washes either a ceiling or a wall plane, and is reflected deeper into the space. It is essential to recognize that walls and ceilings are part of the daylighting design. For greatest efficiency and visual comfort, they should be painted white, or a very light color. Even pastel-colored paint absorbs 50% of the light that strikes it, correspondingly reducing daylight levels. Saturated colors should be used only in small areas, for accents or special effects.



Deeply coffered ceiling helps to diffuse light from four skylights. There are no electric lights on in this photo. Photo courtesy SunOptics.

Advanced daylighting designs take advantage of additional exterior and interior reflecting surfaces to shape the distribution of daylight in the space. Light-colored walkways and overhangs can help reflect daylight. Light shelves can be used to bounce daylight deeper in the space (see Guideline DL3), or a series of reflective or refractive surfaces built into the glazing itself can redirect sunlight onto the space's ceiling. These approaches are integral to the architecture of the building and are designed differently for each cardinal orientation. For example, classrooms may have light shelves on the south side of the building, but none on the north. In this way, the design is "fine tuned" to optimize the daylight delivery for each orientation.

3. Avoid Glare

Excessively high contrast causes glare. Direct glare is the presence of a bright surface relative to the surroundings (for example, a bright diffusing glazing or direct view of the sun) in the field of view that causes discomfort or loss in visual performance. This glare can have negative effects on student and staff performance. A recent study showed that skylights admitting direct sun (and presumably glare) into classrooms correlated with a *decrease* in student performance on standardized tests⁴. Eliminate glare by obscuring the view of bright sources and surfaces with blinds, louvers, overhangs, reflectors, and similar devices.

Placing daylight apertures next to reflective surfaces reduces glare in addition to distributing the daylight more evenly. It brightens interior surfaces to reduce their contrast with the bright glazing surface. If washing a wall with daylight is not possible, some glare reduction can be achieved by splaying window reveals and skylight wells. Blinds or drapes can also reduce contrast by controlling

⁴ Heschong Mahone Group, "Daylighting in Schools—An Investigation into the Relationship between Daylighting and Human Performance," prepared for Pacific Gas & Electric Company and funded by California utility customers, 1999. Heschong Mahone Group and New Buildings Institute, "Re-Analysis Summary: Daylighting in Schools, Additional Analysis." February, 2002.

the amount of brightness at the windows, and diffusing the light. Punched windows (simple holes in the middle of a wall) represent the worst scenario for glare and are not recommended.

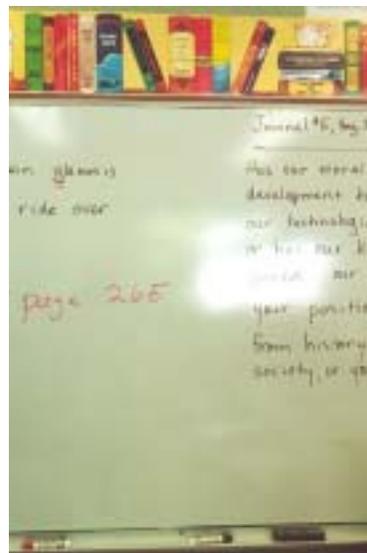
Glare can also occur when daylight strikes a reflective surface, like a computer screen or a whiteboard, and produces shiny reflections that make it difficult or impossible to see. You can predict when these reflections will be a problem by placing an imaginary (or real) mirror on the screen or whiteboard and seeing if any bright light sources or surfaces are visible in the mirror. If they are visible, reorient the screen/whiteboard or redesign the apertures to eliminate their reflection in the surface.

VDT Screens

When video display terminals (VDTs) are located in daylight spaces, the designer must take great care to minimize daylight reflections from the VDT screen. This problem is especially acute when the computer screen is oriented so that the screen is facing the daylighting aperture (that is, the student's back is to the window or skylight). Under these conditions, reflected glare may completely wash out the screen, making work impossible without completely closing window blinds or drapes. If the VDT screen is located so that the screen viewing orientation is parallel to or 45° to the windows (see figure on left), reflected glare poses less of a problem and, if present, can usually be reduced by using polarizing filters or meshes attached directly to the screen. Flat screen monitors have fewer glare problems.

4. Provide Control of Daylight

Daylight is highly variable throughout the day and the year, requiring careful design to provide adequate illumination for the maximum number of hours while contributing the least amount possible to the cooling load. The ideal daylighting design would have variable apertures that respond



Glare from windows or light fixtures reflecting off of shiny surfaces, such as computer screens or whiteboards, can reduce student performance. Photo courtesy Lisa Heschong.



Horizontal blinds allow control of brightness from lower view windows. Note that high clerestory windows have no blinds so that daylight can reach deep into classroom. Most classrooms do not need complete black out capability for viewing of modern video equipment. Photo courtesy Barbara Erwine.



Reflections of luminaires in computer screens can cause veiling glare. Careful lighting and daylighting design avoids these problems. Photo courtesy Lisa Heschong.

to changes in the availability of daylight. The apertures would become smaller when daylighting is abundant and larger on cloudy days or at times when daylight is less available. While electrochromic glazing may permit variable daylighting apertures in the future, with today's technology the size of the aperture and its transmission are fixed. The principal means of control is through the use of shades or blinds located inside or outside the window.

Teachers should have easy access to controls for these shades or blinds to adjust light levels as needed throughout the day. These systems should be reliable, as well as easy and economical to clean and repair. Manually operated controls are slightly less convenient but also less expensive and less likely to need repair. Avoid the use of moveable exterior shades; they are exposed to weather conditions that may degrade their performance. Ensure that fixed exterior shading devices are sloped slightly so they drain water.

5. Integrate with Electric Lighting Design

The daylight and the electric light systems must be designed together so they complement each other to create high quality lighting and produce energy savings. This requires an understanding of how both systems deliver light to the space. For example, if daylight lights the two sidewalls, electric light may be used to highlight the teaching wall. The Design and Analysis Tools section later in this chapter discusses tools to help visualize the overall light distribution in the space.

Color

Daylight is a “bluer” light source than most electric lighting. Fluorescent lights that are designed to match the color of incandescent light will appear yellow in comparison with daylight. The color temperature of a light source is a number that describes its relative blueness or yellowness. When mixing daylight and electric light, most designers choose fluorescent lamps in the blues range, with a color temperature of 3500°K to 4100°K or even higher.

Controls

Daylighting is also more thermally efficient than electric lighting, meaning that the cooling load created by daylighting illumination is much lower than that created by electric lighting providing the same light level. Since electric lighting is a major contributor to the cooling load in schools, substituting daylight for electric lighting reduces cooling costs as well as lighting costs. But these energy savings will only be achieved if the electric lights are turned off or dimmed in response to the daylight.

The electric lighting should be laid out, circuited, and controlled to coincide with the patterns of daylight in the space, so that the lights can be turned off in areas where daylight is abundant and left on where it is

deficient. Controls can either be manual or automatic. Automatic controls use a small photosensor that



Lighting Controls, Oakridge High School: Automatic photosensor controls turn off first bank of lights next to skylight well. The light fixtures are arranged parallel to skylights to left and windows (out of picture) to right, while whiteboard is located perpendicular to windows and skylights. Photo courtesy Lisa Heschong

monitors light levels in the space. Manual controls are substantially less expensive, but need to be convenient and well labeled to ensure their use. Automatic controls guarantee savings, but are more expensive and must have overrides so the teacher can darken the room for audio/visual use. Lighting controls are discussed in more detail in the chapter on Electric Lighting and Controls.

6. Plan the Layout of Interior Spaces

Successful daylighting designs must include careful consideration of interior space planning. Since daylighting illuminance can vary considerably within the space, especially with sidelighting, it is important to locate work areas where appropriate daylighting exists. Perhaps more importantly, visual tasks (especially the teaching wall) should be located to reduce the probability of discomfort or disabling glare. In general, work areas should be oriented so that daylighting is available from the side or from above. Facing a window may introduce direct glare into the visual field, while facing away from a window may produce shadows or reflected glare.

Sidelighting vs. Toplighting

The location, orientation, and size of the daylighting apertures are of paramount importance, as is the selection of the glazing materials used and how they are shaded from direct sun. When possible, it is always better to locate daylighting apertures in the ceiling plane — a strategy known as toplighting. This reduces the likelihood of glare and allows for a more even distribution of daylight within the space. Toplighting, of course, can only be provided for one-story buildings or for the top floor of multi-story buildings. The other basic strategy, sidelighting, allows daylight to enter through windows in vertical walls. With windows, uniform illuminance is more difficult to provide, as there is always more light next to the window. Glare is also more difficult to control. But there are design techniques that can substantially reduce problems associated with sidelighting.



Sidelighting: Library receives daylight from two sidelighting strategies: 1) view windows at perimeter, and 2) high clerestories that bring daylight into the center of the space.

The basic sidelighting pattern provides windows on one or more walls of the space. The depth of daylighting penetration from vertical windows is largely dependent on the height of the window head (that is, the top of the window). For a simple sidelighting scheme, a rough rule of thumb is that useable daylight will be available about 1.5 times the window head height. So for good daylight delivery, sidelighting windows should be located as high as possible in the wall. However, to provide exterior views, windows need to be at eye level. Since these requirements clearly conflict, advanced daylighting designs differentiate between the functions of view and task daylighting, frequently providing separate windows for each of these.

The orientation of a sidelighting aperture strongly affects the quantity, quality, and distribution of daylight. For sidelighting and no shading, north-facing windows provide the most even illuminance. The

quantity of light is diminished, but a larger aperture will compensate, providing adequate and more even illumination.

Exterior Shading Strategies

Shading devices for sidelighting strategies minimize solar gains and glare, and can also be designed to increase illumination levels. Shading devices — both overhangs and fins — can be either opaque or translucent, and solid or louvered. It is best to place shading devices outside the glazing to stop solar gains before they hit the window and to reduce potential glare from bright window views. Exterior overhangs should be deep enough to minimize direct sun on the window for the hottest hours of the day during the cooling season. For south-facing windows in sunny (clear sky) climates with very high air conditioning loads, a good rule of thumb is to design the overhang with a shading cutoff angle about equal to 90° minus the site latitude. This provides full shading between March 21 and September 21. Many areas are likely to experience their hottest weather in September, and still need full shading that time of year. Overhangs for climates with lower air conditioning loads and/or more summer overcast can increase this angle by 5° to 15° . Overhangs or fins for windows facing east or west do not lend themselves to simple rules of thumb and should be carefully designed for the specific site, climate, and space. North-facing windows usually do not need exterior overhangs or fins, but may occasionally require interior blinds or louvers to control glare.

Interior Shading Strategies

Interior shading devices for windows reduce solar heat gain somewhat (by reflecting solar gain back out through the glazing) but are most effective at controlling glare. The most common interior glare control devices are horizontal mini-blinds, vertical blinds, shade screens, and curtains. Mini-blinds positioned between the panes of glass in double-glazed fenestration do not have to be cleaned and may have the lowest maintenance costs, but their initial cost is substantially higher. They can also pose replacement problems if a window is broken. Interior shading devices can also be used for security purposes to obscure the view of room contents when a space is unoccupied. Many school spaces will also require blackout shades. All these operable devices should have robust, reliable controls that are easily accessible to the teacher. However, operable louvers, blinds, and drapes are frequently left in a non-optimal daylighting setting — either fully closed or fully open. Systems that have fixed louvers or settings for the daylight glazing and operable glare control for view glazing will be more likely to deliver dependable daylight throughout the year.

Landscaping

Daylight is also affected by obstructions on the site, such as trees and other buildings. Landscaping can serve an important shading and sun control function if it is strategically placed or incorporated into a trellis device. Deciduous trees and vines positioned to the south of a window are extremely useful for providing shade during overheated summer months while admitting more sun in areas with cold or overcast winters. Evergreens provide shade year-round in consistently overheated climates. They are also useful for blocking low east and west sun.

Toplighting

Providing daylight from above, generically referred to as “toplighting”, can generally provide the most uniform illumination throughout a space. Examples of toplighting strategies include roof monitors, unit skylights, and tubular skylights. The vast majority of schools are one or two stories, and so a large proportion of school spaces can easily be lit from above. Toplighting schemes have many other advantages, including freeing up walls for tack space or storage, and increasing security by reducing access to fenestration.

Toplighting schemes can provide much more useful illumination from smaller apertures than sidelighting when they capture and diffuse sunlight. Sunlight is roughly 10 times brighter than light from the sky or clouds. If the sunlight is diffused through the use of lenses, baffles, or reflecting surfaces, it can be diffused and spread over a large area. Thus, one ft² of a diffusing skylight can provide illumination to about 10 times the area of one ft² of equivalent window glazing.

As with any lighting design, it is important to strive for good lighting quality with toplighting, which is best done in two ways. First, design openings so that they maximize illumination on vertical surfaces. Skylights or roof monitors should be placed preferentially adjacent to important walls that should be highlighted. Be careful that ceiling returns or structural members do not create shadows on important vertical surfaces. Secondly, design for uniform illumination by using many openings spread out uniformly across the space. The higher the daylight aperture, the more broadly the light will diffuse in the space. Thus, it is easier to successfully toplight spaces with high ceilings. As a rule of thumb, skylights should be spaced apart no more than one-and-a-half times the ceiling height. (When the skylight well is broadly splayed, the vertical distance can be measured to the top of the splay.) This means that spaces with low ceilings will require more small skylights spaced closer together than the spaces with the same floor area but a higher ceiling. The Excel tool SkyCalc™ has a calculator that helps to figure out appropriate skylight spacing relative to ceiling heights and structural grids.

Glare is also an issue with skylights. Diffuse glazing, such as fiberglass or white acrylic, can become extremely bright in direct sunlight, and should be kept out of direct view of the occupants. Recessing skylight diffusers behind other elements, such as structural members, banners, or splayed wells, all help prevent glare. Lensed glazing can also help to break sunlight up into smaller bits, reducing glare potential. The designer should assess glare potential of any toplighting product and design in direct sunlight conditions.

Horizontal vs. Vertical Glazing

Toplighting designs can have either horizontal or vertical glazing. Because the sun is higher in the sky during the summer than in the winter, toplighting schemes with horizontal glazing receive more direct



Monitors provide diffuse light into gymnasium at the Durant Middle School gym. Photo courtesy Innovative Design.

sun in the summer (when it is generally not needed) and less in the winter (when it is needed). The opposite is true with south-facing vertical glazing schemes. So in terms of optimizing yearly heating and cooling balance, south-facing vertical glazing tends to be most efficient. North facing glazing will receive much lower and more uniform levels of diffuse daylight, and thus need to be sized significantly larger than south-facing apertures to achieve equivalent illumination levels. East and west orientations show large variations in light levels throughout the day and the greatest solar gains in the summertime, and therefore are not recommended.

However, horizontal glazing or skylights have a number of other advantages. First of all, skylights' energy performance on a flat roof is fairly independent of orientation, allowing more architectural freedom on other issues. Skylights actually deliver more daylight into a space over the course of a year than comparable vertically oriented glazing. Pyramid, bubble, or arched-shaped diffusing skylights are effective at collecting daylight during the very low sun angles of early morning or late afternoon when it is most needed. And during overcast days, the sky is brightest straight up, so horizontal glazing will deliver the most light under these conditions. Solar heat gains in skylights tend to be less than expected due to stratification of heated air in the skylight wells. The advantages of skylights in collecting daylight throughout the year allow them to have a smaller aperture than vertical glazing for the same amount of illumination delivered, which also reduces relative heat loss and heat gain.

Another consideration in the decision between vertical versus horizontal glazing is cost. Prefabricated skylights, which are inserted into a roofing system, can be much less expensive than custom-built roof monitors requiring extensive structural modifications and flashing. Integration of the toplighting scheme with the HVAC, ceiling, and lighting systems is also an important concern. The final decision for horizontal or vertical glazing is a balance of these concerns for the specific building and climate, as well as the ability to integrate into the architecture.

Toplighting Shading Strategies

Shading for monitors may not be needed if the light well design prevents direct sun from entering the space. Exterior shading devices for skylights are available, but are not recommended due to maintenance problems. Rooftop devices are usually exposed to more severe weather, dust, and debris but have less maintenance supervision than windows. Sturdy, dependable performance is an essential criterion. Thus, it is a good idea to protect any shading or operable equipment for skylights below at least the first layer of skylight glazing. Some skylight manufactures offer fixed or operable louver options for sun and daylight control, to reduce solar gain and excessive daylight. Others offer movable insulation devices that can be operated, either manually or automatically, to reduce both solar gain and nighttime heat losses.



Linear skylight in multipurpose room includes electrically operated louvers to reduce brightness when needed. Photo courtesy Lisa Heschong.

Structural Considerations

All toplighting schemes represent penetrations through the roof diaphragm, which is often a critical part of the building's structural system, designed to stiffen the building and resist forces that tend to twist the structural frame. This structural diaphragm can have various numbers and sizes of holes in it and still continue to function. But at some point, additional holes will weaken its strength, limiting the size and location of toplighting apertures. However, if more toplighting apertures are desired than allowed by the structural system, the project's structural engineer may be able to devise ways to strengthen the diaphragm to allow additional penetrations.

The light well connecting the toplighting aperture with the space below may also intersect HVAC ducting, electric lighting layouts, and fire sprinkler systems. Careful coordination of the structural and mechanical designs will ensure compatibility among these systems.

Fenestration Products

High performance fenestration features include double glazing, low-emissivity coatings, and blue/green tints. These have become a very important means of energy conservation in modern construction to reduce both thermal losses and solar gains. Fenestration has three principal energy performance characteristics, which have been identified by the National Fenestration Rating Council (NFRC) to be tested and labeled on manufactured windows: Visible light transmittance, solar heat gain coefficient, and U-factor. Site-built windows and skylights may or may not have such tested information available.

- *Visible light transmittance (VLT)* is the fraction of light that is transmitted through the glazing. Light is that portion of solar radiation that is visible, meaning it has a wavelength between about 380 and 780 nanometers. Single clear glass has a VLT of about 0.9, while highly reflective glass can have a VLT as low as 0.05. The quantity of daylight that enters a window or skylight is directly proportional to the VLT. In general, VLT should be as high as possible, provided it does not create glare or other visibility problems.
- *Solar heat gain coefficient (SHGC)* measures the solar heat gain through a window. A window that has no solar gain would have a SHGC value of zero, while a perfectly transmissive glazing would have a SHGC of 1.0. These extremes are both theoretical concepts that are not possible in the real world. Except in passive solar applications where solar heat gain is desired, everything else being equal, glazing materials should be selected with the lowest possible SHGC. However, glazing materials with a low SHGC (like dark gray and bronze tints) may also have a low VLT, so the challenge is to identify specialized "selective" low-e products and blue/green tints that combine the lowest SHGC with the highest VLT.
- *U-factor* measures the heat flow through a window assembly due to the temperature difference between the inside and outside. The lower the U-factor, the lower the rate of heat loss and of heating energy consumption. Everything else being equal, the U-factor should be as low as possible. The fenestration frame and glazing edge spacers degrade the U-factor of an insulated glass assembly. So two U-factors are frequently specified: the center of glass (COG) value, which is the U-factor measured at the center of the assembly, and the whole-window value, which is the overall U-factor of the glazing plus the spacer and frame system. (The whole-unit value will be higher than the COG value.) Single pane windows typically have a U-factor in the range of 1.0 to 1.2 COG; double pane windows range from 0.65 to 0.45 COG. With low-e coatings, inert gas fills, and multiple glazings, the U-factor can be as low as 0.1 COG.

Other glazing considerations include diffusion, transparency, and durability:

- **Diffusion and Transparency.** Transparent glazing materials provide views, but diffuse materials can spread daylight better in the space. Diffusion is one of the most important characteristics in selecting a skylight. Good diffusing glazings maximize the spread of light in the space and minimize “hot spots” and glare. Diffusion may be accomplished by using a white pigment, a prismatic surface, or embedded fibers. Unfortunately, specifications on diffusion properties are rarely available for fenestration products. Thus, samples of diffusing glazing materials should be visually evaluated to see how well they diffuse direct sunlight. A simple test is to place the product in the sun and see if it allows your hand to cast a shadow. A fully diffusing material will blur the shadow beyond recognition and will not concentrate the sunlight into local hot spots. Note that diffusing glazing placed in direct sunlight can be glaringly bright if it is within the field of view. It should be placed above the direct line of sight or be obscured by baffles.
- **Durability.** Characteristics such as UV degradation (yellowing and other aging effects), structural strength, scratch resistance, breaking and fire resistance, along with replacement cost and availability, should be considered in selecting a glazing material.



Pyramid skylights on experimental portable classroom design integrates skylights into a high efficiency modular design. Photo courtesy Lisa Heschang.

The fenestration frame holds the glazing material in place and forms the structural link with the building envelope. The frame and the spacer between the glazing panes in multiple glazed units form a thermal short circuit in the insulating value of the fenestration. This degradation of the U-factor at the fenestration perimeter can be minimized with high performance frame and spacer technologies now available. This is important both for energy conservation and the potential for condensation on the frame.

Frames are available in metal, wood, vinyl, composite, and fiberglass. Metal frames conduct the most heat and must have a thermal break for good performance. Insulated vinyl and fiberglass frames have the lowest U-factor. The NFRC has established a rating system to evaluate the whole window performance including the frame, spacer, and glazing. More information can be found at their website, <http://www.nfrc.org>. The whole-window U-factor, VLT, and SHGC is shown on a label attached to all rated windows. Rated windows should be purchased for all school projects and frame/spacer performance should be compared based on these overall ratings. Site-built windows and skylights will not have these ratings available.

Design and Analysis Tools

There are three general categories of tools for evaluating daylighting and fenestration: physical models, lighting computer simulation programs, and whole-building energy simulation programs.

Physical Models

Physical scale models are probably the easiest and most intuitive way to understand daylighting design options. Scale models can be easily built that quickly and accurately illustrate the daylighting conditions created by any given design. They also help non-professionals, such as teachers and parents, to see

lighting quality issues directly, and understand why one design might work better than another. Photographs of the interior of scale models are an easy way to record the impacts of various design options. Many daylighting textbooks include a chapter on the construction and testing of daylight models. An excellent training video — Daylight Models, available from the Lighting Design Lab in Seattle — also describes how to build and test these models. (See the References section below for more information.)

Daylighting models can also be used for numerical analysis. The models may be tested either outside under real sky conditions or in artificially constructed overcast sky and direct sun simulators. Small light measuring devices (photocells) can be used to record light levels within the model. Sun simulators (heliodons) can be set to represent the correct sun angle for the site latitude and hour of day, and are used to visualize the movement of light during a typical day. Measurements in a simulated sun or sky are more reproducible than in the real sky, which is constantly changing. Several California universities and electric utilities, including the Pacific Energy Center in San Francisco, have sun and overcast sky simulators, associated video equipment, and photocell arrays.

Lighting and Daylighting Computer Simulations

Electric lighting and daylighting computer simulations such as Radiance, Superlite, LumenMicro, and Lightscape give information about the distribution of lighting in spaces with contributions from windows and skylights as well as electric lighting systems. Unlike the energy simulation programs described below, these programs produce results for a single instant in time. Multiple calculations are needed to study varying sky and solar conditions. These computer-based tools give light level values and gradients for both daylight and electric light across the space. Some of these tools also produce realistic renderings of lighting within the space, which may be linked to generate an automated “walkthrough” of the space for a particular day and time or to simulate the daylight variations through the hours of the day. The programs that are easiest to use may be constrained by the complexity of shapes they can simulate. The more complex programs can simulate almost any room shape or material, but require significantly more expertise and modeling time.

Whole Building Energy Simulations

Whole building energy simulation tools, such as DOE-2, EnergyPlus, BLAST, and spreadsheet estimating programs like SkyCalc consider all aspects of the fenestration’s impact on building energy use, including solar gains, impact on HVAC equipment sizes, and reduction of electric lighting energy. Many of the energy simulation programs have user-friendly interfaces to make it easier to construct models and evaluate results. Most of these tools have simplified daylighting simulation algorithms that may not accurately represent daylight levels from complex designs (like light shelves). For these designs, daylight predictions from one of the computer simulations mentioned above may need to be input to the energy program to accurately predict daylight’s potential to save energy by turning off or dimming electric lights.

Other Design Considerations

The on-line Appendix that supports the Best Practices Manual has details of additional design considerations, including the following:

- Natural ventilation
- Noise control
- Radiant comfort
- Safety and security
- Air and water leakage
- Condensation
- Replacement
- Maintenance
- Fire resistance

Applicable Codes

The California Energy-Efficiency Standards for Nonresidential Buildings (Title 24) limit the window-wall ratio to 40% of the exterior wall. Since mid-2001, the code requires high performance glazing, including thermal break frames and low-e coated double glass, although the requirements vary somewhat with climate. The standard does not require daylighting or daylighting controls, but it does offer credits when automatic controls are installed.

Resource Efficiency

In terms of energy performance, windows and skylights are two of the most important considerations in building design. They also provide an opportunity to address other environmental objectives, including material efficiency, indoor air quality (IAQ), and pollution prevention during manufacturing.

To achieve material efficiency, windows are now being manufactured with durable alternatives to wood frames and sashes, including options made with post-industrial waste. Unfortunately, many of these products can contribute to pollution during manufacture, and possibly even to IAQ problems. For now, the best environmental performance strategy is to select durable frame and sash options that enhance energy performance as well as meet programming and daylighting needs. Table 2 lists currently available options that are environmentally preferable from a material efficiency perspective.

Table 2 – Strategies for Constructing Resource Efficient Fenestration Systems

Window Frame and Sash	Strategies	Environmental Benefits & Considerations
Wood	Select windows produced with wood certified by Forest Stewardship Council (FSC), Scientific Certification Service (SCS). Specify factory-applied finish.	Prevents degradation to forest and wildlife habitat; wood can be high maintenance. Good energy performance. Typically more durable than field-applied. More controlled finishing environment prevents pollution.
Wood and Plastic Composite	Durable options combine wood fiber and post-consumer waste plastic, and combine recycled PVC scrap, virgin PVC, and fiber from recycled wood scrap.	Utilizes industrial waste, stretching the wood supply. Very durable and low maintenance. Manufacture of PVC can contribute to pollution, however. Good energy performance
Vinyl	Vinyl frames include foamed PVC insulating core.	Low maintenance. Needs no paint. Manufacture of PVC can contribute to pollution, however and high coefficient of thermal expansion can lead to premature failure of seal. Excellent energy performance.
ABS Plastic		Low maintenance. Needs no paint. Manufacture can contribute to pollution however, and high coefficient of thermal expansion can lead to premature failure of seal. Moderately good energy performance.
PVC Plastic		Low maintenance. Manufacture can contribute to pollution, however, and high coefficient of thermal expansion can lead to premature failure of seal.
Fiberglass	Pultruded fiberglass frame members have a hollow profile usually insulated with fiberglass or polyurethane foam.	Promotes durability. However, difficult to recycle. Emissions contribute to IAQ problems and manufacture contributes to air pollution. Moderately good energy performance.
Metal	Specify durable, factory-applied finishes, anodized, polyvinylidene fluoride, and siliconized polyester.	Promotes durability and reduces potential pollution on-site. Energy-intensive production, however. Not the best energy performance. Do not use metal frames that lack thermal break.

Source: GreenSpec: The Environmental Building News Product Directory and Guideline Specifications.

For specific product recommendations, see GreenSpec: The Environmental Building News Product Directory and Guideline Specifications, <http://www.buildinggreen.com> and OIKOS's Redi Guide (Resources for Environmental Design Index). Iris Communications, 800-346-0104, <http://www.oikos.com>.

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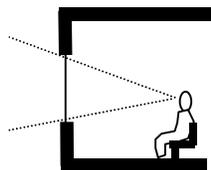
Related Volume III CHPS Criteria

Energy Prerequisite 1: Minimum Energy Performance.

Energy Credit 1: Superior Energy Performance.

IEQ Credit 1: Daylighting in Classrooms.

Guideline DL1: View Windows



Recommendation

Provide access to exterior views through view windows for all interior spaces where students or staff will be working for extended periods of time.

Description

A view window is vertical glazing at eye level, which provides a view to the exterior or interior adjacent spaces.

Applicability

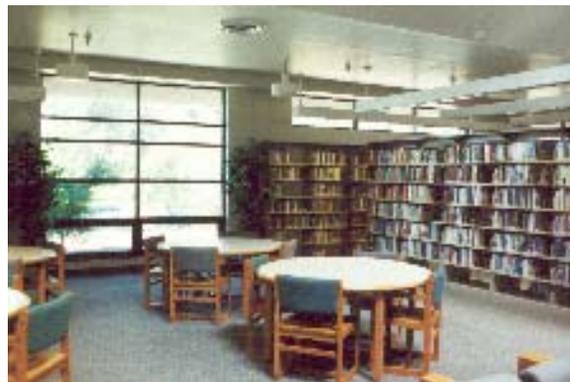
View windows are essential in all school spaces (except spaces requiring visual privacy) to provide relaxing views and information about exterior natural conditions, and also to allow people outside of a space to view and connect with activities inside. They are applicable to all climate regions and should be planned in the schematic design phase.

Applicable Codes

The California Energy Code does not require that view windows be installed. However, the code does specify the minimum performance of fenestration products and it limits window area to a maximum of 40% of the exterior wall area.

Integrated Design Implications

- **Balance with other program needs.** View windows serve a broad range of important functions for view, social communication, egress, ventilation, and energy conservation (see Benefits below). However, view windows are often inefficient at supplying working daylight to the space. The square footage of view windows will reduce the allowable area for windows and skylights placed higher in the wall and ceiling that can be designed to deliver more useful daylight across the space. View windows also decrease valuable classroom wall space and pose potential acoustic and vandalism problems. A balance should be achieved among these conflicting needs.
- **Integration with mechanical ventilation.** Operable view windows should be used to naturally ventilate the space and reduce mechanical ventilation needs. Evaluate prevailing wind conditions to assess the feasibility. A statistical analysis of 650 schools by the Florida Solar Energy Center found a strong correlation between the presence of operable windows and a decrease in indoor air quality complaints.⁵



View windows at Camaron Library expand the space outward and connect the reading area with the natural landscape. Lisa Hescong, photographer.

Applicable Spaces	Climates	When to Consider
Classrooms	South Coast	Programming
Library	North Coast	Schematic
Multi-Purpose / Cafeteria	Central Valley	Design Dev.
Gym	Mountains	Contract Docs.
Corridors	Desert	Construction
Administration		Commissioning
Toilets		Operation
Other		

⁵ M. Callahan et. al. Energy Efficiency for Florida Educational Facilities: 1996 Energy Survey of Florida Schools Final Report. Report # FSEC-CR-951-97. Florida Solar Energy Center. Submitted to Florida department of Education, July 1997.

- **Integration with HVAC.** View windows should decrease overall seasonal heating and cooling loads on the building if they are oriented, glazed, and shaded correctly. This can reduce the initial size of the HVAC system and annual energy costs. The analysis of Florida schools noted above also found that the presence of windows strongly correlated with an overall reduction in total building energy use.
- **Thermal Comfort.** Window surfaces that are considerably above or below the mean radiant temperature of other room surfaces will be uncomfortable for occupants adjacent to them. Shade the windows, use high performance glazing, and design HVAC to minimize radiant thermal discomfort.
- **Space Planning.** View windows should be oriented relative to the location of stationary tasks, such as desks, teaching wall, computer locations, and reading areas. Avoid reflected glare from windows in computer screens or on whiteboard surfaces. The best classroom location for view windows is perpendicular to the teaching wall.
- **Design Phase.** To function well, view windows must be at eye level, glare-free, oriented toward views that will not distract occupants, and designed to reduce building energy loads. A requirement for view windows should be identified in the building program; their location and design objectives should be determined in the early phases of schematic design.

Cost Effectiveness

Costs for view windows are typically low. View windows are (or should be!) standard practice for classrooms. The incremental cost of energy-efficient glazing ranges from \$0.75/ft² to \$2.50/ft² of glass. Daylight energy savings from view windows are negligible because the shading elements required to minimize glare usually render them unreliable for reducing electric light consumption.

Costs	L			
	M			
	H			
		L	M	H
		Benefits		

Benefits

View windows provide numerous benefits, serving a broad range of important functions for view, social communication, egress, ventilation, and energy conservation

The outward views they provide are essential for mental stimulation and relaxation for eye muscles. Optometrists recommend access to long views for any sedentary workers (such as students) for frequent shifting of eye focal length, which promotes eye health and good vision. This may be especially important for young children while their eyes are still developing.

View windows provide occupants a connection with nature, weather, cardinal orientation, and some natural light (though not evenly distributed across the space). Occupant productivity and connection with place may increase through the associated views. Studies have shown that the primary reason people prefer having a window is view, preferably a view of nature. Research suggests that natural views elicit positive feelings, hold interest, and reduce fear and stress.⁶ Teachers have reported a reduction in stress levels when they have access to a relaxing view from their classroom.⁷

View windows, especially on the first floor of school buildings, also provide an important social communication function, allowing teachers, administrators, and parents to quickly assess what is going on inside a classroom. When installed with clear glass, they are often used to display art work and current student projects, contributing to both pride and awareness of other's efforts.

Operable view windows provide emergency egress and natural ventilation. A recent study has shown that natural ventilation in classrooms correlates with higher student test scores.⁸

⁶ Norris and Tillett. 1997. "Daylight and productivity: Is there a causal link?". Glass Processing Days Conference, Tampere, Finland (Sept.).

⁷ Hescong Mahone Group, "Daylighting in Schools—An Investigation into the Relationship between Daylighting and Human Performance," prepared for Pacific Gas & Electric Company and funded by California utility customers, 1999.

⁸ Ibid.

Well-designed view windows can reduce the overall building heating and cooling loads and north-facing view windows can also deliver enough dependable daylight to reduce electric lighting loads with manual or photocontrols. Other orientations, however, often have blinds or curtains drawn. Thus, unless a view window faces north or has a head height over 8 ft, and separate glare control for at least 2 ft of the top glazed area, it should not be counted on to provide sufficient daylight to merit the installation of automatic photocontrols and reap predictable savings from reduced electric lighting use.

Design Tools

The physical models and daylight simulation tools noted in the Overview can be used to evaluate potential daylight levels, and energy programs can be used to understand building energy implications.

For critical view areas, access to views and view angles from various positions in the space can be evaluated graphically with scaled drawings or with the use of a scale physical model. For a physical model analysis, it is helpful to have a “lipstick” video camera head, which can be moved around inside the model to record the views available at each location.



View windows at RI library are separated from the daylight feature overhead and use lower transmission glass to reduce glare. Lisa Heschang, photographer.

Design Details

- **Orientation.** Orient view windows toward the north or south to avoid low angle east/west sun. Up to 15° variance from true north or south is acceptable, but will reduce performance.
- **Shading devices.** Since view windows are within the occupants’ normal field of view, the contrast between the bright window view and other interior surfaces is an important glare consideration. Use exterior shading devices (overhangs, fins, etc.) or landscaping to eliminate direct sun and reduce brightness. If this is not possible, use a lower transmission glazing adjusted for the window orientation (about 40% transmission for south windows, 30% for east/west windows and 60% to 85% for north windows). On south, east, and west orientations, add an interior shade (shade screen, blinds, or drapes) so the teacher can adjust brightness and sun penetration as needed. In general, visible transmission of view glazing should not be reduced below 30% in clear sky climates or below 50% in heavily overcast climates. If tinted glazing is used, evaluate its effect on distortion of colors (for example, the graying of greens and blues in the landscape) in both overcast and clear skies. Provide blackout capability for view windows as needed.
- **Reflectance.** Deep splayed walls or mullions will also reduce glare. Paint all surfaces near windows white or off-white to further reduce contrast between the brightness of the window and its surrounding wall. Place view windows adjacent to a perpendicular surface to reflect daylight onto adjacent surfaces. Placing view windows adjacent to walls is best. Avoid punched holes in walls, as they create the worst glare conditions.



View windows promote communication between interior and exterior spaces. Lisa Heschang, photographer.

- **Outside reflective surfaces.** Be aware of bright reflective surfaces outside the view window that may create glare when they are in sunlight. Reflected sun off a car windshield can be especially troublesome. Light-colored walls within view can also create glare sources when they are in direct sun. Plant hedges or trees to reduce the glare potential from these exterior sources.
- **Thermal comfort.** Window surfaces that are considerably above or below the mean radiant temperature of other room surfaces will feel uncomfortably cold or hot for occupants sitting next to them. In very cold or hot climates (desert, mountain and Central Valley), use double glazing with a low-e coating to maximize comfort and energy efficiency. Single glazing is sufficient for coastal climates in California.
- **Views.** In classrooms, orient views toward “passive” nature scenes. In administration areas, views may be oriented toward the school entry or other security concerns.
- **Teaching surface.** In classrooms, the teaching wall should be perpendicular to the window wall for best illumination.
- **Computer screen location.** Orient computers at a 45° angle from view windows to avoid glare from reflections of the window in the VDT screen. Flat screen computers and adjustable-angle LED screens also help to reduce glare.
- **Security.** Provide operable interior shades and/or laminated glass for security in ground level rooms that contain computers or other valuables.
- **Durability and accessibility.** Use sturdy mechanisms for all operable ventilation and shading devices. Make them easily accessible to the teacher and easily repairable.
- **Noise transmission.** Since windows are frequently the “weakest link” acoustically in a building structure, double glazed windows are often the only alternative to controlling exterior noise. Normal therma-pane double paned windows with ¼ in. or ½ in. airspace are not acoustically effective. For better acoustic performance, windows should have laminated glass on at least one pane, as well as significant airspace between the two panes. In high noise areas (from exterior traffic and/or aircraft), it is not uncommon to require thicker laminated glass and 2 in. to 4 in. of airspace between the panes.
- **Balancing with electric light.** If view windows are the only daylight apertures in the room, and they appear on only one wall of the space, balance their brightness in the room by washing other interior walls with electric light.

Operation and Maintenance Issues

View windows should be washed on a schedule. Elements provided to reduce glare and allow blackout conditions (blinds, drapes, blackout shades, etc.) need to be cleaned and replaced over time. Give consideration to the robustness of operable shade mechanisms that are accessible to students. Coordinate selection of glazing materials with the maintenance staff to ensure ease of cleaning and replacement. Districts may have district-wide standards to ensure quick replacement of broken glass, but ensure that it is replaced with the same type of glass.

Design ventilation devices to prevent physical entry as well as any rain or maintenance water penetration.

Commissioning

None.

References/Additional Information

See the Overview section of this chapter.

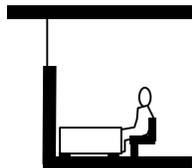
Related Volume III CHPS Criteria

See the Overview section of this chapter, and:

Energy Credit 2: Natural Ventilation.

IEQ Credit 6: Controllability of Systems.

Guideline DL2: High Sidelighting—Clerestory



Recommendation

Use high clerestories in perimeter walls to increase daylight delivery deeper in classrooms, offices, libraries, multipurpose rooms, gymnasiums, and administrative areas.

Description

High sidelighting clerestories are vertical glazing in an exterior wall above eye level (usually above 7 ft). Since the penetration of daylight from vertical glazing is about two times the window head height, moving the window higher in the wall increases daylight penetration in the space.

Applicability

High clerestory windows can be used in all school spaces to provide deep penetration of daylight.

They are applicable to all climate regions and should be planned in the schematic design phase.

Applicable Codes

The California Energy Efficiency Code does not require that high clerestories be installed. However, the code does specify the minimum performance of fenestration products and it limits window area to a maximum of 40% of the exterior wall area.

Integrated Design Implications

- **Design phase.** High sidelighting requires high ceilings and perimeter walls. North and (shaded) south orientations are preferable, although east, and west orientations can be acceptable if diffusing glazing is used, or if low-angle sun penetration will not be bothersome in the space. High sidelighting is most appropriate for open plan interior layouts that allow unobstructed daylight penetration. It should be considered in the early schematic design phase.
- **Balance with other daylight needs.** Applied to one wall, this approach creates a decreasing gradient of useable daylight about two times the clerestory head height into the space. For spaces of 20 ft to 40 ft in width (classrooms, etc.), it can be balanced with a daylighting scheme on the opposite wall to provide even lighting across the entire space. View windows should also be provided. The total glazing area should be apportioned among these needs.



Classroom with high clerestory window. Lisa Heschong, photographer.

Applicable Spaces	Climates	When to Consider
Classrooms	South Coast	Programming
Library	North Coast	Schematic
Multi-Purpose / Cafeteria	Central Valley	Design Dev.
Gym	Mountains	Contract Docs.
Corridors	Desert	Construction
Administration		Commissioning
Toilets		Operation
Other		

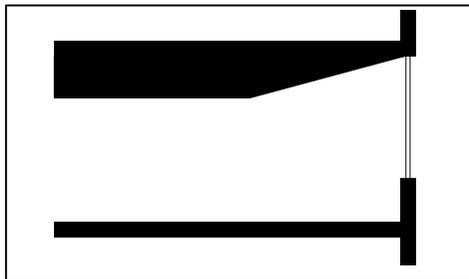


Figure 1 -- Sloped Ceiling

Sloped ceiling at perimeter increases window head height by reducing plenum space

- **Reduced plenum space.** Clerestory sidelighting requires ceiling heights of 9.5 ft or more at the window wall. This extra ceiling height may be accomplished with minimal increase of the floor-to-floor height by careful integration of the structural system, HVAC ducts and electric lighting in the plenum space. Sloping (or stepping) the ceiling upward at the perimeter (see figure) — essentially reducing the plenum space there — can also yield additional perimeter ceiling height. For ceiling-ducted HVAC systems, this requires routing ducts away from perimeter walls.
- **Natural ventilation.** High windows can be especially beneficial for natural ventilation, by allowing heated air to escape out near the ceiling. The ideal location for high operable windows is on the leeward side of a building.
- **Integration with HVAC.** High sidelighting glazing impacts HVAC loads by its vulnerability to solar gains during the cooling season and heat loss in the heating season. Good design (appropriate glazing orientation, size, glazing materials, shading and photocontrol of electric lights) can reduce the overall HVAC loads and potentially reduce HVAC system size and first costs.
- **Duct work.** Keep ductwork away from high windows to avoid blocking daylight.
- **Integration with electric lighting.** High sidelighting creates linear zones of daylight that run parallel to the clerestory windows. Electric lighting should be circuited parallel to this and photocontrolled (or manually controlled) in response to available daylight.

Cost Effectiveness

Costs for high sidelighting are low to moderate. Windows are standard practice for classrooms. A balance of view and clerestory windows can be provided for each classroom with minimal increase to the overall glazed area. The incremental cost of energy efficient glazing ranges from \$0.75/ft² to \$2.50/ft².

Costs	L			
	M			
	H			
		L	M	H
		Benefits		

Benefits

High sidelighting provides a moderate level of benefits. The general energy saving, productivity and visual comfort benefits of daylighting are discussed in the Overview section to this chapter. Clerestory sidelighting both saves energy and improves lighting quality. Energy savings come from reduced electric lighting energy use. Lighting quality is improved by a more uniform distribution of daylight across the space.

Design Tools

Computer simulation programs and scale models as outlined in the Overview can be used to demonstrate daylight distribution. If the design includes sloped surfaces, check to ensure the simulation program can accommodate these. Check for daylight levels across the space under both clear sky and overcast sky conditions and check direct sun penetration through the clerestory glazing for the lowest expected sun angles. Even occasional penetration of low sun angles can be extremely bothersome to occupants and may lead to blocking a window.

Energy savings from minimized HVAC loads and control of electric lighting in response to daylight can be estimated with the DOE-2, EnergyPlus, and Energy-10 programs available.

Design Details

- **Ceiling height.** High sidelighting glazing works best in spaces with high ceilings. A minimum perimeter ceiling height of 9.5 ft is recommended. Generally, the higher the ceiling height, the better.
- **Balancing with view windows.** Lower view windows are frequently coupled with high sidelighting schemes, but they do not have to coincide for the whole perimeter. The high glazing should be continuous along the whole area to be daylit. View windows can be selectively spaced beneath these high windows as needed. This balance between high clerestories and view windows can leave lower perimeter wall space available for other uses.
- **Shading devices.** Design high sidelighting clerestories with exterior shading, diffusing glazing, operable blinds, or light shelves to eliminate direct sun penetration. Mini-blinds positioned between the panes of glass in a double glazed window accomplish this with minimal maintenance. (A light shelf or louver system may also be used; see Guideline DL3.) Dedicated blinds or shades for the upper clerestory glazing can allow lower view windows to be controlled separately for glare. Blackout shades may need to be provided.
- **Glazing materials.** New glazing materials (prismatic, lensed, holographic, or laser cut acrylic) may be available to redirect daylight to the ceiling from the clerestory. These can deliver daylight deeper in the space but may cause very bright glazed areas and should be tested to see if they produce glare.
- **Orientation.** Clerestories are most effective on south and north orientations, but should be carefully evaluated on east and west orientations to assure that low sun angle penetration and direct solar gain into the space is minimized. Shade exterior glazing with an overhang on east-, west-, and south-facing glazing to minimize solar gain or use a selective low-e coating (SHGC less than .45).
- **Visible transmission.** Use high transmission, clear glazing (visible transmission 60% to 90%) on the upper window to admit the maximum daylight to the space. Double clear low-e glazing is recommended in the desert, mountain and Central Valley climates; single clear glass is recommended in coastal climates.
- **Stepped ceiling.** Clerestories may create a comparatively dark area along the wall directly beneath them. An interior stepped ceiling in a multi-story building can create a clerestory that reflects daylight back onto the wall to brighten it and deliver reflected daylight to the space.

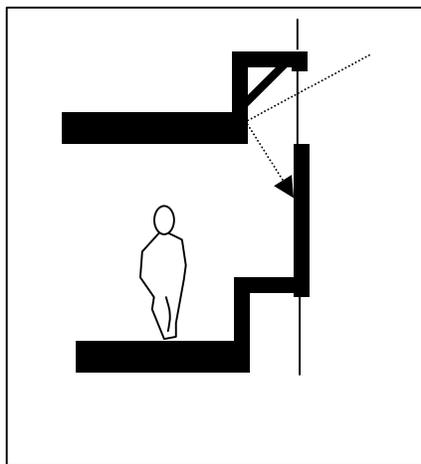


Figure 2 – Clerestories in Multistory Buildings

Clerestories in multistory buildings can redirect daylight onto the perimeter wall to brighten it.

- **Reflectance.** Paint all surfaces near the clerestories white or off-white to reduce contrast between the brightness of the clerestory and its surrounding wall. The adjacent ceiling should also have a

highly reflective (>70%) white or off-white surface to help diffuse a maximum amount of daylight into the space. Use specially designed “high reflectance” ceiling tiles if the budget allows.

- **Teaching surface.** In classrooms, the teaching surface should be perpendicular to the window wall for best illumination. Avoid orientations that will put students’ or teachers’ faces in silhouette or cause reflected glare on whiteboards or computer screens.

Operation and Maintenance Issues

For operable louvers, it is best to have preset angles that are seasonally adjusted by maintenance staff so the louvers are not inadvertently closed and forgotten or left at a non-optimal angle.

For shades or blinds that are operated by teachers, ensure that their control mechanisms are accessible, robust, and easily repaired.

Clerestory windows should be washed on a regular schedule.

Commissioning

Set adjustable louvers at their correct seasonal angle to eliminate direct sun penetration.

References/Additional Information

See the Overview section of this chapter.

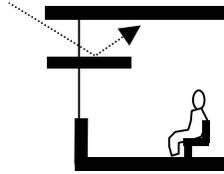
Related Volume III CHPS Criteria

See the Overview section of this chapter, and:

Energy Credit 2: Natural Ventilation.

IEQ Credit 6: Controllability of Systems.

Guideline DL3: High Sidelighting—Clerestory with Light Shelf or Louvers



Recommendation

Use light shelves or louvers with high clerestory glazing in perimeter walls to improve daylight distribution, block direct sun penetration, and minimize glare in classrooms, offices, libraries, multipurpose rooms, gymnasiums, and administrative areas.

Description

A light shelf is a horizontal panel placed below high clerestory glazing (with a view window generally below it) to bounce daylight deeper into the space. Light distribution is improved as daylight reflects off the top surface of the light shelf or louver onto the ceiling. A series of smaller horizontal louvers (6 in. to 24 in. wide) can replace a single large light shelf with a slight sacrifice in performance. The larger the louver, the deeper it will deliver daylight into the space. Light shelves and louvers can be located on the exterior, interior, or both. Exterior shelves shade the lower window from solar heat gain and reflect high angle summer sun into the room. Interior shelves reflect lower angle winter sun while blocking the penetration of direct sun and reducing glare from the upper glazing.

Applicability

High clerestory windows can be used in most school spaces to provide deep penetration of daylight. They are applicable to all climate regions and should be planned in the schematic design phase.

Applicable Codes

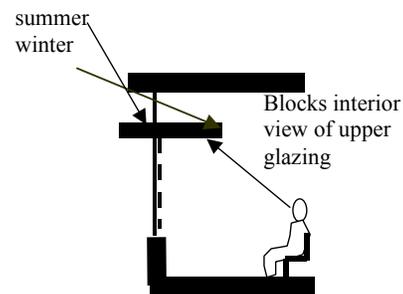
The California Energy Efficiency Code does not require that high side lighting with light shelves be installed. However, the code does specify the minimum performance of fenestration products and it limits window area to a maximum of 40% of the exterior wall area.

Integrated Design Implications

- Design Phase.** Clerestories with light shelves require perimeter access to south-facing (+/- 15°) sidelighting and impact many aspects of building massing. They also benefit from open plan interior



Photo of Liberty Elementary School with exterior lightshelves to reflect sunlight onto classroom ceilings. Photo courtesy of Liberty Elementary, Boise School District, Boise, ID



Exterior light shelves shade lower window and reflect summer sun into room. Interior shelves reflect winter sun while reducing glare.

Applicable Spaces	Climates	When to Consider
Classrooms	South Coast	Programming
Library	North Coast	Schematic
Multi-Purpose / Cafeteria	Central Valley	Design Dev.
Gym	Mountains	Contract Docs.
Corridors	Desert	Construction
Administration		Commissioning
Toilets		Operation
Other		

layouts that allow unobstructed daylight penetration. They should be considered in the early schematic design phase. Calculation of the size and cutoff angles of the light shelf or louver system is critical.

- **Balance with Other Daylight Needs.** Applied to one wall, this approach creates a decreasing gradient of useable daylight about 2.5 times the clerestory head height into the space. For spaces of 20 ft to 50 ft in width (such as classrooms), it can be balanced with a daylighting scheme on the opposite wall to provide even lighting across the entire space. Lower view windows are frequently coupled with light shelf schemes, but they do not have to coincide for the whole length of the light shelf. The high glazing with light shelf should be continuous along the whole area to be daylighted. View windows can be selectively spaced beneath the light shelf as needed. This balance between high sidelighting and view windows leaves some lower perimeter wall space available for other uses. Total glazing area should be apportioned among these needs.
- **Integration with Ceiling Plenum.** Clerestories with light shelves require ceiling heights of 9.5 ft or more at the window wall. This extra ceiling height may be accomplished with minimal increase of the floor-to-floor height by careful integration of the structural system, HVAC ducts, and electric lighting in the plenum space. Sloping (or stepping) the ceiling upward at the perimeter — essentially reducing the plenum space there — can also yield additional perimeter ceiling height. For ceiling-ducted HVAC systems, this requires routing ducts away from perimeter walls.
- **Integration with HVAC.** Glazing above a light shelf impacts HVAC loads by its vulnerability to solar gains during the cooling season and heat loss in the heating season. Good design (appropriate glazing orientation, size, performance, shading, and photocontrol of electric lights) can reduce the overall HVAC loads and potentially reduce HVAC system size and first costs. Light shelves also must be designed so as not to interfere with circulation of air from the HVAC system.
- **Integration with Electric Lighting.** Clerestories with light shelves create linear zones of daylight that run parallel to the clerestory windows. Electric lighting should be circuited parallel to this and photocontrolled (or manually controlled) in response to available daylight. Light shelves and louvers deliver daylight indirectly to the space; they work well when coupled with direct/indirect pendant electric lighting. Sometimes the first row of electric lighting is incorporated into the light shelf itself.
- **Integration with Other Mechanical Systems.** Design light shelves so they do not interfere with the operation of a fire sprinkler system.

Cost Effectiveness

Clerestories with light shelves or louvers are relatively expensive, but downsizing cooling systems may offset some cost (if electric lights are automatically switched or dimmed in response to daylight). Energy savings from reduced lighting and cooling energy are adequate to recover the initial investment in about eight to 12 years.

Costs	L			
	M			
	H			
		L	M	H
		Benefits		

Benefits

Clerestories with light shelves or louvers produce a high level of benefits. The general energy saving, productivity, and visual comfort benefits of daylighting are discussed in the Overview section to this chapter. Clerestories with light shelves or louvers both save energy and improve lighting quality. Energy savings come from reduced solar gains (when an exterior light shelf shades lower glazing) and reduced lighting energy use.

Lighting quality is improved because daylight is delivered deeper in the space, creating a more even distribution of daylight. Interior light shelves and louvers restrict the view of the bright upper glazing, eliminating glare.

Design Tools

Computer simulation programs and scale models as outlined in the Overview can be used to demonstrate daylight distribution. If the design includes sloped surfaces, check to ensure the simulation program can

accommodate these. Check for daylight levels across the space under both clear sky and overcast sky conditions, and check direct sun penetration through the upper glazing for the lowest expected sun angles.

Most whole-building energy simulation programs (like DOE-2 and EnergyPlus) do not accurately represent the increased daylight distribution from a light shelf or louver system. For more accurate simulations of electric lighting energy savings, the daylight distribution should be simulated with a physical scale model or daylight simulation program and then input to the energy program.

Design Details

- **Ceiling height.** Provide a minimum perimeter ceiling height of 9.5 ft (the higher, the better). Position the light shelf at 7 ft or more above the floor. Coordinate shelf position with pendant electric lighting, door headers, shelving, fire sprinklers, and other interior features.
- **Orientation.** Light shelves are most effective on south orientations, and occasionally on the north (to reduce glare from the upper glazing). They should be avoided on east and west orientations.

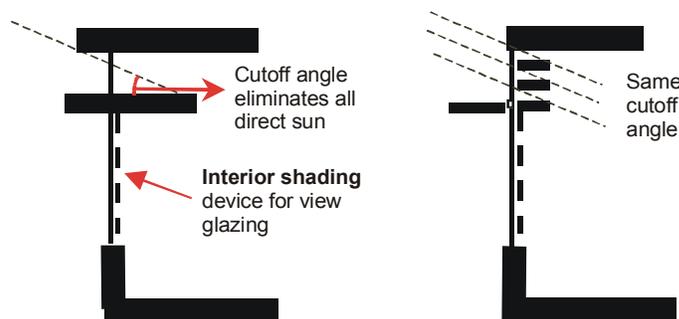


Figure 3 – Cutoff Angle of Light Shelves

Set the cutoff angle of light shelves or louvers to eliminate direct sun penetration during normal school hours.

- **Cutoff angle.** Set the cutoff angle of the light shelf or louvers (see the figure above) to eliminate direct sun penetration during normal school hours. (Use a cutoff angle of 27° for latitudes north of Chico. Use a cutoff angle of 23° for latitudes between Chico and Bakersfield. Use a cutoff angle of 20° for latitudes south of Bakersfield.) Cutoff angle can be increased by 10° if there are operable shades on the upper glazing, and increased by 20° if operable louvers will be seasonally adjusted.
- **Visible transmission.** Use high transmission, clear glazing (visible transmission 60% to 90%) on the upper window to admit the maximum daylight to the space. Double glazing with low-e is recommended in the desert, mountain and Central Valley climates. Single clear glass is acceptable in coastal climates.
- **Reflectance.** The top surface of the light shelf or louvers should be highly reflective (greater than 80% reflectance and with a diffuse, not mirrored, surface). Paint all surfaces near the clerestories white or off-white to reduce contrast between the brightness of the clerestory and its surrounding wall. The adjacent ceiling should also have a highly reflective (>70%) white or off-white surface to help diffuse a maximum amount of daylight into the space. Use specially designed “high reflectance” ceiling tiles if the budget allows.

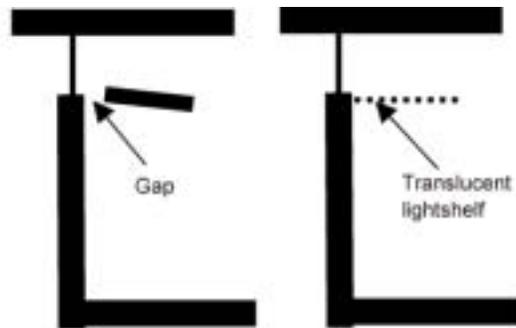


Figure 4 – Creating a Wall Wash

If opaque light shelves aren't coupled with view windows, consider leaving a gap between the light shelf and the wall to create a wall wash. Translucent shelves provide a soft light under them.

- **Materials.** Light shelves and louvers may be opaque or translucent and constructed of wood, metal panels, GFRC (glass fiber reinforced concrete), plastic, fabric, or acoustic ceiling materials. Choice of material should include consideration of reflectivity, structural strength, cost, ease of maintenance, and durability. Some curtain wall or window manufacturers can assist in developing details for light shelves and offer add-on products as part of their service. Fabric “shelves” can be suspended from the ceiling at their interior edge.
- **Top surface.** The top surface of a row of lockers or casework that lines a perimeter wall can also be used as a light shelf if its reflectivity and dimensions are appropriate. Slope the top surface so it will not be used for storage.
- **Opaque vs. translucent shelves.** Opaque shelves may create a dark space along the wall directly under them if they are not coupled with a view window. Leave a gap between the light shelf and the wall to create a wall wash or use electric lighting to brighten this wall. Translucent shelves provide a soft light under them but must be carefully evaluated so the direct view of the under side does not create glare. See Figure 4 above.
- **Dirt accumulation.** To reduce accumulation of dirt, exterior shelves should be sloped at least 0.25 in./ft so that rain can help keep it clean and not pool on the shelf. Also slope interior shelves so they are not used for storage. Fabric construction is another way of preventing this.
- **Accessibility.** Both exterior and interior light shelves can be an “attractive nuisance” in school buildings, inviting students to climb or hang on them. Minimize access to the shelf or use a series of louvers instead.
- **Access for cleaning.** Detail the light shelf or louver system so it is easy to clean the glass above it, both inside and out. Large light shelves may need to be moved away from the window by six inches to allow for window cleaning equipment to be inserted from below the shelf.
- **Teaching surface.** In classrooms, the teaching surface should be perpendicular to the window wall for best illumination.

Operation and Maintenance Issues

The glazing and light shelf/louver system forms a light delivery system that must be kept clean to ensure maximum delivery of daylight to the space. The top surface of the shelf or louvers should be cleaned each time the windows are washed. Make sure light shelves or louvers are detailed correctly to allow easy window cleaning. For operable louvers, it is best to have preset angles that are seasonally adjusted by maintenance staff so the louvers are not inadvertently closed and forgotten or left at a non-optimal angle.

Commissioning

Unless the light shelf or louvers are moveable, commissioning should not be necessary. Set adjustable louvers at their correct seasonal angle to eliminate direct sun penetration.

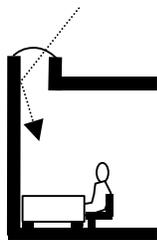
References/Additional Information

See the Overview section of this chapter.

Related Volume III CHPS Criteria

See the Overview section of this chapter.

Guideline DL4: Classroom Daylighting—Wall Wash Toplighting



Recommendation

Use wall wash toplighting for interior classroom walls to balance daylight from window walls, brighten interior classrooms, and make them seem more spacious.

Description

Wall wash toplighting provides daylight from above through a linear skylight or monitor to wash an interior wall. The glazing is obscured from direct view by the skylight or monitor well. Daylight is diffused with diffusing glazing, baffles or reflections off of matte reflective light well and interior walls.

Applicability

A toplighting scheme applies to single-story buildings or the top floor only of a multistory building. Appropriate spaces for wall wash toplighting may include classrooms, libraries, multipurpose spaces, gyms, corridors, and administration offices. It is applicable to all climate regions, and must be planned for in schematic design.

Applicable Codes

The California Energy Code specifies the minimum performance of fenestration products and it limits window area to a maximum of 5% of the exterior roof area.

Integrated Design Implications

- **Balance with other daylight.** Applied to one wall, this approach creates even daylight across approximately two-thirds of a classroom. It should be balanced with a daylighting scheme on the opposite wall to provide even lighting across the entire classroom. View windows should also be provided. The total glazing area should be apportioned among these needs.
- **Skylights vs. vertical glazing.** The glazing for this wall wash toplighting scheme may be either horizontal or vertical (facing north, east, south, or west). See Daylighting Design Considerations in the electronic Appendix for a discussion of the energy performance of sidelighting versus toplighting facing in different orientations for all of the California climate zones. Skylights can offer an advantage of lower construction costs.



Skylit wall wash delivers daylight across two-thirds of this classroom. Lisa Heschong, photographer.

Applicable Spaces	Climates	When to Consider
Classrooms	South Coast	Programming
Library	North Coast	Schematic
Multi-Purpose / Cafeteria	Central Valley	Design Dev.
Gym	Mountains	Contract Docs.
Corridors	Desert	Construction
Administration		Commissioning
Toilets		Operation
Other		

- **Integration with HVAC.** Placement of skylights and monitors and their associated light wells must be coordinated with the location of rooftop HVAC equipment and interior duct runs. If it is oriented, glazed, shaded, and integrated with electric lighting controls, toplighting should decrease overall seasonal heating and cooling loads on the building. This can reduce the initial size of the HVAC system and annual energy costs.
- **Integration with mechanical ventilation.** Operable rooftop fenestration can be used to naturally ventilate the space. Evaluate thermal stratification of air in the space and prevailing wind conditions to assess the feasibility.
- **Integration with structural system.** Skylights and monitors interrupt the roof diaphragm and structural system. Their size and location may be limited by this and must be coordinated with the structural system to maintain its strength and integrity. See Daylighting Design Considerations in the electronic Appendix for more details.
- **Safety and security.** Toplighting scenarios on relatively flat roofs have liabilities for both safety and security. Refer to Daylighting Design Considerations in electronic Appendix for more details.

Cost Effectiveness

Costs for wall wash toplighting are moderate to high, depending on design. Commercial, single glazed skylights are usually the least expensive approach.

Costs	L			
	M		■	
	H			
		L	M	H
		Benefits		

Benefits

Wall wash toplighting provides a moderate to high level of benefits. This approach washes a wall with light, and bounces glare-free daylight into the classroom. It will make the space appear larger and brighter. The uniform light from this approach can easily light the inner two-thirds of a classroom. It is excellent when combined with another wall wash or a sidelighting technique that increases daylight on the opposite side of the room (for example, a perimeter window) to create even, balanced daylight across the whole room.

This approach saves electric lighting energy if the first row or two of lights adjacent to the wall wash are switched off or dimmed in response to the daylight. Savings for controlled fixtures may be 40% to 80% during daylight hours.

If this scheme is used to provide natural ventilation, it may increase student performance. Natural ventilation has been correlated with higher student scores on standardized tests and lower overall building energy use.

Design Tools

The computer simulation programs and scale models described in this chapter's Overview can be used to demonstrate daylight distribution. If the design includes sloped surfaces, check to ensure the simulation program can handle this situation.

Design Details

General

- **Orientation.** Optimize the toplighting design for the climate, orientation, and budget. A skylight will perform better in a predominantly overcast sky condition and for non-north/south orientations. A well-designed monitor with north- or south-facing glazing will be more expensive, but may perform better than a skylight in sunny climates with high air conditioning loads.
- **Diffusion.** Diffuse the daylight before it washes the wall. Eliminate direct sun patches with diffusing glazing, baffles, or a deep well. For skylights, use a high performance diffusing material, such as prismatic acrylic, to maximize light transmission while minimizing hot spots. For clear glazed, baffled systems, design fixed baffles to cut off all expected sun angles or provide adjustable baffles.
- **Visible transmittance.** Use glazing with the highest visible transmittance to bring in the most daylight relative to the glazed area. For vertical glass, use a low-e coating to minimize heat loss; use a selective low-e coating to minimize solar gain on solar orientations.

- **Light wells.** A light well connects the upper aperture with the ceiling plane of the classroom. Light well walls should be highly reflective (>80% reflectance). Diffusely reflecting light wells should be less than 8 ft deep; mirrored reflecting wells can be used for deeper wells when necessary.
- **Surface colors.** The top of the wall that is washed should be light in color (>70% reflectance) so it can reflect daylight into the space. It should not have protrusions that will cast objectionable shadows.
- **Balancing daylight.** Combine wall wash toplighting approach with another linear approach on the opposite wall to balance daylight in the space.
- **Insulation.** Insulate light well walls to minimize thermal losses and reduce condensation.
- **Task and accent lighting.** In addition to ambient lighting, this approach can be used for task lighting on the wall (lighting lockers) or accent lighting (lighting artwork). It is excellent for corridors and other circulation spaces.
- **Blackout capability.** The aperture will need blackout capability for most classrooms.
- **Integrating with electric light.** Consider an electric lighting wall wash luminaire to illuminate the wall at night, or during heavily overcast conditions. Photoswitch this light in response to daylight levels.
- **Safety and security.** Operable mechanisms should prevent any physical entry. A safety/security grating can be placed in the light well under the glazing for this toplighting scheme. (Light control louvers and baffles may also serve this function.) Make sure this grating does not create a shadow pattern on the wall. See Daylighting Design Considerations in the electronic Appendix for more discussion of safety and security issues with toplighting.
- **Leakage.** All roof penetrations have leakage liabilities. Use well-tested curb design details and flashing kits provided by the manufacturer. Any operable opening should prevent rain penetration.

Monitors

Monitors with glazing oriented north/south (elongated east/west) will exhibit the least variation of daylight levels throughout the day and will be easiest to design for good energy performance. South-facing vertical glazing should have an overhang, or spectrally selective low-e coating (SHGC less than .45) to reduce solar gains during the cooling season combined with baffles or diffusing glazing to eliminate direct sun. Monitors with glazing oriented east or west are more likely to show variations in light level and quality from morning to afternoon. If the east-west orientation is required, a skylight may perform better than a monitor.

Operation and Maintenance Issues

- Educate teachers about how wall wash toplighting delivers daylight to the space; discourage them from placing dark colored artwork and posters high on the washed wall.
- Clean glazing on a schedule. Horizontal glazing needs more frequent cleaning in climates with low rainfall.
- The mechanisms for operable louvers and blackout shades should be robust, accessible to the instructor and easily repaired.
- The janitorial service should check all operable windows or skylights for closure daily.

Commissioning

Check to ascertain that operable louvers and shades are working. Set angles of adjustable louvers to eliminate direct sun penetration.

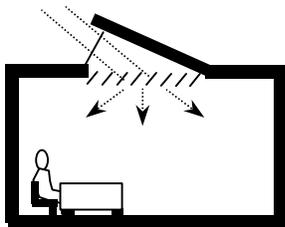
References/Additional Information

See the Overview section of this chapter.

Related Volume III CHPS Criteria

See the Overview section of this chapter.

Guideline DL5: Central Toplighting



Recommendation

Use central toplighting in single-story classrooms to provide high levels of even, balanced daylight across the entire room.

Description

Central toplighting uses a central monitor or skylight (or cluster of skylights) to distribute daylight evenly across the room. Daylight is diffused with diffusing glazing or baffles that can be fixed or operable. Daylight levels are highest directly under the aperture and gradually reduce toward the perimeter of the space.

Applicability

Central toplighting is applicable in single-story or top floor spaces including classrooms, libraries, multipurpose spaces, and administrative offices. It is appropriate for all climate regions, and should be considered during the programmatic, schematic, and design development phases of a school building project.

Applicable Codes

The California Energy Code specifies the minimum performance of fenestration products and it limits window area to a maximum of 5% of the exterior roof area.

Integrated Design Implications

- **Integration with site plan.** This toplighting scheme applies to single-story buildings or the top floor only of a multi-story building. It must be planned for in the schematic design.
- **Skylight vs. vertical glazing.** The glazing for a central toplighting scheme may be either horizontal or vertical (facing north, east, south, or west). See Daylighting Design Considerations in the on-line Appendix for a discussion of the energy performance of horizontal versus vertical glazing facing in different orientations and an evaluation of the relative HVAC loads.
- **Balance with other daylight.** This scheme may be combined with view windows in perimeter walls. Since the toplighting aperture provides most of the ambient daylight, smaller windows can be judiciously spaced in exterior walls to optimize views and valuable wall space can be relinquished for other needs. The total glazing area should be apportioned among these needs.
- **Integration with HVAC.** Placement of skylights and monitors, and their associated light wells, must be coordinated with the location of rooftop HVAC equipment and interior ducts.



Central sawtooth monitor provides even illumination across desktops in this classroom. Photo courtesy: Barbara Erwine.

Applicable Spaces	Climates	When to Consider
Classrooms	South Coast	Programming
Library	North Coast	Schematic
Multi-Purpose / Cafeteria	Central Valley	Design Dev.
Gym	Mountains	Contract Docs.
Corridors	Desert	Construction
Administration		Commissioning
Toilets		Operation
Other		

- **Integration with electric lighting.** Central daylighting schemes often fail to provide bright illumination on interior walls. Electric lighting wall wash fixtures may be needed to supplement the daylight.
- **Integration with mechanical ventilation.** If the toplighting fenestration is operable, it can be used to naturally ventilate the space. Evaluate the thermal stratification of air in the space and the prevailing wind conditions to assess the feasibility.
- **Safety and security.** Toplighting scenarios on relatively flat roofs have both safety and security issues that should be considered. The Daylighting Design Considerations in the on-line Appendix discusses these concerns in more detail.



Classroom with central skylight and splayed light well walls.
Photo courtesy PJHM Architects

Cost Effectiveness

Costs for central toplighting are medium to high, depending on design. Commercial, double glazed skylights or a diffusing, double wall panel system with a sheetrocked well will be the least expensive. Site-built monitors with vertical or sloped glazing will cost more.

Costs	L			
	M			■
	H			■
		L	M	H
		Benefits		

Benefits

Central toplighting provides a high level of benefits. With good diffusion, this approach creates even, balanced daylight across the classroom, which has been correlated with higher standardized test scores. (However, uncontrolled direct sun toplighting in classrooms has been associated with lower standardized test scores. See this chapter's Overview for details.)

This approach saves electric lighting energy if the electric lights are switched off or dimmed in response to the daylight. Savings may be 40% to 80% during daylight hours.

Operable louvers can provide variable amounts of daylight for different classroom activities.

Operable skylights or monitor glazing can provide the top outlet for a natural ventilation scheme that draws fresh air in through a lower aperture. Natural ventilation may improve student performance, having been positively correlated with higher student scores on standardized tests.

Design Tools

The computer simulation programs and scale models described in this chapter's Overview can be used to demonstrate daylight distribution and resultant daylight levels. If the design includes sloped surfaces, check that the simulation program can handle this. The SkyCalc program can be used to optimize the size and energy performance of a central skylight scheme.

Design Details

General

- **Visible transmittance.** Use high visible transmission glazing materials (greater than 60%) to maximize daylight while minimizing the size of the glazed area with its relatively low U-factor. Single glazing is adequate for most California climates. Double glazing is recommended for mountain regions. Alternatively, larger areas of low-transmission glazing with high insulation levels, such as insulated fiberglass panels, may be used successfully. The balance between visible transmittance and insulation levels is best studied with an hourly climate simulation software tool.

- **Orientation.** Optimize the toplighting design for the climate and budget. A skylight will perform better in a predominantly overcast sky condition or non-optimum orientation. A well-designed, north- or south-facing monitor will be more expensive, but may perform better than a skylight for sunny climates with high air conditioning loads.
- **Reflective materials.** A light well connects the upper aperture with the ceiling plane of the classroom. Light well walls should be highly reflective (>80% reflectance). Bright white, flat paint works best. Diffusely reflecting light wells should be less than 8 ft deep; specular reflecting wells can be used for deeper wells when necessary.
- **Diffusion.** Diffuse the daylight with diffusing glazing or baffles. Design baffles to cut off all expected sun angles or to be adjustable. Avoid placing diffusing glazing within the normal field of view, as it will cause excessive glare.
- **Splayed light wells.** Splay light well walls to spread the daylight more effectively in the space and reduce glare. A 45° to 60° angle works best.
- **Insulation.** Insulate light well walls to an R-value at least equivalent to the code requirement for wall insulation to minimize thermal losses and reduce condensation.
- **Blackout capability.** Add blackout capability, as needed, and louvers to modulate the daylight levels.
- **Integration with electric lighting.** If the light well is visible (not obscured by baffles), provide some electric light so it does not become a “dark hole” at night. Pendant uplight fixtures work well. Photoswitch these lights in response to daylight levels. See the Electric Lighting and Controls chapter for information about control of electric lights in response to available daylight.
- **Safety and security.** A safety/security grating can be placed in the light well under the glazing for this toplighting scheme. (Light control louvers and baffles can also serve this function.) Make sure this grating does not create a shadow pattern on the wall. See Daylighting Design Considerations in the on-line Appendix for more information about safety and security issues with toplighting.
- **Leakage.** All roof penetrations have leakage liabilities. Use well-tested curb design details and flashing kits provided by the manufacturer.
- **Reflectors.** A reflecting device may be placed below the light well to redirect daylight onto the ceiling or walls of the space. This ceiling/wall wash will make the space appear larger and brighter, even though horizontal footcandles measured at desk height may be reduced. The reflector may consist of flat or curved mirrored or matte reflective surfaces. It may also be partially translucent (fabric, plastic, or perforated metal). This device will require extra floor to ceiling height and should be studied with a physical scale model to evaluate daylight distribution.

Skylights

Use a glazed area of about 3% to 12% of the floor area. Use the lower end of this range for spaces with high air conditioning or heating loads, and the higher end for temperate climates with more overcast skies. In cold climates, consider south-facing clerestories instead of skylights.

Monitors

A sawtooth monitor with glazing oriented north will exhibit the least variation of daylight levels throughout the day and will have better energy performance than east or west glazing. South-facing vertical glazing should have an overhang or spectrally selective low-e (SHGC less than .45) to reduce solar gains during the cooling season. Avoid sawtooth monitors with glazing oriented east or west; they will show large variations in light level and quality from morning to afternoon, and will have poor thermal performance.

Operation and Maintenance

- Clean glazing on a regular schedule. Horizontal glazing needs more frequent cleaning in climates with low rainfall.
- Mechanisms for operable louvers and blackout shades should be robust, accessible to the teacher, and easily repaired.

Commissioning

Check that operable louvers and shades are working. Set angles of adjustable louvers to eliminate direct sun penetration.

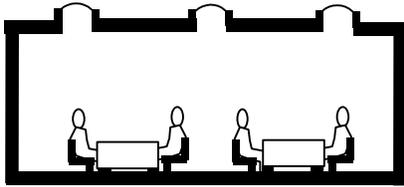
References/Additional Information

See the Overview section of this chapter.

Related Volume III CHPS Criteria

See the Overview section of this chapter.

Guideline DL6: Patterned Toplighting



Recommendation

Use patterned toplighting in interior spaces that need even, low glare illumination across a large area.

Description

Patterned toplighting provides daylight through a two-dimensional grid of skylights or rows of linear monitors (sawtooth or square). It provides even, glare-free daylight across large areas. Spacing of the pattern is largely a function of the ceiling height.

Applicability

This daylighting pattern is useful for any large area that needs even daylight levels. It is especially good for gymnasium, library, multipurpose, or cafeteria spaces. For gymnasium ball courts, add baffles or high light well cutoff angles to minimize direct views of bright glazing surfaces during ball games (See Design Details below). Patterned toplighting is appropriate for all climate regions, and should be considered during the programmatic, schematic, and design development phases.



Grid of skylights in Peoria Gymnasium provide even illumination across the space. Photo courtesy Natural Lighting Co., Inc.

Applicable Spaces	Climates	When to Consider
Classrooms	South Coast	Programming
Library	North Coast	Schematic
Multi-Purpose / Cafeteria	Central Valley	Design Dev.
Gym	Mountains	Contract Docs.
Corridors	Desert	Construction
Administration		Commissioning
Toilets		Operation
Other		

Applicable Codes

The California Energy Code specifies the minimum performance of fenestration products and it limits window area to a maximum of 5% of the exterior roof area.

Integrated Design Implications

- **Integration with site plan.** This toplighting scheme applies to single-story buildings or the top floor only of a multi-story building. It must be planned for in the schematic design.
- **Skylight vs. vertical glazing.** The glazing for these patterned toplighting schemes may be either horizontal or vertical (preferably facing north or south). See Daylighting Design Considerations in the on-line Appendix for a discussion of the energy performance of horizontal versus vertical glazing facing in different orientations and an evaluation of the relative HVAC loads.
- **Balance with other daylight.** This scheme may be combined with view windows in perimeter walls. Since the toplighting aperture provides most of the ambient daylight, smaller windows can be judiciously spaced in exterior walls to optimize views, and valuable wall space can be relinquished for other needs. The total glazing area should be apportioned among these needs.

- **Integration with HVAC.** Placement of skylights and monitors and their associated light wells must be coordinated with the location of rooftop HVAC equipment and interior duct runs.
- **Integration with mechanical ventilation.** If the toplighting fenestration is operable, it could be used to naturally ventilate the space. Evaluate the thermal stratification of air in the space and prevailing wind conditions to assess the feasibility.
- **Integration with structural system.** Skylights and monitors interrupt the roof diaphragm and structural system. Their size and location may be limited by this and must be coordinated with the structural system to maintain its strength and integrity. See Daylighting Design Considerations in the on-line Appendix for more information about integrating toplighting with structural systems.
- **Safety and security.** Toplighting scenarios on relatively flat roofs have both safety and security issues that should be considered. Check the Daylighting Design Considerations in the on-line Appendix for further discussion of these.

Cost Effectiveness

Costs for patterned toplighting range from low to high, depending on design. A grid of skylights with unfinished wells will be the least expensive; monitors with reflecting devices will be much more expensive. Costs include the expense of the skylight or monitor device; rooftop installation; curbs and waterproofing; interior well construction and finish; and electric lighting controls to switch or dim in response to daylight.

Costs	L			
	M			
	H			
		L	M	H
		Benefits		

Benefits

Patterned toplighting provides a high level of benefits. This approach creates even, balanced, low-glare daylight across the space. This approach saves electric lighting energy if the electric lights are switched off or dimmed in response to the daylight. Savings may be 40% to 80% during daylight hours.

Operable louvers can provide variable amounts of daylight for different activities. Operable skylights or monitor glazing can provide the top outlet for a natural ventilation scheme that draws fresh air in through a lower aperture. Natural ventilation may improve student performance, having been positively correlated with higher student scores on standardized tests.

Design Tools

The computer simulation programs and scale models described in this chapter's Overview can be used to demonstrate daylight distribution and resultant daylight levels. If the design includes sloped surfaces, check to ensure the simulation program can handle this. The SkyCalc program can be used to optimize the size of skylight schemes.

Design Details

General

- **Optimize for climate and budget:** A grid of skylights will perform better in a predominantly overcast sky condition. A series of well-designed monitors will be more expensive, but will perform better than a skylight for sunny climates with high air conditioning loads.
- **Visible transmittance:** Use high visible transmission glazing materials (greater than 60%) to maximize daylight while minimizing the size of the glazed area with its relatively low U-factor. Single glazing is adequate for most California climates. Double glazing is recommended for mountain regions. **Diffusion:** Diffuse the daylight with diffusing glazing or baffles. Design baffles to cut off all expected sun angles or to be adjustable. Avoid placing vertical diffusing glazing within the normal field of view.
- **Played light wells:** For deeper, narrow light wells, splay the light well walls to spread the daylight more effectively in the space and reduce glare. A 45° to 60° angle works best.
- **Reflectance:** A light well connects the upper aperture with the ceiling plane of the classroom. Light well walls should be highly reflective (>80% reflectance). Bright white flat paint works best. Diffusely

reflecting light wells should be a maximum of 6 ft to 8 ft deep; specular reflecting wells can be used for deeper wells when necessary.

- **Insulation:** Insulate light well walls to minimize thermal losses and reduce condensation. Use an R-value at least equivalent to the code requirement for wall insulation.
- **Blackout capability:** Add blackout capability, as needed, and louvers to modulate the daylight levels.
- **Safety and security:** A safety/security grating can be placed in light wells under the glazing for this toplighting scheme. (Light control louvers and baffles can also serve this function.)
- **Leakage:** All roof penetrations have leakage liabilities. Use well-tested curb design details and flashing kits provided by the manufacturer.

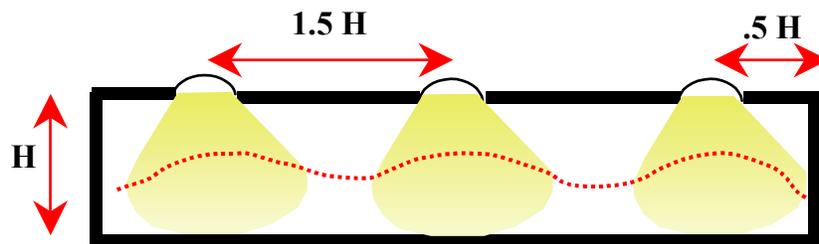


Figure 5 – Skylight Grid Spacing

Skylight Grid

As a rough rule of thumb, skylights should be spaced about one-and-a-half times the floor-to-ceiling height (H in Figure 5 above). Their glazing should be about 3% to 12% of the floor area to be lighted. (Use SkyCalc to optimize the design.)

Series of Monitors

Sawtooth monitors with glazing oriented north will exhibit the least variation of daylight levels throughout the day and will have better energy performance than east or west glazing. South-facing vertical glazing should be smaller and should have an overhang or spectrally selective low-e coating (SHGC less than .45) to reduce solar gains during the cooling season. Avoid sawtooth monitors with glazing oriented east or west; they will show large variations in light level and quality from morning to afternoon, and poor energy performance.

Operation and Maintenance

- Clean glazing on a regular schedule. Horizontal glazing needs more frequent cleaning in climates with low rainfall.
- Mechanisms for operable louvers and blackout shades should be robust, accessible to the instructor, and easily repaired.

Commissioning

Check that operable louvers and shades are working. Set angles of adjustable louvers to eliminate direct sun penetration.

References/Additional Information

See the Overview section of this chapter.

Related Volume III CHPS Criteria

See the Overview section of this chapter.

Guideline DL7: Linear Toplighting

Recommendation

Use linear toplighting as a single downlighting element in a long, linear space (such as a corridor) to direct movement or establish a visual orientation. Use it on two sides of a space to define separate functions or activities, to define edges in a larger space, and/or to downlight the space from two directions.

Description

Linear toplighting is a downlighting scheme that provides a line of high intensity daylight directly under it, which diminishes as an individual moves perpendicularly away from it. It establishes a strong longitudinal orientation in the space and is best coupled with a corresponding circulation pattern or linear visual cue. Used bilaterally (from two sides), it can frame a larger space.

Applicability

This daylighting pattern is useful for enclosed hallways and linear walkways within a larger space, or for use bilaterally to frame centrally focused areas like gymnasiums, libraries, and multipurpose areas. Linear toplighting may also be used in covered exterior walkways to minimize their shadow, especially in covered walkways adjacent to rooms with sidelighting.

Applicable Codes

The California Energy Code specifies the minimum performance of fenestration products and it limits window area to a maximum of 5% of the exterior roof area.

Integrated Design Implications

- **Design Phase.** This toplighting scheme applies to single-story buildings or the top floor only of a multistory building. It must be integrated with the site plan and building massing and should be planned for in the schematic design phase.
- **Balance with other daylight.** Since overall glazing area is limited, the amount of glazing in a linear toplighting scheme must be balanced with the need for view windows and other apertures in the space.
- **Integration with electric lighting.** Electric lighting should be aligned with the toplighting without blocking it and causing shadows on the floor.
- **Integration with structural system.** Skylights and monitors interrupt the roof diaphragm and structural system. Their size and location may be limited by this and must be coordinated with the



Linear skylight in this library spreads daylight to adjacent spaces and organizes the circulation

Applicable Spaces	Climates	When to Consider
Classrooms	South Coast	Programming
Library	North Coast	Schematic
Multi-Purpose / Cafeteria	Central Valley	Design Dev.
Gym	Mountains	Contract Docs.
Corridors	Desert	Construction
Administration		Commissioning
Toilets		Operation
Other		

- **Diffusion.** Either diffuse daylight or direct sun may be used in circulation and transition areas. Daylight diffused with translucent glazing or baffles will spread the daylight evenly in the space, making the most effective use of the light. Occasional patches of direct sun can create a vibrant splash of light to emphasize major intersections and circulation spines. Some designs have successfully combined patterns of diffusing glazing with smaller areas of transparent glazing to animate a circulation space.
- **Shared daylighting.** Consider sharing diffuse corridor daylight with adjacent spaces by glazing the upper portion of the wall. Avoid this in areas where acoustic separation is important. In multistory buildings, consider sharing daylight from the top floor corridor with the lower floor by periodically cutting light wells to the lower level.
- **Splayed light wells.** For diffusing skylights with deeper, narrow light wells, splay the light well walls to spread the daylight more effectively in the space and reduce glare. A 45° to 60° angle works best.
- **Insulation.** Insulate light well walls to an R-value at least equivalent to the code requirement for wall insulation to minimize thermal losses and reduce condensation.
- **Safety and security.** A safety/security grating can be placed in the light well under the glazing for this toplighting scheme. (Light control louvers and baffles can also serve this function.) Make sure this grating does not create a shadow pattern on the wall.
- **Leakage.** All roof penetrations have leakage liabilities. Use well-tested curb design details and flashing kits provided by the manufacturer.

Operation and Maintenance

Clean glazing on a schedule. Horizontal glazing (and clear glazing) needs more frequent cleaning in climates with low rainfall.

Commissioning

Check that operable louvers and shades are working. Set angles of adjustable louvers to eliminate direct sun penetration.

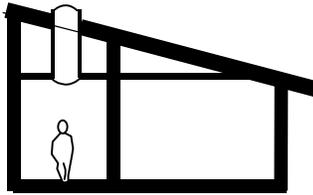
References/Additional Information

See the Overview section of this chapter.

Related Volume III CHPS Criteria

See the Overview section of this chapter.

Guideline DL8: Tubular Skylights



Recommendation

Use tubular skylights for toplighting in areas with relatively deep roof cavities and for low-cost retrofits to existing spaces.

Description

Tubular skylights are small clear-domed skylights with mirrored reflective ducts connecting them to the ceiling plane of the space. They have an interior diffuser at the ceiling plane to spread daylight in the space. They may have electric lighting within the duct or diffuser that is switched or dimmed in response to the available daylight. Since they depend on multiple reflections to deliver daylight to the space, they perform better under direct sun than overcast sky conditions.

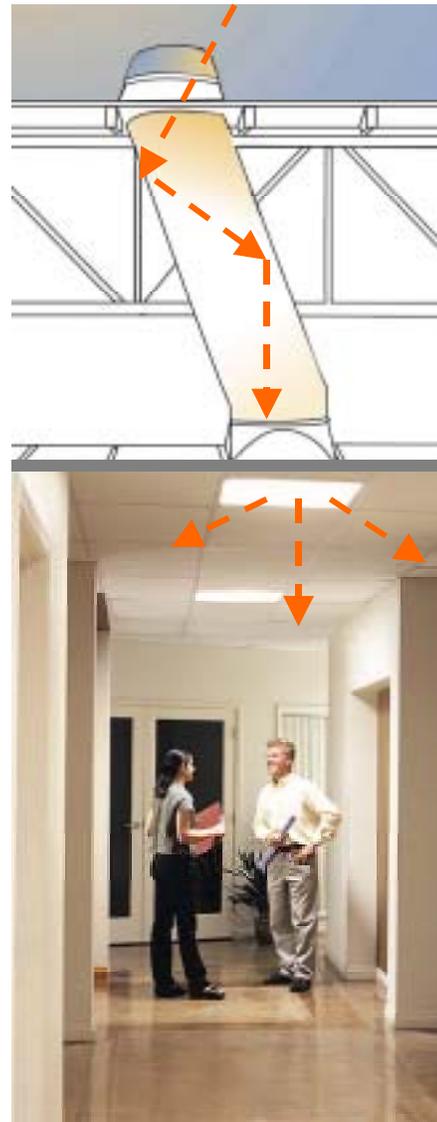
Applicability

Tubular skylights are especially good for small spaces, such as toilet rooms, locker rooms, kitchens, interior corridors, enclosed staff work areas, and other interior spaces that are sporadically occupied and would benefit from a low-cost toplighting solution. They are also good for retrofit into any existing school space that needs extra daylight or needs to balance an existing asymmetric daylight distribution.

These units will work significantly better in clear sky climates than in overcast climates. As the duct gets longer, less daylight is delivered; so they are limited to spaces with roof cavities of 8 ft or less.

Applicable Codes

The California Energy Code specifies the minimum performance of fenestration products and it limits window area to a maximum of 5% of the exterior roof area.



Tubular skylight. Photo courtesy Solatube, Inc.

Applicable Spaces	Climates	When to Consider
Classrooms	South Coast	Programming
Library	North Coast	Schematic
Multi-Purpose Cafeteria	Central Valley	Design Dev.
Gym	Mountains	Contract Docs.
Corridors	Desert	Construction
Administration		Commissioning
Toilets		Operation
Other		

Integrated Design Implications

- **Integration with site plan.** This toplighting scheme applies to single-story buildings or the top floor only of a multistory building. It must be planned for in schematic design.
- **Balance with other daylight.** This scheme may be combined with view windows in perimeter walls. Since the toplighting aperture provides most of the ambient daylight, smaller windows can be judiciously spaced in exterior walls to optimize views and valuable wall space can be relinquished for other needs. The total glazing area should be apportioned among these needs.
- **Integration with HVAC.** Placement of tubular skylights must be coordinated with the location of rooftop HVAC equipment and interior duct runs. Although the reflective ducts can jog to avoid barriers in the ceiling plenum space (within reason), efficiency of daylight delivery is reduced with each change in direction.
- **Integration with structural system.** Skylights interrupt the roof diaphragm and structural system. Their size and location may be limited by this and must be coordinated with the structural system to maintain its strength and integrity. The small diameter of these units reduces their impact on the structural system relative to larger framed skylights. See Daylighting Design Considerations in the on-line Appendix for more on integrating toplighting with structural systems.
- **Integration with electric lighting.** Some tubular skylights come equipped with compact fluorescent (or incandescent) electric lights within the duct or ceiling plane diffuser that can be switched or dimmed in response to daylight. Ascertain that any included electric light not block the daylight delivered through the device.
- **Safety and security.** Unless these skylights are larger than 16 in.², they should not pose a safety or security liability.

Cost Effectiveness

Costs for tubular skylights are low. For smaller spaces like hallways and offices, 10 in. and 14 in. tubular skylights cost approximately \$300 and \$400 (not including installation costs), respectively.

Costs	L	■	■	
	M	■	■	
	H	■	■	
		L	M	H
		Benefits		

Benefits

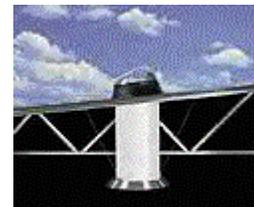
Tubular skylights provide a moderate level of benefits. This approach provides daylight “fixtures” that deliver daylight through a ceiling plenum to an interior space. Arranged in a grid, they can provide even, balanced daylight across the space, though daylight levels will fluctuate widely between direct sun and overcast sky conditions. Daylight in classrooms has been correlated with higher standardized test scores. See this chapter’s Overview for details.

This approach saves electric lighting energy if the electric lights are switched off or dimmed in response to the daylight. Savings may be 20% to 60% during daylight hours.

Design Tools

The specular reflective tube makes it difficult to simulate the performance of these skylights with physical scale models and computer tools. Local case studies, test installations, and estimating tools from the manufacturers are the best tools for evaluating performance. Designers should take note that many manufacturers of tubular skylights have made exaggerated claims about both daylight delivery and R-value of their products.

Energy performance of these skylights is also handicapped by the lack of U-factor and SHGC data. As this information becomes available, hourly building energy evaluation programs like DOE-2, EnergyPlus, and Energy-10 can be used to evaluate the energy impacts.



*Cross section of tubular skylight.
Courtesy of Solatube, Inc.*

Design Details

- **Length and bends.** Minimize the overall length and minimize bends in the reflective duct running from the skylight to the ceiling plane.
- **Reflective ducts.** Use a product with a highly reflective cylindrical duct. Do not use a corrugated duct; the corrugations trap light.
- **Half dome vs. full dome.** In predominantly sunny climates, use a tubular skylight with a south-facing, reflective half-dome under the skylight “bubble” to increase the reflection of low angle winter sun into the skylight (see Figure 6 below). In predominantly overcast climates, use a full clear dome. Special lenses or geometric shapes can also help to catch low angle sun and direct it downward.

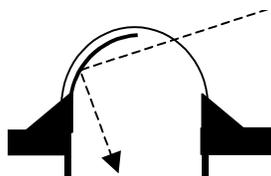
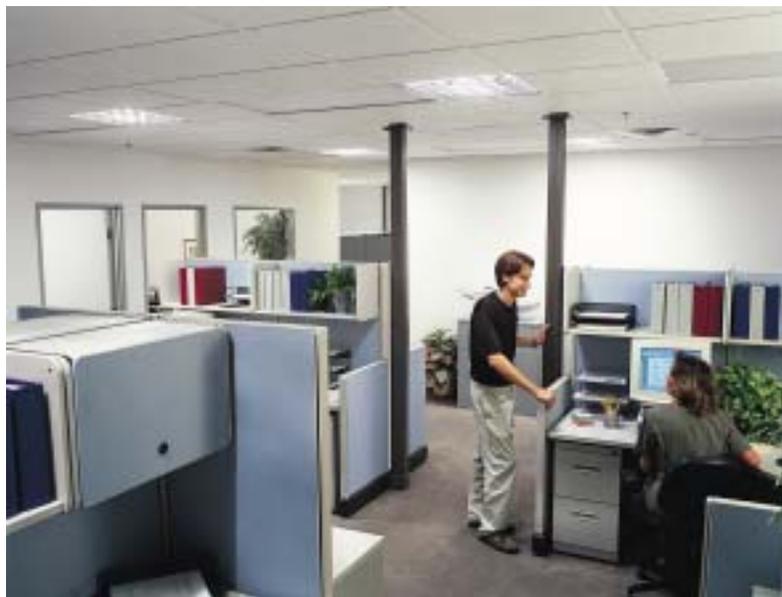


Figure 6 -- Section of Reflective Half Dome

- **Diffusers.** Some products have a flat bottom diffuser that fits into a standard 2 ft x 2 ft or 2 ft x 4 ft dropped ceiling grid. These may incorporate the electric lighting in them or may alternate in a grid with recessed fluorescent electric lighting fixtures.



Tubular skylights in interior administrative office provide high lighting levels even when electric lights are off. Skylight diffuser panel fits into a standard suspended ceiling system. Photo courtesy of Solatube.

- **Insulation.** For ducts installed in uninsulated ceiling or attic spaces, insulate the duct to an R-level at least equivalent to the code requirement for air ducts to minimize thermal losses and reduce condensation.
- **Leakage:** All roof penetrations have leakage liabilities. Use well-tested curb design details and flashing kits provided by the manufacturer.

Operation and Maintenance

Clean glazing on a schedule. Horizontal glazing needs more frequent cleaning in climates with low rainfall.

Commissioning

None.

References/Additional Information

See the Overview section of this chapter.

Related Volume III CHPS Criteria

See the Overview section of this chapter.

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