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A Study of Current and Potential Use of Daylight in Designing Military Facilities

by
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This study was conducted to determine the potential applicability of daylighting in military construction as an energy conservation strategy. Daylighting can have a major effect on energy cost as well as consumption because it reduces two of the largest end-users of electricity: lighting and air-conditioning. Design techniques and analytical methods typically used in the private sector are described. Case studies of operating buildings indicate the range of facility types and climates to which daylighting has been applied successfully. A summary of surveys and interviews with U.S. Army Corps of Engineers (USACE) architects and engineers discusses how daylighting has been used in previous USACE projects and how the current design-and-build process may inhibit its successful implementation.

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FOREWORD

This study was conducted for the Directorate of Military Programs, Headquarters, U.S. Army Corps of Engineers (HQUSACE), under Project 4A162784AT45, "Energy and Energy Systems"; Work Unit EA-XJ9, "Micro-Based Computer Aided Energy System Design." The HQUSACE Technical Monitor was Dwight Beranek, CEMP-EE.

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1 INTRODUCTION

Background

Daylighting and other passive solar strategies have seen renewed interest in the construction industry as energy costs soar and the U.S. public recognizes that resources are being depleted. The daylighting concept appears especially attractive for reducing electrical lighting needs: electrical lighting has been found to consume nearly half the total energy in nonresidential buildings.* This high rate of energy consumption is compounded at Army installations, which typically have many facilities that are nonresidential.

In addition to reducing the need for electrical lights, daylighting can lower the cooling demand by (1) substituting daylight for some of the heat-producing artificial lights and (2) providing a design that does not let direct sunlight into the building. Because of its potential for reducing the two major energy consumers (lights and cooling), daylighting is considered the most effective passive solar strategy for almost all commercial building types.[1] It can reduce both total energy use and peak demand consumption. Reducing electrical energy use can have major impact on a national level because three units of primary energy (coal or oil) are usually required to generate one unit of electricity.

Daylighting does not replace artificial lights; its purpose is to supplement the electrical lighting. On sunny days, it can be the sole source of lighting; on cloudy days, the full lighting system may be needed to raise the illumination to the required level.

The use of daylight for illumination is not new. In fact, daylight use was universal before the era of electrical lighting systems. An understanding of daylight design is evident in ancient Greek and Roman architecture, which made rational use of atria, overhangs, and building orientation. Many early high-rise buildings with U-shaped plans reflect the designer's concern for effective penetration of side lighting. Before the 1950s, architects used the building envelope as a mediator between exterior and interior environments. Lighting, heating, and cooling control was limited and somewhat at the mercy of nature. Buildings were designed to take advantage of solar radiation when needed and to be protected when sunlight was not needed. Illumination was provided mostly by daylighting. The 1950s saw the development of the self-contained building. Heating, lighting, and cooling systems were being developed and controlled by humans. Consideration of nature was being phased out of the design process. Buildings could be more extravagant since energy was cheap and abundant. There was little concern for saving energy until the early 1970s.

Daylight must work with other elements of a building. The method and extent to which daylight is used must be considered from the onset of the building programming and design. When daylighting is considered in the initial design process, it can often represent a no-cost change in the building. The potential to take advantage of daylight exists in most buildings because windows, skylights, or clere-stories are already part of the design. Therefore, the use of daylighting primarily requires awareness of the potential in an existing situation.

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* Measured as Btus consumed, lighting may be secondary to heating and cooling, but the cost of delivering electricity for lighting is two to three times higher.

[1] C. Robbins, *United States Air Force Passive Solar Handbook*, Vol I (Architectural Energy Corp., July 1989).

Objective

The primary objective of this study was to learn how U.S. Army Corps of Engineers (USACE) design teams view the use of daylighting and how they interact in the design process while incorporating daylight design. A secondary objective was to survey current daylighting design techniques and present case studies of nonresidential buildings that have used daylight as a light source successfully.

Approach

USACE architects and engineers at several District offices were interviewed by telephone and/or written surveys to determine their awareness of daylighting techniques, attitudes toward daylighting use in military facilities, and experiences (if any) with daylighting design. Concurrently, the literature was reviewed to learn what daylighting strategies have proven successful in the past and determine to what extent prior research has succeeded in demonstrating the effectiveness of daylighting as an energy conservation measure. These findings were summarized for USACE designers who may not have extensive experience with daylighting.

Mode of Technology Transfer

It is recommended that the findings of this study be summarized in an Engineering Improvement Recommendation System (EIRS) Bulletin.

2 DAYLIGHTING TECHNIQUES

Daylight has been used in architecture as a light source for centuries. The availability of daylight structured the daily cycles of work, play, and rest. Daylighting design was (and remains) the conscious effort to design a building in which daylight is used for illumination. Buildings designed to use daylight respond to direct sunlight and daylight modified through diffusion or reflection by natural or manmade elements.

A resurgence of interest in the use of daylight has occurred in recent years as the building industry has become more aware of its potential benefits. Daylight is no longer viewed as merely an amenity, but also as a source of energy that can be used to reduce lighting, cooling, and heating loads.

This chapter describes some of the benefits that can be obtained through the use of daylight. Basic design considerations also are discussed to give an overview of the tasks encountered by the designer in planning for the use of daylight.

Benefits of Daylighting

The energy crisis of the 1970s resulted in high energy costs and increased awareness in the United States that resources are being depleted. A response to this situation has been the building industry's search for alternative renewable sources to supplement lighting, heating, and cooling energy in structures. It was found that electrical lighting was consuming nearly half of the energy in nonresidential buildings. Therefore, daylighting and other passive solar strategies appeared promising as design solutions for energy efficiency.

The concept of daylight design is to use natural light as a supplement for electrical lighting in buildings. Daylighting systems use the sky as a source of light, but avoid letting direct light into a building. Daylight design can reduce the need for electrical lighting, but does not *eliminate* it. Electrical lights need not be used when daylight is present in sufficient quantity; when there is too little daylight due to weather or time of day, the electrical lighting system is used to raise illumination to required levels. Daylighting can reduce both electrical light and cooling energy consumption; therefore, it can reduce peak energy use as well as total energy consumption.

Current estimates are that 30 to 50 percent of the energy used in commercial buildings is spent on interior illumination.[2] Therefore, reducing the need for electric light will significantly lower the building energy requirements. As electrical lighting need is reduced, electrical energy use drops as does energy cost. Since lighting in nonresidential buildings is a major end use that adds a substantial amount of heat, it has a direct impact on the heating and cooling loads.

A common belief is that window size must be increased to use daylight as a light source. This design would likely increase both heating and cooling loads. However, this objection is not justified. Increased window size is not necessary. Instead, daylighting design uses window placement, room layout, reflections, and obstructions to achieve its goals.

All light, whether natural or electrical, adds heat to a building. Most lighting systems are inefficient: to produce light, they must produce heat. For an incandescent light, only about 10 percent of the input energy is emitted as light. The rest is converted to heat. In the case of fluorescent light, about 20 to 35 percent of the input energy is emitted as light. Daylight also adds heat to a building, but about 55 percent of the solar radiation admitted is in the form of visible light.[3] Since daylight is

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[2] C. Robbins (1989).

[3] C. Robbins, *Daylighting Design and Analysis* (Van Nostrand Reinhold, 1986).

more efficient at providing light than most electric light sources, less heat is produced for the same amount of light. Therefore, less cooling is required.

Because lighting systems add heat to the building, turning off the electric lights or using a more efficient light source may increase heating loads. However, if shading devices are designed properly, more solar radiation should be able to reach the interior of the building during the winter months when sun angles are lower. This strategy can be used to offset the potential increased heating need.[4]

The combined reduction of lighting, cooling, and peak energy use that often results from daylighting can lower the total energy cost of a building.[5] Peak energy use is considered separately from total or annual energy consumption because the rate structures of many utilities are based on both total consumption and peak use. Peak demand is the maximum energy use of electricity in a building during a given time period. When the electrical light and cooling loads can be reduced during peak demand hours, energy costs will be lowered.

Another frequent criticism of daylighting is that building costs increase due to the addition of lighting control systems, shading devices, and other elements of a daylighting system that are not required in conventional buildings. As the case studies presented later demonstrate, however, the reductions in energy cost due to the use of daylight can compensate for the higher first costs. Furthermore, when daylighting is considered from the beginning of the design process, cost increases can be kept to a minimum. There are also benefits to first cost when daylighting is used; for example, since the cooling load can be reduced, the cooling plant size can be smaller for a savings. Even if the heating load increases, the smaller cooling plant will save money because it is often more expensive per unit of input energy than the heating plant.[6]

Daylighting Techniques

Daylight must work with the other elements of a building. The method and extent of daylight to be used must be considered from the outset of building programming and design. When daylighting strategies are included in the initial design phases, it can often represent a no-cost option for the building. There is a potential to take advantage of daylighting in most buildings because windows, skylights, or clerestories are already part of the design. In these cases, using daylight to benefit often simply requires an awareness of daylighting strategies. Therefore, designers must understand daylighting techniques so that these features can be incorporated into the building.

The purpose of a daylighting system is to provide light to the interior of a building to enhance occupants' visual performance. The amount of glare, contrast, and color of light in the work space affect visual performance. Daylight procedures manipulate the building envelope to filter natural light in, providing ambient and/or task lighting where needed. The objective of a daylighting system is to optimize the building design to allow the occupants to benefit from the available daylight. Daylight systems use the sky as the source of light and avoid letting direct sunlight into a building. Since direct sunlight is avoided, daylighting systems perform well on overcast as well as clear days.

Daylight can be incorporated into a design in several ways. The daylight system can be as simple as a combination of windows and interior shading devices or as complex as a sawtooth roof with baffle

[4] C. Robbins (1986).

[5] G. Ander, "Daylighting and Thermal Analysis Program" presented at the 1986 International Daylighting Conference, Long Beach, CA (November 3, 1986).

[6] C. Robbins (1986).

shading. System components include apertures, glazing media, shading and sun control devices, and electrical lighting controls. Daylighting systems can be separated into three basic types:

- Sidelighting
- Toplighting
- Core lighting.

Louis Sullivan's Wainwright building and the Larkin building by Frank Lloyd Wright incorporate all three of the above features.

Sidelighting

Sidelighting concepts use the walls of a building as locations for apertures that allow daylight to pass through. Sidelighting is easiest when buildings are narrow. Areas away from the perimeter receive less light than areas near windows. The distance to which light penetrates from wall apertures is a constraint on building dimensions. This situation can be alleviated to a degree by increasing the ceiling height, but the ratio of daylight to floor area remains limited by the geometry of the window in relation to the rest of the room. For window systems, the rule of thumb is that daylight penetrates into the room about 2.5 times the head height of the aperture (Figure 1).[7]

Window location affects the distribution of daylight into the room. Low windows have the most uniform illumination because they allow reflected daylight deep into the room (Figure 2). However, low windows place the light source near or below eye level, therefore maximizing the potential for glare.[8]

High windows give the deepest penetration of daylight into a space (Figure 3). The high location of the maximum brightness region is beneficial because it reduces the potential glare interference for

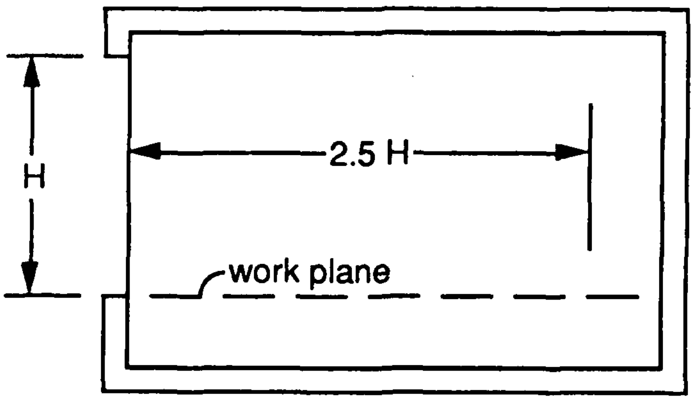

Figure 1. Rule of thumb for sidelighting.

[7] C. Robbins (1986); J. E. Kaufman (Ed.), *Illuminating Engineering Lighting Handbook* (Illumination Engineering Society of North America, 1981).

[8] W. Lam, *Sunlight as a Formgiver for Architecture* (Van Nostrand Reinhold, 1986).

video display terminals (VDTs). However, high windows provide less favorable light distributions. Light enters the space directly from the source, causing more sharp shadows and creating dark areas in the work space. This problem can be avoided by using baffles or lightshelves (horizontal units placed in the upper portion of a window) to redirect the light so that it can be reflected off the ceiling to create a more diffuse light.[9]

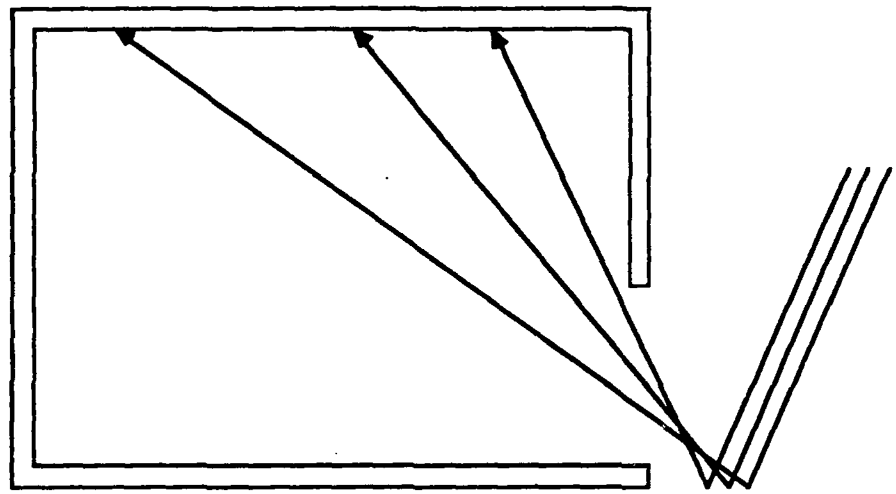

Figure 2. Low window reflected light distribution.

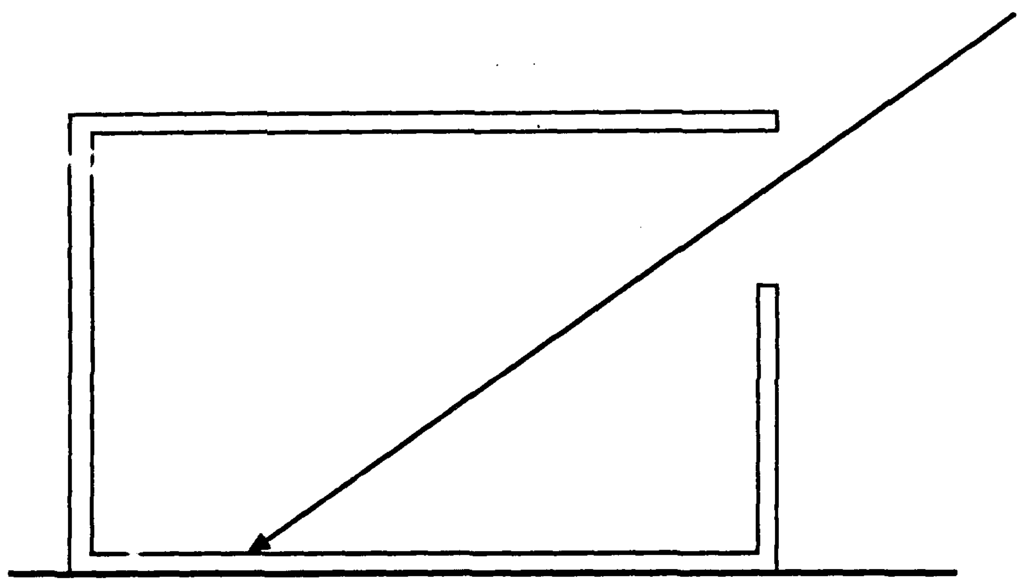

Figure 3. Daylight penetration from a high window.

[9] W. Lam.

Window placement in the middle portion of the wall is frequently preferred because it generally provides a view for the occupants. However, the daylight distribution of a mid-wall window is not as effective as that of a window placed in the upper or lower portion of the wall. The brightness of the view also maximizes the potential for reflections on VDT screens.

Top Lighting

Clerestories, sawtooth apertures, roof monitors, and skylights are forms of top lighting. A sawtooth roof is a toplighting system that includes a glazed vertical or angled surface and a sloped roof (Figure 4). The sloped ceiling surface helps direct daylight into a room. Typically, sawtooth lights have glazing on only one surface which usually faces the same direction as the main window. Regular sawtooth apertures provide uniform illuminance (lumens or footcandles/unit area) throughout a space, with small variations in brightness patterns. The configuration, height, depth, and spacing of sawtooth apertures affect the distribution pattern and quantity of daylight in the space. Sawtooth lights can be an excellent daylighting concept in lighting situations for which even illuminance is needed over a large task or circulation area, such as in offices, schools, hospital wards, libraries, lobbies, and vestibules. Sawtooth apertures may also be called clerestories.

Monitor lights (Figure 5) are similar in many respects to sawtooth lights. They have traditionally been used in industrial facilities where a central high bay area lies between two low bay areas. The monitor serves to illuminate the high bay area and part of the adjacent low bay areas. A space arrangement of this type also may be found in the stack area of libraries, retail stores, and warehouses. Sawtooth and monitor apertures are appropriate in most one-story buildings that have large open areas. Both are typically used to illuminate horizontal and vertical task surfaces, provide general lighting, and illuminate three-dimensional objects.

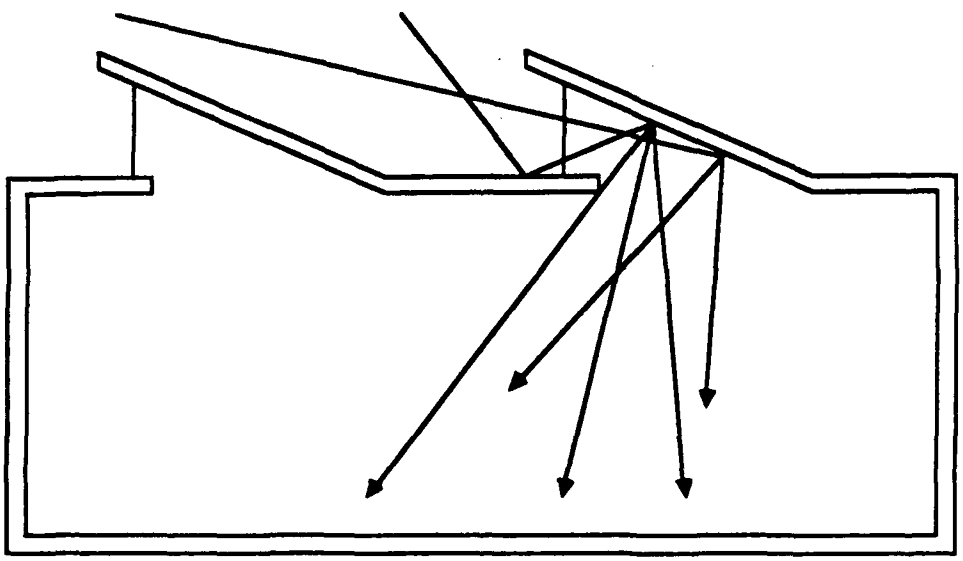

Figure 4. Sawtooth roof apertures.

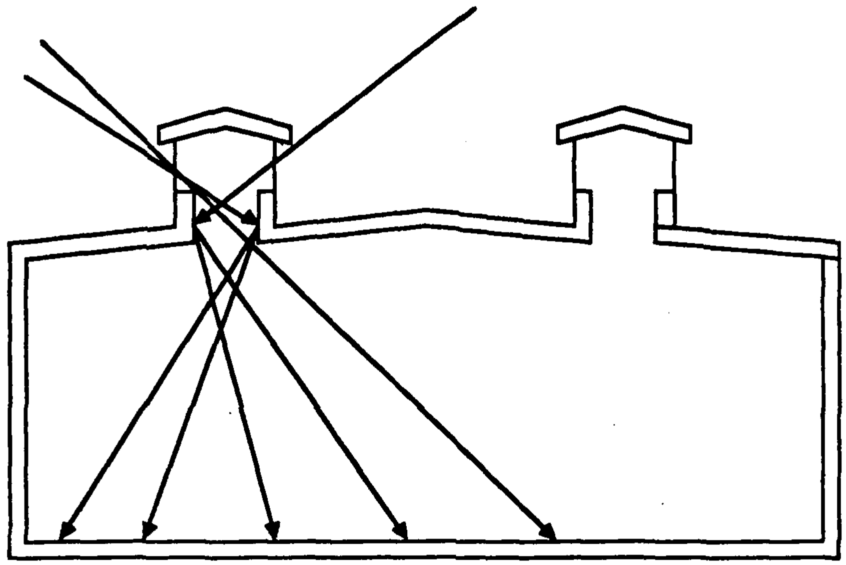

Figure 5. Roof monitors.

Core Lighting

Skylights are horizontal apertures cut through the roof of a building. They provide a relatively uniform level of illuminance throughout a space and allow for the use of both skylight and sunlight as interior illuminants, although the inclusion of direct sunlight is often discouraged. Skylights are most commonly used to illuminate horizontal work planes, such as desktops, drafting boards, and workbenches. They are also very effective when used to provide general lighting or to illuminate a three-dimensional display or a piece of sculpture. In multistory buildings, the most difficult location to daylight is the center or "core" of the building. If an atrium space is designed into a building, the core is opened up so that it can be daylighted. This core space is usually shielded from the outdoor environment by a horizontal aperture (Figure 6).

Shading and Redirecting Devices

Horizontal Overhangs

An overhang is a projection from a building that functions as a single shading element. An overhang can be incorporated as part of the building construction or achieved by using awnings. Overhangs provide shading without redirection of daylight. With this design feature, ground-reflected light is the primary source of daylight illumination. Overhangs shade the window from direct sunlight and reduce the luminance of the upper part at the cost of reducing the amount of light reaching the interior space. Overhangs do not provide shading at all times. They should be designed to shade the window in summer and let solar heat in during the winter.[10] Awnings tend to be the less durable option and require maintenance, but they have other advantages. For example, the first cost is usually less. Also, retractable awnings can be lowered to give buildings the benefit of shading when the sun is out and raised to provide maximum input of skylight under overcast conditions.

[10] J. E. Kaufman (Ed.).

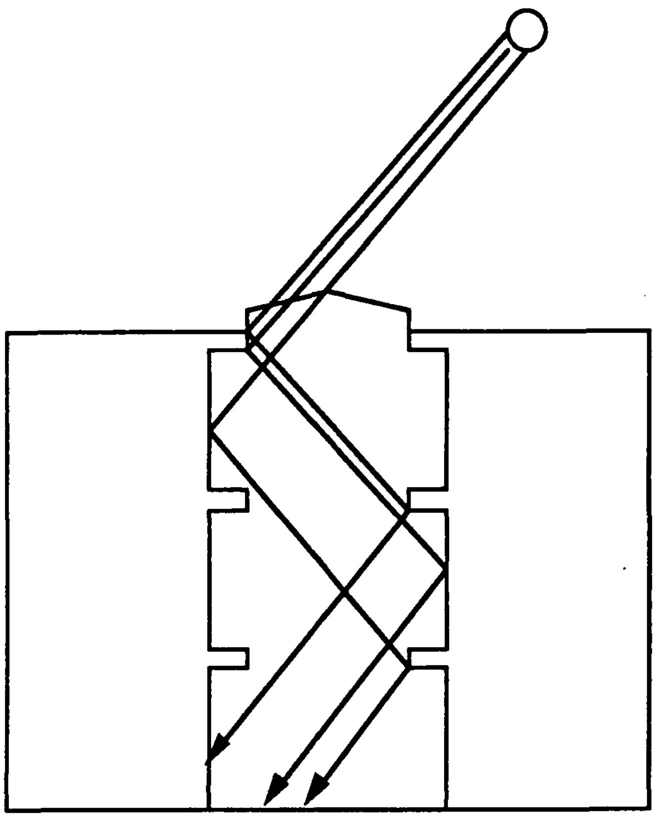

Figure 6. Atrium with skylight aperture.

Louvers

Louvers are used widely as shielding elements in daylighting design. The slats can be fixed or adjustable, horizontal or vertical. They can prevent entrance of direct sunlight and reduce radiant heat, while reflecting a high proportion of sun, sky, and ground light into the interior. For fixed louvers, spacing and height of the slats should be chosen so as to shield the light source (skylight) at normal viewing angles. Overhangs for sun control are often made with louver elements so that more of the skylight can reach the windows. Louvers are also used in top lighting arrangements, sometimes with two sets of slats set at right angles to form an egg crate.[11]

Lightshelves

Lightshelves provide shading without cluttering views and distribute daylight while minimizing glare (Figure 7). Lightshelves reduce the illumination near the window and redistribute the light to increase illumination deeper in the space. Consideration must be given in design to height, depth, shading requirements, the location of the glazing, the finishes and reflectances used, and the slope of the shelf, as well as the method of construction.[12]

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[11] J. E. Kaufman.

[12] W. Lam.

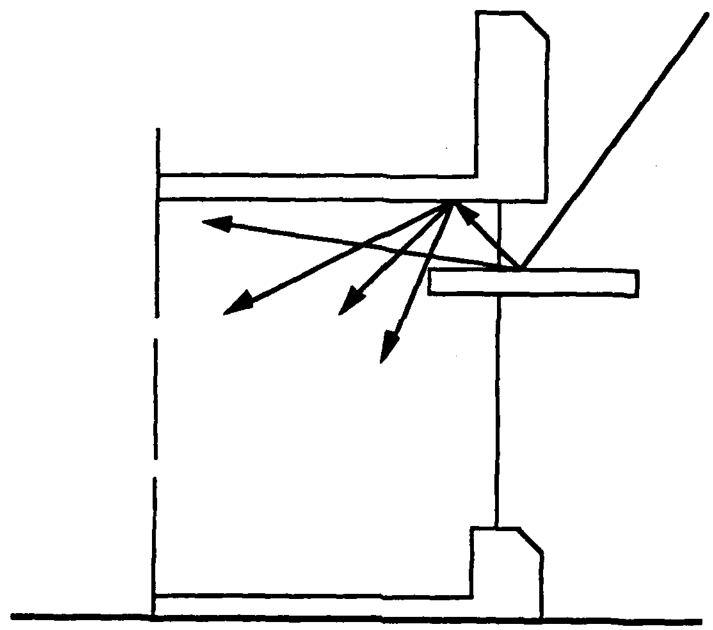

Figure 7. Lightshelf.

Lightshelves should be located as low as possible in the facade in order to reflect daylight to the ceiling. While lighting performance alone dictates a height just above eye level (about 6 ft), other considerations increase this height to 6 ft 8 in. to 7 ft. This height allows clearance for doors and/or alignment with door headers, indirect lighting systems, or beam bottoms.

The depth of a lightshelf is a function of window height and shading angle requirements, which in turn are determined by latitude and orientation. The upper, "clerestory" portion of a lightshelf facade should block the penetration of direct sunlight into the space, thereby controlling glare and eliminating the need for supplementary shading. Total shading year-round is not important for the lower window. During the summer months, shading is important to minimize cooling loads. Some penetration of sunlight in winter may be useful to reduce the heating load.[13]

Both the clerestory window and the "lower" window (beneath the lightshelf) need to be shaded. This can be accomplished by projecting the lightshelf beyond the rest of the facade or by recessing the lower window. Projection of the lightshelf beyond the clerestory shade is helpful for capturing more daylight. If the edge of the lightshelf is flush with the glazing, most of the lightshelf will be in the shade during the summer on the south facing facade. If this is the case, insufficient levels of daylight will be reflected off the lightshelf into the room.

Lighting Control Strategies

Electrical lighting control systems are found in every building, usually in the form of manual on/off light switches. Switching patterns for a building may range from individual luminaire control to control over an entire floor's lights. A well designed lighting control strategy is the key to a successfully

[13] W. Lam.

integrated daylight/electrical lighting system--one that will save energy as well as provide comfortable illumination for occupants.

In a correctly designed daylighting system, where energy conservation is taken into consideration, the electrical lights should be turned off, stepped down, or dimmed whenever daylight is sufficient. An electrical lighting system control concept appropriate for a daylighted building usually includes lighting control zones (areas in the building that use daylight and electrical light jointly to provide task, background, or general illuminance) and automatic control strategies.

Success in reducing energy use depends on the combination of lighting zones and the appropriateness of control strategies chosen for the zones. The size or location of zones is not as important as the use of a proper control strategy. There are four basic types of control strategies:

- Manual on/off switching
- Automated on/off switching
- Automated step switching
- Automated linear continuous dimming.

Manual Control

Manual control is an unreliable alternative for ensuring that lights will be turned off when not needed. Its use is feasible in cases where the space user is aware that daylight is to be used as a light source. In such cases, occupants retain some personal control over the operation of electrical lighting affecting their work area and are often willing to turn the lights off when possible. This behavior has been observed in studies conducted in England, Australia, and New Zealand.[14] In the United States, neither the recent trend of using daylight as a light source nor the awareness to turn lights on or off as needed exists.

If manual controls are used, simplicity in the control strategy increases the likelihood that the lights will be turned off. Simple on/off switches may provide adequate control for perimeter offices (usually within 10 to 15 ft of the perimeter). The most difficult task is persuading occupants to turn off the lights when they are not needed.[15]

Automated On/Off Switching

An automated on/off switch, also called a "two-step switch," is used in areas where daylight is expected to be above the design illuminance most of the time. The lights are turned off (step 1) when the interior illuminance from daylight is equal to or greater than the design illuminance. The lights are turned on (step 2) when the interior daylight is less than the design illuminance for the lighting zone. "Lights off" is the first step in all of the step and dimming control strategies.

Automated Step Switching

The three basic types of automated step switching differ only in the number of controlled lamps in the luminaire. The three-step controller is used with luminaires that have two lamps. The three steps are: both lamps off, one lamp on, and both lamps on. Similarly, the four-step controller is used in luminaires that have three lamps and the five-step controller with four lamp luminaires. The steps for these controllers is analogous to the three-step case.

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[14] V. H. C. Crisp, *The Light Switch in Buildings*, PD122/27 (HMSO, Building Research Establishment, 1977).
[15] C. Robbins (1986).

Switching controls are the least expensive lighting control systems and can provide a large savings in energy if used properly. However, switching also produces the most noticeable changes in illumination--a potential source of distraction.

Dimming Controls

Dimming systems may use continuous dimming controls alone or in combination with off controls. Continuous dimming controls vary the interior illuminance from electrical light sources in response to the level of interior daylight. These control systems cannot turn off lamps when interior daylight is above the design level. Continuous dimming with off controls does not suffer from this deficiency.

Continuous dimming devices offer two advantages over multistep switching. First, because the electrical lighting in the room is changed in direct response to the level of interior daylight, the total illuminance can be close or equal to the desired design illuminance. Second, since minimum use is made of electrical light, the lighting, cooling, and peak loads are reduced.

Dimming achieves a more graceful blend of natural light with electrical light and is less likely to be noticed than with switching systems. However, the initial cost of dimming systems is higher than that of switching systems. Energy cost savings are generally higher with dimming systems than with switching systems, though, which makes the dimming systems more affordable over the long term. Studies have shown that dimming systems are cost-effective at a 50 percent dimming level and can provide a 3-year payback. This payback period can be reduced to as little as 1 year when cooling savings are taken into account.

Daylight Analysis Techniques

Daylight analysis techniques range from simple manual methods to sophisticated computer programs. All daylight calculation procedures are derived from one of three mathematical algorithms. These procedures vary in complexity and level of accuracy. The simpler mathematical procedures are generally used in preliminary design to obtain a general idea of how much daylight is available. As the design progresses, more quantitative and complex calculations are performed. Computer programs have been developed to perform one or all of the mathematical modeling techniques. It is imperative that designers using these programs understand program capabilities and limitations as well as the assumptions underlying each modeling procedure.

Basic Modeling Methods

Procedures for calculating interior illumination from natural sources can be grouped into two general categories: (1) analyses that determine absolute illuminance (usually measured in lux or footcandles) and (2) analyses that determine relative illuminance (usually measured as a percentage of the exterior available illuminance).[16]

Analyses that determine absolute illuminance allow the designer to predict interior illuminance at a given station point in a room or space. The absolute illuminance varies with time, aperture orientation, and sky condition. Methods that determine relative illuminance allow the designer to predict the percentage of exterior illuminance provided by daylight at a given station point in the room being analyzed. Relative illuminance is a valuable measure because it is often perceived as a constant with respect to time of day and aperture location. The concept of relative illuminance assumes overcast sky conditions; the assumption of constant illuminance breaks down under clear sky conditions because clear skies are subject to change.[17]

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[16] C. Robbins (1986).

[17] *How to Predict Interior Daylight Illumination* (Libbey-Owens-Ford Co., 1976).

Methods of analysis that provide absolute luminance predictions include the lumen input and the flux transfer methods. Daylight factor analysis is the primary technique for establishing relative illuminance values in a room or space. Each procedure has some specific capability that is not included in the other methods because of differences in the limiting assumptions made during development.

Lumen Method. This method, sometimes call the "lumen input" method or the "total flux" method, is based on the assumption that the illuminance reaching a station point in a room is a function of the amount of light present at the plane of the aperture. A modified version of this method is currently recommended by the Illumination Engineering Society (IES) and is used in the Libbey-Owens-Ford daylighting manual.

The lumen method assumes that, in small rooms illuminated from vertical apertures, the exterior ground plane and the interior surface reflectances play important parts in determining the illuminance provided by daylight. Knowing the illuminance at every possible station point in the room is considered unnecessary for designing and analyzing the needed quantity of daylight. Therefore, absolute illuminance is determined for only three station points located on a work plane at a height of 2.5 ft. The three station points are located along a line centered on the aperture and projecting into the room. The station point closest to the aperture is designated SP_{max} and is located 5 ft into the room from the aperture. The second station point, designated SP_{mid}, is located in the center of the room. The third station point, designated SP_{min}, is located 5 ft from the back wall. The absolute illuminance at each station point is designated E_{max}, E_{mid}, and E_{min}, respectively.

Lumen method variables affecting the amount of light reaching the windows from above the horizon are: the brightness and brightness pattern of the clear or overcast sky, the angular position of the sun with respect to the window, and the intensity of the sunlight. These variables describe the sun and sky as a daylight source. Variables affecting the amount of light reaching the windows from below the horizon are: the global illuminance striking the ground for clear and overcast conditions and the reflectivity of the ground. Variables affecting the amount of light leaving the inner surface of the window are: the glazed area of the aperture, the transmissivity of the glazing, the ratio of actual glazing area to aperture area, and the effect of dirt accumulation on the transmissivity of the glazing. Variables affecting the use and distribution of light on the work plane after the light has left the inner surface of the window include: the distribution of reflected light in the room, window dimensions, and room dimensions.

This method assumes that only the aperture above the height of the work plane is significant. The aperture sill height and work plane height are assumed to be equal, and windows that extend below the work plane height are assumed to provide little additional light. The aperture is assumed to extend from one sidewall to the other and up to the ceiling line.

The lumen method was designed to complement the IES technique for calculating average levels of electrical light in a room. The variables for daylighting given above are very similar to those used to describe electrical lighting. Four sky conditions can be considered in the lumen method:

- The Commission Internationale de l'Eclairge (CIE) standard overcast sky, in which illuminance on a vertical surface is independent of the surface orientation.

- The clear sky, with no sun on the window, in which the illuminance striking the aperture varies with aperture orientation.

- The clear sky, with direct sun on the window, which can be used only if an internal shading device is present.

- A uniform sky, which also can be used only if an internal shading device is present.

The unique feature of the lumen input method is its ability to analyze the impact of sun control devices such as horizontal venetian blinds or interior curtains. When accounting for shading devices, coefficients of utilization are employed. The coefficient of utilization represents the effect the shading device has on the transmittance of daylight. The lumen input method also can analyze rooms with overhangs. Calculating illuminance at the three station points in a room having an overhang requires that an equivalent room be established in which the size of the room is increased to compensate for the depth and length of the overhang.[18]

Daylight Factor Method. The daylight factor (DF) method, also called the "sky factor" or "split flux" method, is currently the CIE recommended procedure for determining the performance characteristics of daylight systems. The daylight factor is defined as the ratio of interior illuminance on a horizontal surface (E_i) to the exterior illuminance on a horizontal surface (E_e) simultaneously available outdoors from an overcast sky, expressed as a percentage:

$$DF_o = (E_i/E_e) \times 100 \qquad \text{[Eq 1]}$$

A DF_o of 2.0 percent means that 2 percent of the available exterior illuminance is reaching a given station point inside the building. For example, for a 1000-fc overcast sky on the horizontal plane, a simultaneous interior measurement of 20 fc would be found at a point with $DF_o = 2$. Because DF is expressed as a ratio of the interior and exterior illuminance, it is a relative measure of illuminance, not an absolute measure as in the lumen method.

The most common method of calculation using daylight factors separates DF into three components:

- Sky component (SC)
- External reflectance component (ERC)
- Internal reflectance component (IRC).

SC is the relative illuminance striking a given station point and consisting of light received directly from the sky. ERC is the relative illuminance striking a station point and consisting of light received directly from external reflecting surfaces, such as the facades of adjacent buildings. IRC is the relative illuminance striking a station point and consisting of light received directly or indirectly from the daylight that is reflected around the room.[19] Since the daylight factor is based on an overcast sky, any direct contribution from the sun is excluded.

The daylight factor method does not apply to the clear sky condition as directly as it does to the overcast sky because interior illuminance under the clear sky depends on solar location, whereas it does not under the overcast sky. Studies applying the daylight factor method to clear sky conditions have been conducted ever since the method was first proposed more than 60 years ago. Because of the predominance of clear skies in the United States, the effort has been especially great in this country to refine and extend the method's application to clear sky conditions. The clear sky daylight factor (DF_c) is described using the same three terms and the same general equation as the overcast sky.[20]

[18] C. Robbins (1986).
[19] J. E. Kaufman (Ed.).
[20] C. Robbins (1989).

The Flux Transfer Method. The lumen input method is accurate, but it provides values for only three points. The daylight factor method can also be accurate and has been developed into a manual design analysis tool. However, these two methods share several major limitations; neither method can:

- Account for direct sunlight in the space at a station point or sunlight reflected off interior surfaces
- Account for reflected light in rooms or spaces adjacent to a room with daylight apertures or for daylight reflected off sloped surfaces in the daylighted room.
- Analyze a wide range of different types of daylight apertures under both clear and overcast sky conditions.
- Analyze indirect daylighting systems.

The flux transfer method addresses some of these deficiencies and is widely recognized as one of the most comprehensive daylighting analysis methods. It has evolved into a major analytical technique for studying daylight penetration and distribution in interior spaces. It can use the CIE clear or overcast sky and can work with either illuminance or luminance of the aperture to determine the illuminance of any given surface in a daylighted room. This method is frequently incorporated into computer analysis programs, including both mainframe computer and microcomputer applications.

In the flux transfer method, the total absolute illumination from natural light at any station point on a surface can be defined in terms similar to those used in the daylight factor method of analysis:

$$E_P = E_S + E_{SE} + E_{ERE} + E_{IRE} \qquad \text{[Eq 2]}$$

where E is illuminance and the subscripts SE, ERE, and IRE refer to the sky, external, and internal components of daylight illuminance. The subscript S above refers to the interior illuminance from the direct component of daylight--sunlight. As with the other methods, the flux transfer approach focuses on determining the illuminance for the sky (E_{SE}) and the internally reflected illuminance (E_{IRE}) observed in the room.

The flux transfer method can determine either the absolute illuminance or the daylight factor in a room or space. Because all surfaces and all light sources are accounted for, reflected light reaching station points that do not have direct views of daylight apertures can still be estimated. This allows the analyst to calculate the illuminance from clerestories, sawtooths, monitors, skylights, and atria. In addition, vertical fins, overhangs, and lightshelves can be analyzed as reflecting surfaces to account for their impact on interior illuminance.[21]

Implementation of Basic Daylighting Calculations

Computer Programs

Microlite I. Microlite I[22] is a design-oriented program developed around a set of input menus in which design parameters can be created, stored, changed, or replaced to determine the effects of design alternatives. It has provisions for both clear and overcast sky conditions and is limited to

[21] C. Robbins (1986).

[22] H. J. Bryan and D. L. Krinkel, "Microlite I: A Microcomputer Program for Daylight Design," Proc. Seventh National Passive Solar Conference, August 1982, pp 405-410.

window openings. The contribution of skylights cannot be analyzed. Microlite calculates illuminance or daylight factor values at any point within a room. It separates the light reaching the point of interest into two components: (1) light arriving directly from the sky (SC) and (2) light reflected from external and internal surfaces (ERC and IRC, respectively). The output is in architectural graphic forms of plans, sections, and axonometric projections.

Daylite. Daylite[23] calculates daylight factors for a room using the flux transfer method, with a point-specific IRC algorithm (not available in other programs) for overcast and clear sky conditions (including direct sunlight contribution). It can accommodate light shelves, overhangs, vertical exterior fins, saw-toothed roofs, monitors, and tilted glazing. Daylite calculates hourly absolute illuminance and the resultant hourly solar heat gains to determine peak cooling periods. Glare and contrast can be analyzed for specific locations. An electrical lighting subroutine allows the specification of overhead task/ambient electrical lighting with yearly lighting power budgets for five control strategies.

The program has both graphic and numerical outputs. The graphic output is in two- or three-dimensional format illustrating daylight penetration, design illuminance, and the percentage of space illuminated to design level. The numerical output lists illuminance, the IRC at specified station points for both clear and overcast sky conditions, and solar heat gains under both sky conditions. Both numerical and graphic outputs are given for electrical light use along with power budget estimates relative to a nondaylight base case and the use of daylight with different control strategies.

Annual energy performance is calculated for 244 cities using the Robbins-Hunter method.[24] This method estimates energy savings attributed to daylight based on predictions of the percentage of the year that electrical lighting systems are in use. This percentage is a function of the electrical lighting control strategy, standard working hours, local weather data, and the amount of daylight (expressed as a daylight factor) reaching a given reference point in the building. The weather data used are based on recent daylight and sunlight availability research for selected cities in the United States.

Daylighting Performance Evaluation Methodology Development (DPEM). Lawrence Berkeley Laboratories is developing a technique for evaluating daylight performance relative to a nondaylighted base case.[25] This approach uses both measured and modeled performance comparisons. Computer simulation forms the basis of the illumination model and the electrical lighting control model. Because of adjustments made during the calibration with actual building data, the simulations need not be so complex that they predict each hour's activities with high precision. Simulation results are tuned so that long-term effectiveness can be predicted using a detailed daylighting performance model.

DPEM has two major uses. The first is to evaluate an existing building. When applied to an operating building, DPEM calculates the electrical lighting energy saved through the use of daylighting. The result can tell the owner or designer whether the building is performing as designed. If not, the evaluation may identify the source of poor performance, i.e., the daylighting design, the electrical lighting control system, or both. To the extent that poor performance is the result of ineffective lighting control, the method and its software could be used to identify solutions.

The second application is to buildings yet to be designed or built. Early in the design, DPEM can give an indication of how cost-effective a proposed system may be. It should be possible to determine the general effectiveness of daylight acceptance, daylight distribution, illumination measurement or estimation, automatic control, and manual control. The stages of the daylighting process that most require improvement can be identified and enhanced for greater daylighting effectiveness in future buildings.

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[23] W. Ashton and C. Evans, *Daylite* (SolarSoft, Inc., 1984).

[24] C. Robbins (1986).

[25] B. Anderson, B. Erwine, R. Hitchcock, and R. K. Kammerud, *Daylighting Performance Evaluation Methodology* (Lawrence Berkeley Laboratory, University of California, LBL24002, 1987).

CEL-1. The Conservation of Electric Lighting Computer Program (CEL-1)[26] helps the illumination engineer design energy-efficient rooms. CEL-1 contains a design synthesizer that selects from among a set of user-specified luminaire locations the subset that best satisfies the user's design criteria. Lighting metrics that may be calculated include illuminance, luminance, equivalent sphere illuminance, and visual comfort probability. Energy profiles resulting from lighting controls that respond to daylight can be evaluated using CEL-1.

An interface between the Building Loads Analysis and System Thermodynamics (BLAST)[27] Program and CEL-1 was used to perform computer simulations of daylighted building energy performance. The BLAST program simulates heat transfer between the building and its environment, and determines energy requirements for space conditioning. The CEL-1 program enables detailed simulation of the lighting systems, including daylighting effects. CEL-1 allows the modeling of actual luminaires, interior obstructions, drapes, blinds, lightshelves, skylights, clerestories, sawtooth structures, and exterior obstructions. Lighting schedules resulting from CEL-1 analysis were provided to BLAST through the interface.

Graphic and Manual Methods

BRE Protractor Method. The best known graphic technique for determining the sky component is the Building Research Establishment (BRE) daylight protractor method.[28] These protractors provide an excellent design analysis tool during the early stages of design for determining the amount of daylight available within a space. Due to ease of use, they can analyze different design options readily.

A set of BRE protractors consists of five protractors for the uniform sky and five for the CIE overcast sky. The five in each group are individual protractors for use with vertical, 30 degree, 60 degree, horizontal, and unglazed apertures. The BRE protractors simplify the daylight calculations and allow daylight measurements to be made directly from architectural drawings. The BRE protractors are based on the daylight factor method, also known as the CIE method, for calculating interior illuminance under overcast or uniform skies.

Each BRE protractor is composed of two parts. The primary (sky component) protractor is overlaid on a building section to find the sky component for an infinitely long window. The auxiliary protractor (correction factor) is overlaid on a corresponding floor plan to determine a correction factor for the given window width. The BRE protractor can consider the effect of external obstructions, such as buildings, overhangs, and vertical fins, on the sky component of daylight and calculate the external reflectance component.

Libbey-Owens-Ford Sun Angle Calculator. In this method, a sun angle calculator is designed for use with a manual to provide a simple method for determining solar angle values and interior illuminance from daylight.[29] The sun angle calculator is used to determine how the sun's rays will strike a building and how far the sunlight will penetrate through the building's openings. Three station points are analyzed. This information helps the designer identify areas to shade. It also projects the effects of overhangs, fins, and other obstructions on the surface of the building.

The prediction formulas follow the lumen output method. The manual is intended to provide an easy analysis technique for comparing and evaluating building design variations. The mathematical operations are simplified to make these evaluations as easy as possible. As in the lumen method,

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[26] *CEL-1 Lighting Computer Program* (Naval Civil Engineering Laboratory, September 1981).

[27] D. C. Hittle, *The Building Loads Analysis and System Thermodynamics (BLAST) Program*, Technical Report E-119/ADA048982 (U.S. Army Construction Engineering Research Laboratory [USACERL], 1977); *BLAST 3.0 User's Manual* (BLAST Support Office, University of Illinois, April 1986).

[28] J. Longmore, *BRE Daylight Protractors* (Department of the Environment, Building Research Establishment, 1967).

[29] *How To Predict Daylight Illumination.*

daylight availability charts and coefficient of utilization tables list standard variables pertaining to sky conditions, room geometry, and room reflectance. This method cannot analyze skylights or horizontal apertures.

Summary

As this brief survey indicates, there is a variety of strategies for incorporating daylighting design and a collection of tools appropriate to different phases of the design process. However, the effective use of daylighting also requires creative thinking and analysis; the methods described in this chapter are not intended to replace engineering judgment, but are tools to help with decisionmaking.

3 CASE STUDIES: BUILDINGS THAT USE DAYLIGHTING

As the source of daylight, fenestration can save energy through reduced lighting loads. However, it is commonly held that the use of daylight increases both cooling loads and heating loads. Although research has sought to develop accurate methods of determining the effects of daylight use on energy consumption, data comparing daylight performance predictions (by manual or computer analyses) to actual building performance are limited. This chapter summarizes some case studies of buildings that show evidence of potential savings.

The following case studies are divided into two groups: (1) examples of buildings for which daylight and energy analyses were performed with no followup monitoring and (2) buildings for which daylight and energy analyses were performed with followup monitoring. The energy simulations and monitoring of these case studies are representative of several research efforts by Southern California Edison Company, the Tennessee Valley Authority (TVA), the U. S. Department of Energy (DOE), and Lawrence Berkeley Laboratory (LBL). The studies were chosen because the buildings are similar to those found on Army installations.

Examples Without Monitoring

Soddy Daisy High School, Soddy Daisy, TN

Soddy Daisy is a small town that needed a new high school, but had a very low budget. Consequently, the design team adopted a simple, low-cost approach.[30] Daylight strategies selected included a central atrium space for circulation, eating, lockers, and other informal gatherings, and bilateral illumination of the classrooms by placing windows on exterior walls and clerestory windows on the interior walls to borrow light from the atrium. The gymnasium was daylighted by lightscoops (curved forms with glazing on one side which project from the roof, similar to sawtooth apertures) facing the north and south wall.

Final development, including daylight testing and energy analysis of the project, was performed by TVA's solar group design branch. Daylight analysis indicated that illumination would always be higher in the south block classrooms and would need little supplementary lighting during daylight hours. Light levels were shown to be lower in the north block; therefore, some supplementary light was needed on sunny or bright overcast days. Unlike the south block classrooms, where the levels of daylight would always be highest near the exterior window wall, the north block rooms would be brightest on the atrium side on sunny days and brightest on the exterior walls on overcast days.

Data from the TVA report predicted energy performance would exceed both the original base case energy goals of the project and the Building Energy Performance Standards (BEPS)[31] building--despite an inefficient air-conditioning system, minimal level of roof insulation, and single glazing. The BEPS had been proposed by DOE as energy efficiency targets for newly designed buildings based on research initiated during the energy crisis of the early 1970s. This research has been discontinued and there is controversy over the accuracy of the standards; nevertheless, BEPS was an accepted (if not statutory) standard at the time and is the only basis of comparison available today.

[30] G. Ander.

[31] *Building Energy Performance Standards* (Department of Energy, 28 November 1979).

Canfield Hall, U.S. Coast Guard Reserve Training Center, Yorktown, VA

The training center is a triangular building in which the legs of the triangle are double-loaded corridors with classroom areas and the central portion is an atrium.[32] The classrooms are daylighted by sidelighting strategies consisting of windows with lightshelves incorporated to diffuse incoming daylight. The building program required that conditions optimal for audiovisual presentations be provided in every classroom. To meet this requirement, the amount of daylight is controlled by electrically operated blackout window shades.

The daylighted atrium provides a circulation space. Light is borrowed from the atrium to provide additional daylight in office areas. Borrowed light is not used in the classroom areas since it was felt there would be visual competition between the clerestory window, chalkboards, and projection screens. The red brick and concrete building differs little in appearance from other brick buildings that surround it. Except for the fenestration, the building gives no visible clue that it represents an aggressive attempt at energy efficiency.

Government Service Insurance Systems Headquarters, Manila, Philippines

The location of this office building in the Philippines dictated that solar heat gain be minimized.[33] The designers were faced with the challenge of controlling the light and heat entering the east and west facing windows. The desire for maximizing a harbor view to the north led designers to incorporate a series of north facing courtyards.

The solution employed was a combination of lightshelves and baffle trellises spanning the courtyard. Lights striking the baffles at angles higher than the 45 degree cutoff angle would be reflected by the lightshelves. Daylight at angles lower than 45 degrees would be reflected and diffused by the trellis. Model testing verified that the trellis would work as intended.

Lightshelves were used on both the north and south elevations because, at 15 degrees north latitude, the sun's path is in the south in December and in the north in the summer. The dimensions of the lightshelves were designed to achieve complete shading for each facade. Additional shading was necessary to the east and west ends of the project. In those areas, additional horizontal louvers were provided to block direct sunlight until it dropped below 22.5 degrees. The lightshelves make the lighting more uniform, reducing the light near the window and increasing it farther into the space. They also function as a scaling element, making the offices near the windows more esthetically pleasing.

This "low tech" design is effective in reducing glare and direct sunlight as well as energy use. The building does not look dramatically different from other new office buildings in the area, and provides a pleasant work environment with minimal energy use.

Examples With Monitoring

In 1979, DOE began a large design, development, and field-test program to investigate the potential of passive solar technologies to meet commercial building energy requirements.[34] The program is the largest known attempt to guide design and simultaneously evaluate construction and operational costs, actual energy use, occupancy effects, and reactions in climate-responsive, nonresidential buildings. There were three phases in the DOE program: design, construction, and performance evaluation. More

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[32] G. Anders.

[33] G. Anders.

[34] Burt Hill Kosar Rittelmann Associates, *Commercial Building Design* (Van Nostrand Reinhold, 1987).

than 300 building owner/designer teams asked to participate in the program, but only the best 35 were selected. Of these, 19 buildings distributed across the United States completed design and construction.

Daylight was used in all buildings studied under the DOE program and was emphasized heavily in more than half of them. The types of daylight strategies used included windows to reduce artificial lighting (78 percent), lightshelves (48 percent), clerestories (39 percent), roof monitors (35 percent), borrowed light (13 percent), and skylights (13 percent). In most buildings, daylight provided ambient or background illumination with artificial lighting used to provide task lighting. In three buildings--Mount Airy Library, Security State Bank, and St. Mary's School Gymnasium--daylight provided the majority of the required task lighting.

While it is commonly held that building cost increases with the incorporation of daylight strategies, the DOE study indicates otherwise. All buildings studied in the DOE program fell within industry cost standards and/or the original proposed budget. Five case studies are summarized below.

Mount Airy Public Library, NC

The principal design objective was to reduce the annual energy consumption by 70 percent with respect to the existing library facility. Attainment of this goal would reduce the energy cost to one-third that normally incurred. The design team applied basic rules of thumb and manual calculation methods during the early design stages to establish the 70 percent energy savings objective. The team then simulated the energy performance of a similar sized, conventional building (the "base case") to determine that about 56,000 Btu/sq ft/yr energy use was typical. By simulating the same building with various passive solar strategy combinations and studying scale models of the initial design, the team determined that the Mount Airy Library could use much less that amount.

The analyses in the final design stages projected that the passive solar and conservation measures selected would reduce energy use by the following percentages:

- Lighting - 82
- Heating - 63
- Domestic hot water (DHW) - 56
- Cooling - 47
- Ancillary equipment (mostly fans) - 31

The floor plan design was a major factor in meeting the energy design objectives. It was stepped down into three levels and segmented into separate wings to take full advantage of both the southern exposure and existing shade trees.

The design team determined that lighting was the largest end-use requirement and the best place to begin looking for savings. Because the library is used primarily during the day, the design team sought to develop a daylighting system that could meet most daytime lighting needs. Since the direct rays of the sun can damage library materials, the team developed a system that admits glare-free, diffused light to all major library areas while preventing direct-beam illumination of the stacks.

The final design included south facing windows that provide sidelighting and a view. These window units consist of a lightshelf (above the viewing frame) that reflects sunlight onto a light-colored ceiling, distributing diffused light to the adjacent area. The lightshelf prevents direct beam illumination of interior areas. Overhangs are necessary on the south facing windows to prevent summer overheating. The overhangs were incorporated to shade the south facing glass from April 21 to August 21. By December 21, full sun reaches the building interior.

The daylight system was designed to meet most of the lighting needs and provide more than half of the winter heating. The massive concrete structure can store enough heat to moderate auxiliary heating requirements. The building is well insulated to prevent both heat buildup in the summer and heat loss in the winter.

Although heating occurs through the apertures, glare and hot spots are avoided by the use of light-shelves on the south facing windows and baffles to control, redirect, and diffuse the incoming light from the clerestories.

The library's measured energy use was roughly 40 percent lower than that of the base case--a similar building in the same climate without solar energy features--and approximately half as much as a relatively energy-efficient BEPS building (Figure 8). Heating dominated end-use consumption, accounting for more than two-thirds of the total annual energy use. Annual cooling consumption was very low, with July and August accounting for more than 70 percent of the cooling load. Daylighting system performance greatly exceeded expectations. Lighting energy use was very low--especially for a library, where lights normally constitute a large portion of energy use. The lighting energy consumption amounted to less than one-eighth of the total building energy use.

According to the Means and Dodge construction cost reports (building industry standards for estimating the cost of new construction), the average cost to build a conventional library is as $79/sq ft.[35] The Mount Airy final costs were higher at $88/sq ft. However, the comparison with industry data on conventional libraries of standard construction may be misleading. The white granite cladding, ceramic tile floorings, and cast-in-place concrete frame on the Mount Airy Library are not typical of most libraries. The degree of attention to interior finish and detail in the Mount Airy Library also is atypical. In addition, the quality of construction and finishes for this library are higher than what industry standards require. Compared with other libraries considered to be of superior quality, Mount Airy's cost is not exorbitant (Figure 9).

Johnson Controls Branch Office--Salt Lake City, UT

Johnson Controls designs and operates its own facilities as testing laboratories for new control equipment. A concern over energy cost and conservation led the in-house design team to create a building with energy efficiency as a major focus. The company has developed a highly structured, efficient design process. Approval for building design rests almost entirely on the cost-effectiveness of construction and operation for proposed structures.

The design of other Johnson Control branch offices had been fine-tuned to the point where further cost-effective savings were very difficult to achieve. Because they are extremely energy-efficient, a typical Johnson office served as the base case for this study to determine if additional conservation features in the above design would increase energy savings over those already implemented in other Johnson Control facilities.

High-efficiency lamps, ballasts, and luminaires had been used to conserve energy in previous branch office designs, but lighting still remained the highest energy cost. Johnson Controls estimated that, by incorporating passive solar strategies, the total cost of heating, cooling, and lighting the new office would be less than the cost of lighting alone in its existing buildings.

[35] *Means Construction Cost Data* (R. S. Means Co., 1982); *Dodge Construction Systems Cost* (McGraw-Hill Cost Information System, 1982).

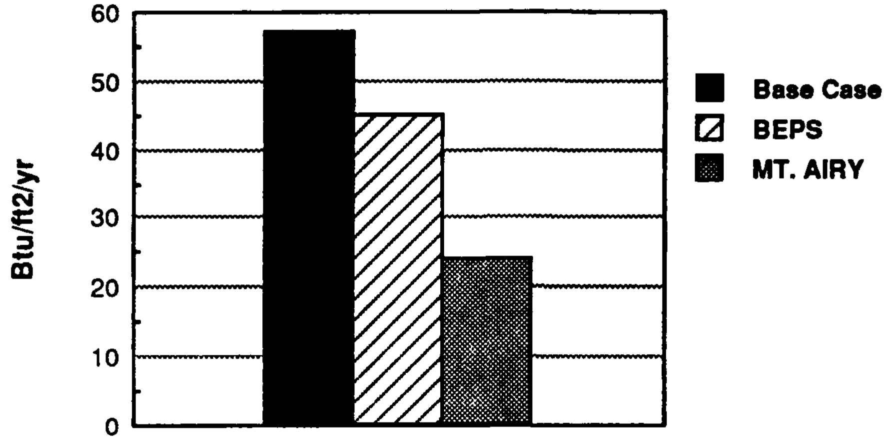

Figure 8. Mount Airy energy use comparison.

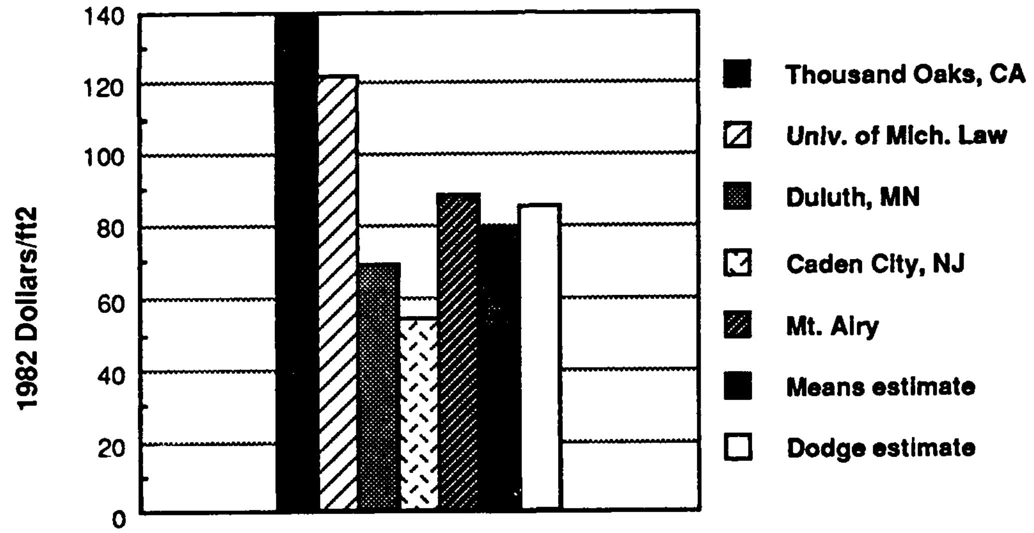

Figure 9. Comparison of library construction costs.

Several passive heating, cooling, and daylighting concepts were tested for both feasibility and cost-effectiveness. The main passive solar techniques applied in the Salt Lake City office were daylighting, direct gain space heating, and evaporative cooling. On clear days, daylighting is often sufficient to eliminate the need for ambient electric lighting in the engineering and reception areas. Building performance monitoring showed the lighting load to be only 4 percent of the total annual energy use, savings are the effectiveness of the clerestory and south facing windows along with the energy-efficient electric lighting system and automated controls.

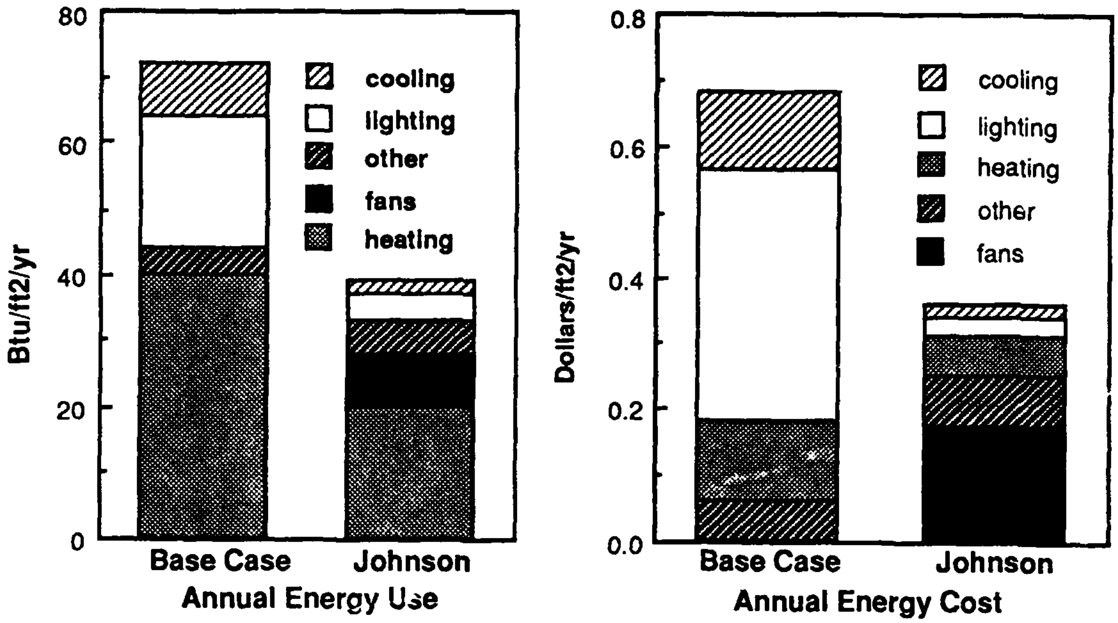

Figure 10. Energy use and cost comparison: Johnson Controls.

The one-story masonry structure cost $57/sq ft, which is within the range of similar nonsolar buildings in that location. This figure falls within both the Means and Dodge cost guidelines (Figure 11) and the original budget provided by the client.

Security State Bank, Wells, MN

The Security State Bank of Wells, MN need for more space led to expansion plans and a newly constructed passive solar building. The new bank has a large amount of glass that opens up the building for substantial use of daylight.

During the first 3 months of the new Security State Bank's operation, utility bills dropped 60 to 70 percent compared with the old bank building (Figure 12). The energy savings were due to the energy-conserving construction, economical heating, ventilation, and air-conditioning (HVAC) systems, and the passive solar features.

The new building is designed to use less than one-tenth of the energy needed to light a comparable building in Minnesota. Heavy insulation and tight construction account for most of the year-round energy savings for the bank's heating and cooling. The primary difference between the Security State Bank and conventional banks, however, is the daylighting system. This system is also the most visible element of the passive solar design. Extensive glass area, hooded by awnings, is used to provide most of the ambient lighting.

Energy consumption is slightly less than three-quarters that of the base case (Figure 13), with the most substantial savings in lighting and cooling. The lighting load represents one-twentieth of the total annual energy use. The actual lighting load amounts to only 12 percent of the base case lighting load. The main reasons for the savings are the effectiveness of the clerestory and south facing windows and an energy-efficient electrical lighting/automated control system.

The clerestory windows are intended to provide most of the task and ambient lighting. Diffuse daylight is required to prevent glare at workstations on the main floor. This diffusion is obtained partly through the use of a baffle system consisting of two 3 by 5 ft box beams that span the length of the

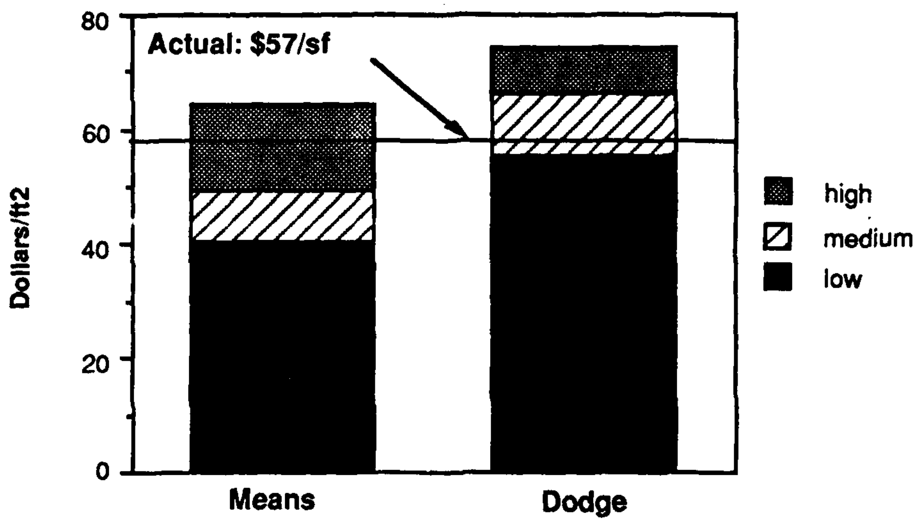

Figure 11. Johnson Controls construction cost comparison.

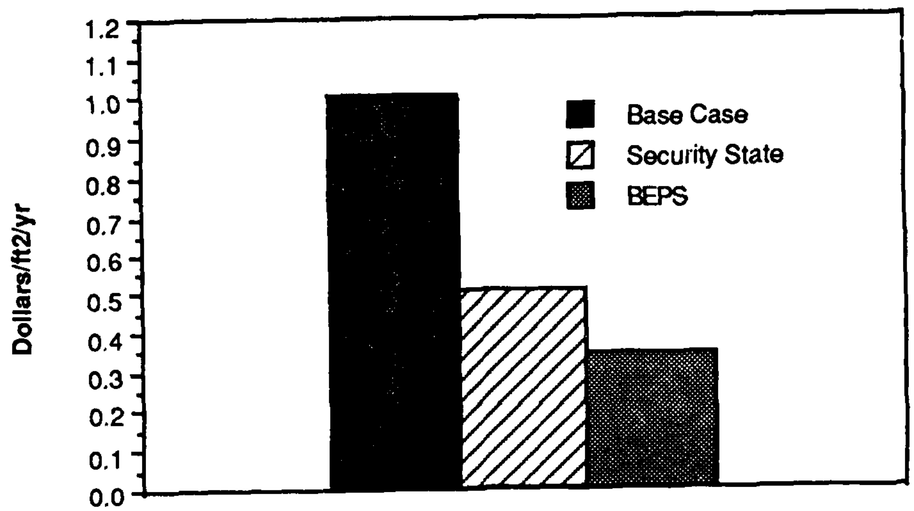

Figure 12. Energy cost comparison: Security State Bank.

building. These large baffles alone cannot lower direct beam illumination enough; therefore, a smaller, lightweight baffle grid is suspended between the two larger baffles to increase the diffuse quality of light. The baffles also house the HVAC ducts and the backup fluorescent lighting system, a dual function making them cost-effective.

Cooling energy is 8 percent of the total energy use, a slightly larger proportion than the lighting. However, the energy use for cooling represents only one-third of that required by the base case. The low cooling requirements are a result of the heavy insulation and the awnings' reduction in undesirable heat gain.

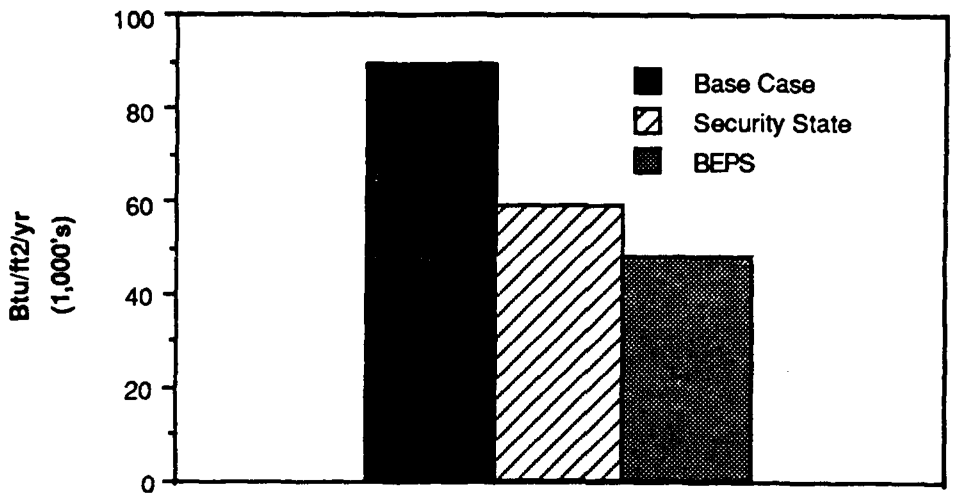

Figure 13. Total energy consumption comparison: Security State Bank.

Construction cost of the Security State Bank was $59/sq ft. This falls in the low range of cost for a similar building according to Means and Dodge data.

Essex-Dorsey Senior Center

The architectural objective of this design was to preserve and convert two 3000 sq ft Victorian school houses into one 13,000 sq ft senior community center by adding another 7000 sq ft. The design was to incorporate passive solar techniques to aid in meeting the occupants' comfort needs.

The energy design objective was to reduce energy use by about 50 percent over the base case, which was a typical nonsolar community center in Washington, DC. The basic energy design concept involved developing a structure that could be opened to summer breezes and closed tightly in the winter, providing natural light year round.

Energy use in the Essex-Dorsey Senior Center for lighting, cooling, and heating has been found to be slightly more than two-thirds the energy use of the base case. While space heating is almost one-fifth higher than the base case, lighting and cooling energy use are reduced by almost 90 percent. Heating costs are about 20 percent higher than the base case, while cooling costs are less than 10% of the base case energy costs. Lighting energy costs are only about 10 percent of the base case building costs (Figure 14).

Total construction cost was $65/sq ft and within the proposed budget. This figure is fairly high compared with industry-wide estimates for a new building of the same size and type and with similar construction. However, in view of the fact that this was a renovation/rehabilitation project with a new addition, the cost is reasonable for the Washington, DC area (Figure 15).

Philadelphia Municipal Auto Shop

An energy-efficient retrofit scheme was needed for one of Philadelphia's most inefficient municipal buildings. Many of the single-glazed steel casement windows were broken or inoperable and the oil-fired boilers were old and obsolete. An energy audit performed as part of a city-wide program showed that the building was consuming 230,000 Btu/sq ft/yr. This level was more than double the average of 96,000 Btu/sq ft/yr for facilities of the same type.

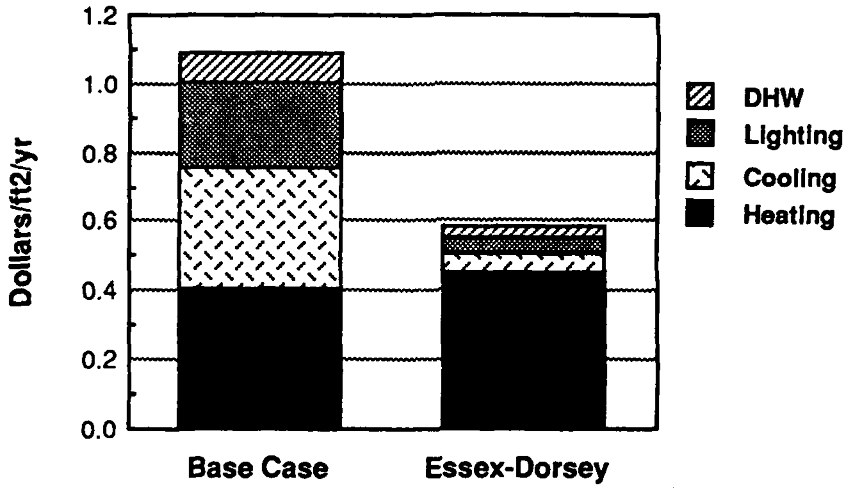

Figure 14. Energy cost breakdown: Essex-Dorsey Center.

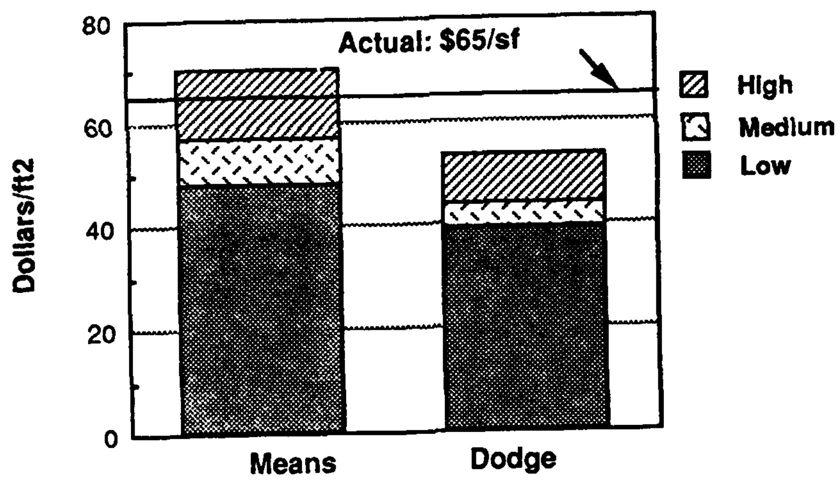

Figure 15. Construction cost comparison: Essex-Dorsey Center.

Heating costs accounted for some 80 percent of the annual energy budget, so the main need was to reduce space heating costs. The design team hoped to exploit the solar heating potential offered by the large window area on the south and southeast walls.

Additional wall and roof insulation was needed to reduce the total heating load. Since single-pane glazing is not effective in preventing conductive losses, several techniques also were considered for increasing window insulation value. This strategy was considered to be cost-effective due to the large amount of glass in the south and southeast facades.

The final window wall design consisted of a standard Kalwall insulation window modified to include the radiant panel, a damper, and a lightshelf. The damper vents the space between the Kalwall and the metal panel during the summer, which helps cool the radiant panels. Opening the vent in the spring and closing it in the fall are the only activities required to operate the windows. The metal radiant panel is perforated to allow light to penetrate, which reduces glare from the window above.

During cold weather, a window is normally a source of heat loss because it presents a colder surface to the space and its occupants than surrounding walls. By providing a warm radiant surface, the absorber panel converts the window from a source of discomfort and conductive loss to an area of warmth. Because radiant heat can provide satisfactory comfort conditions at lower air temperatures, the thermal benefits gained by adding the absorber plate to the window are considerable. At ambient temperatures of 10 to 20 °F on sunny winter days the radiator panels in the window often reach temperatures higher than 100 °F.

A lightshelf and fixed sash are located above the radiator panel. The lightshelf consists of a brushed aluminum plate angled 9 degrees below horizontal, which helps project natural light inside the building. In addition to the lightshelves and glare-reducing perforations, a reflective styrofoam and concrete roof covering is designed to enhance the lighting capabilities of the third-floor clerestories and to improve the thermal integrity of the roof. Repositioning the existing lights beside, rather than across, the repair bays has reduced the total number of fixtures. In addition, a fresh coat of white paint on the building interior is expected to help distribute light more evenly.

Actual performance monitoring showed that the retrofit measures, including the metal absorber/radiator panels mounted behind the insulated portion of the new windows, reduce energy use more than 135,000 Btu/sq ft/yr. The garage requires about 60 percent less total energy per square foot than the original preretrofit building (Figure 16). Although heating energy use is the greatest source of energy savings, lighting loads are very low in both the preretrofit and the retrofit garage because of the large window area and the building's southeastern orientation. Because the building is limited to daytime use and its orientation presents a large glass area to the natural light source, the use of daylighting in this application is highly effective.

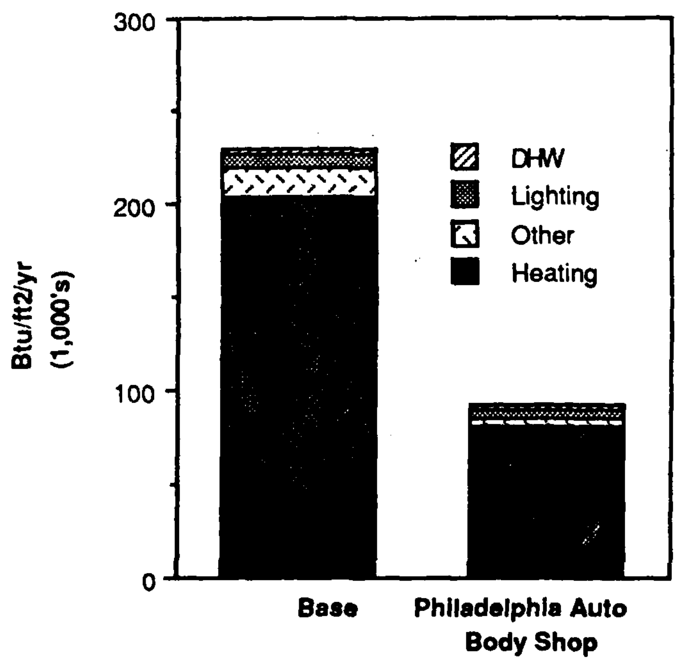

Figure 16. Energy use comparison: Philadelphia auto body shop.

The total reconstruction cost was $8.26/sq ft. Of the total cost, $4.11 was devoted to conservation features. However, total annual average savings of almost $70,000 make :.. energy retrofit a sound investment for the city. The payback from the energy investment alone is less than 3.5 years, with the total construction payback less than 7 years. Given the cost of new construction to replace the old garage, the retrofit and renovation were considered a good investment.

Summary of Monitored Buildings

The DOE Nonresidential Experimental Buildings Program has provided the largest data base of cost, energy, and occupant perception of nonresidential buildings to date. Patterns which have emerged suggest that passive, climate-responsive technology generally can provide substantial utility cost and energy savings at little or no increase in construction cost. Performance parameters contributing to success or failure include occupant behavior and control, fuel cost, the skillful handling of design elements such as solar apertures, thermal mass, and daylighting systems, and their integration with conventional design features.

Daylighting and artificial lighting can be integrated successfully. Optimal integration occurs when:

- Switching of any kind is not necessary for extended periods of time
- Zone switching is provided to supplement variations in daylight distribution according to need in the space
- Zones are arranged parallel to the daylight source rather than perpendicular
- Multilevel switching is used to supplement available daylight as needed.

The main problem identified by the DOE program was the designers' difficulty in learning radically new techniques. Much of the designers' time was spent assimilating new information and developing new design methodologies. Repeated experience with daylighting would presumably eliminate this source of difficulty.

4 USACE EXPERIENCES WITH DAYLIGHTING: SURVEYS AND INTERVIEWS WITH DESIGNERS

The use of daylighting concepts in Army facilities was investigated through conversations with USACE architects, electrical engineers, and mechanical engineers and by a survey (Appendix). The intent of the survey and interviews was to determine how design teams in different climates view the idea of daylighting concepts and how extensive daylighting has been used in USACE. The offices contacted were chosen to represent a variety of climates. These included the Seattle, WA, Sacramento, CA, Tulsa, OK, Fort Worth, TX, Savannah, GA, and New York, NY Districts and the Southwest Division.

To summarize, survey and interview questions addressed the following issues:

- Do USACE designers believe daylight can be cost-effective?
- How does the design process affect the incorporation of daylight design?
- What is the designer's level of knowledge about daylight design?
- What types of daylight strategies have been used in military facilities?
- What is the role of energy analysis in approval or rejection of daylighting?
- What type of daylight analyses have been used?

Responses to each of these questions are summarized in this chapter. A question-by-question tally of responses is in the Appendix.

Attitude Toward the Use of Daylighting

Most USACE designers queried felt that daylight could be used to save energy. The few who said daylight could not save energy believed that their climate was ill-suited for daylighting. For example, it was suggested that daylighting will not work well in cloudy climates.

The Design Process

The design process in the USACE offices contacted presents several obstacles to effective implementation of daylighting. Initial programming is generally done at the installation. If USACE designers are involved early enough in the process, they can propose that daylighting be incorporated. However, the final decision is the installation's. *Usually daylighting is not considered at the programming stage.* By the time USACE designers receive a project for review, there may be no time to consider daylighting. If the job is sent out of house for competition (respondents indicated that 65 percent or more of their jobs are handled this way), the architectural/engineering (A/E) firm may already be contracted and consideration of daylighting may not be included as part of the work. When the A/E is contracted to incorporate daylight design strategies into the overall design, he/she is told that the plans will be reviewed by USACE.

Base personnel often are not familiar with daylight design. In some cases, when a design proposal from USACE is sent to the base for approval, changes may be made which adversely affect how the daylight strategy will perform. One example related by a USACE architect described a training facility where lightshelves were incorporated into the window design. Lightshelves should be finished in a light color so that the daylight will be reflected, not absorbed. In this case the architect specified that the lightshelves should be light blue. When the plans were reviewed, however, the base had changed the color of the lightshelves to brown for esthetic reasons. A lightshelf painted brown is not likely to perform well. Clarifying the functional role of the lightshelf finish might have prevented this outcome.

USACE design guidelines also may limit the incorporation of daylight design. Glazing areas are limited to a fixed percentage of the wall area. In addition, material must be specified in generic terms. Therefore, special glazings and shading devices can rarely be specified. These products are available from a limited number of manufacturers; therefore, to specify them, the designer must write a proprietary specification. This limits sources for the product and makes it likely that the feature will be removed from the design.

The division of labor on a project makes it difficult for the design team to understand and agree upon the solutions that the different members propose. This division of labor is defined clearly in most areas. However, when the issue of daylight design is raised, there is little agreement as to who is responsible for its implementation or analysis. Energy analyses are clearly the mechanical section's domain. However, in-depth analyses are not normally performed to discern how the use of daylight will increase or decrease heating and cooling loads when the lighting load is reduced and solar gain introduced.

Mechanical engineers typically assumed that the electrical engineer would be responsible for doing daylight analyses while the initiation of daylight design is strictly up to the architect. The electrical engineers, however, felt that daylight analyses should be done by the architect. In some Districts, the architects said daylighting analyses were the responsibility of the electrical engineer. When analyses *were* performed, they were typically done by the architects. However, in these instances, even though analyses showed that the use of daylight could reduce the electrical lighting load and be cost-effective, control strategies were not incorporated.

Differing viewpoints between the design teams also may inhibit the incorporation of daylighting. Typical criticisms of daylighting include "daylight design cannot meet energy standards," "it increases construction cost too much to justify its use," and "the controls cost too much." Excessive first cost was cited as leading to elimination of controls from proposed daylight designs. Some personnel also described cases in which lights designed to be switched in banks parallel to windows to take advantage of available daylight were redesigned in a conventional staggered pattern. Clearly, the daylighting proponent on a multidiscipline design team must overcome many obstacles within the design process.

Understanding of Daylight Design Techniques

The conversations and surveys revealed that some USACE personnel are well versed on daylight design and its relationship to other passive solar strategies while others are not. Some personnel suggested that by specifying skylights and/or clerestories in past projects, they had implemented daylight design. However, in discussing the projects further, it was found that daylight analyses had not been performed to predict the amount of daylight available and control strategies had not been considered or implemented. When asked if daylight was used as a supplemental light source, most survey respondents answered affirmatively. These respondents expressed interest in the use of daylight mostly from an esthetic viewpoint, but felt that it also could be a valuable source of light to reduce the electrical light load. They indicated that training or design guidance would be helpful since their knowledge was limited. Respondents said that it is as important for personnel tasked with design review to understand daylighting principles as it is for designers. Because successful application of daylighting depends on having decisions made early in the planning stages carried through to construction intact, a single uninformed link in the design/build chain can completely defeat the designer's intent.

Level of Expertise in Daylighting Design

A few USACE personnel felt that daylight design goes beyond their normal level of complexity. Daylight and passive solar strategies are overlooked because this type of design requires a great deal of rather specialized knowledge and expertise for effective application. Consideration of daylighting and passive solar designs tends to be an environmental concern. It was stated, however, that many USACE designers do not have the experience needed to incorporate environmental technology. Also, time constraints make it difficult to design beyond an acceptable, conventional level in many cases.

Many of those surveyed did not know where to find information pertaining to daylight design. The few sources that were cited were the IES Handbook and Air Force installation design guides. Many held that the use of daylighting and other passive solar techniques could be valuable in saving energy. However, due to lack of experience in designing for daylighting, it is applied infrequently and generally incorrectly. Respondents expressed interest in being educated in daylighting and passive solar design strategies. It was suggested that design guidelines need to be developed, education and training courses in daylighting by experienced lighting designers or A/Es are needed, and education in the use of simple analysis tools that could be used in the design conception stage would be beneficial.

Daylight Strategies Used in Army Facilities

Daylight strategies have been incorporated into several military facilities. However, many of the daylight features seem to have been added primarily for their esthetic quality. In many cases, no daylight analyses were done to determine how well the proposed design would work. Some Districts employed a very small number of daylight techniques while others had tried most of those listed in the survey for one or two projects. None of the Districts contacted had performed any monitoring of daylighted buildings to determine how the different strategies compare with each other in terms of daylight penetration and energy savings. The most common daylight strategies used were skylights, clerestories, window overhangs, and special glazing (see the Appendix). Other daylighting features such as roof monitors, lightshelves, vertical fins, and sensors were used infrequently.

Maintenance affects the performance of daylighting systems and may be an important consideration when a daylight method is selected. Systems that require less maintenance will perform better. For example, dust collection can render a toplighting fixture ineffective. Clerestories and roof monitors may be preferable to horizontal skylights since less dirt should collect on the vertical clerestory surface. However, a clerestory is not totally maintenance-free. The roof surface in front of the aperture must be kept clean to reflect daylight into the building. Some interviewees expressed the desire to design daylight systems that require little or no occupant intervention (e.g., seasonal adjustment only). If a system permits or requires control by occupants, training in its proper use should be provided.

USACE designers cited several buildings that have daylighting features. However, very few examples were for Army facilities. Most buildings mentioned are on Air Force bases. According to these respondents, the Air Force has been interested in daylighting (and passive solar technology, in general) for some time. Daylight design is usually written into the initial building program for Air Force buildings. In fact, the Air Force has implemented a number of guidelines to improve designers' understanding of how energy-conserving strategies work and should be applied. The most recent guidance is a set of passive solar design handbooks.[36] The goal of these handbooks is to help integrate passive solar concepts into the Air Force planning, programming, design, construction, and operation processes for commercial facilities.

Use of Daylight Analyses in the Design Process

As noted above, facilities given as examples of daylight applications were usually designed without the benefit of any type of daylight analysis. Many of the designers were not familiar with daylighting analyses techniques, which could help explain why these analyses often are not done. However, lack of time seems to be a major factor in the frequency of daylight studies. In this regard, daylighting analysis methods which are less time-consuming than current procedures could have a significant benefit.

A few designers were very familiar with the available daylighting analysis techniques. Due to time constraints, daylight analyses are either totally avoided or rely on simple techniques such as the BRE daylighting protractors or the Libbey-Owens-Ford Sun Angle Protractor manual.

The complex computer-based methods have received little use. According to the designers who have used them, program limitations make it difficult to justify their use (i.e., the effort invested in applying these programs does not return enough in terms of information relevant to the design). Examples of these drawbacks include: limitation on building size the program can handle, small range of aperture configurations, lack of detailed energy analysis, and poor user interface (i.e., complicated and time-consuming data input procedures). Failure to make energy analysis an integral part of the daylighting design process is an unfortunate omission. Concept-level energy analyses could help architects understand the ramifications of proposals *before* they are sent to the mechanical engineer for detailed HVAC studies. Energy analysis coordinated with daylighting studies could reduce the number of design revisions.

Another reason daylight analyses are not performed is that, even when the results show that daylight availability would be high enough, the daylighting system rarely survives the design and review process intact. This situation may be due to a lack of communication between different members of the design team. When plans go to the electrical engineer, the reason for the specified control strategies should accompany them. The electrical engineer generally concludes that the control strategy proposed by the architect is not necessary and/or too costly. Therefore the electrical engineer may simplify the plans with no feedback to the architect. Or, if the mechanical engineer is not aware that daylighting is to be used (i.e., reduced lighting consumption and lower internal loads), the energy analysis may show increased cooling or heating loads, which will lead to changes in the architectural design.

Limitations Due to Economic Factors and Energy Standards

Several respondents stated that the use of daylight as a light source would not pay back quickly enough. They said that, although the normal commercial rates for electricity might make daylighting cost-effective, there is no real need for it on bases that purchase electricity at bulk rates ($0.05/kWh or less). Also, it was commonly believed that incorporation of daylight design increases the initial building cost, therefore reducing its desirability. Moreover, economic analyses for daylighting tend to be broad and unfocused, and the low energy cost at some sites makes it difficult to show economic savings. Consequently, respondents indicated that this type of design is not documented appropriately for life-cycle cost analyses. USACE personnel were aware that showing cost savings and energy

[36] C. Robbins (1989).

savings are two different matters. In their opinion, energy analyses are not detailed enough to demonstrate potential overall energy savings from daylighting.

Energy standards (e.g., USACE Architectural and Engineering Instructions)[37] were cited as a major deterrent to the use of daylighting. However, it seemed that designers who wished to use features such as skylights, clerestories, or large expanses of glass were allowed to do so. However, these uses of fenestration were permitted without accompanying daylight controls. Therefore, designers' perceptions and the record seem incongruous on this point.

Buildings that were mentioned as having daylighting elements were mostly projects that had been contracted to A/E firms. This finding led to the question of whether budget constraints and energy standards tend to be less stringent when a project is done out of house. There was a mixed response to this question. One member of a design team would say standards are less stringent for out of house projects, while another would say they are the same for both in-house and contracted projects. Apparently there is no consensus, although a significant number feel that A/E contractors have more freedom to operate. Perhaps this perceived freedom is simply the result of expertise gained through A/E's broader experiences in nonmilitary construction.

Energy standards do not seem to be the critical factor in the approval or rejection of a design proposal. Although several designers said that standards are the same for all buildings, there are many buildings on installations that have large expanses of glass. One designer indicated building function is a more significant influence on whether a strategy such as daylighting will be implemented. If a building is considered to be "high profile," the design will be more visually striking and may include daylighting features. Examples are atria covered with skylights and large expanses of windows to give occupants a view. It was also mentioned that the commander of a facility has much influence on building design for new construction there.

Summary

According to the interviews and surveys of USACE designers, the main factors *perceived* as limiting the use of daylight design are:

- Insufficient understanding of effective design techniques
- Feeling that it is not economically justifiable
- Lack of adequate analysis tools
- Lack of time to do analyses
- Lack of interest and understanding on the part of customers
- Failure to include daylighting in the initial building program
- Constraints due to energy standards.

As the foregoing discussion indicates, these factors interact in a complex way. Another limitation that should be added to this list is inadequate continuity of concept during the design process. The

[37] *Architectural and Engineering Instructions* (Office of the Chief of Engineers, 13 March 1987).

architect was the originator of the daylighting strategy in every case reviewed during this study. Before the architect's ideas were introduced, no allowance had been made for daylighting; after a design left the architect's office, it often encountered repeated, well-intentioned but uninformed revisions that compromised the intent and effect of the strategy. This problem impacts many aspects of the design process and has no easy solution. In the case of daylighting, however, it is clear that more integration and feedback are necessary not only in planning and design, but also in construction and operation of buildings to maximize energy savings when possible.

5 CONCLUSIONS AND RECOMMENDATIONS

Conclusions

This study has surveyed design teams at USACE Districts to learn how they view the use of daylighting in military construction. In addition, case studies of buildings that have incorporated daylighting and other passive solar strategies have been summarized to show what kind of design features are involved and evaluate their success in saving energy.

Responses from the USACE personnel contacted indicate that daylighting is rarely considered during the design process. In cases for which daylighting features were reported as being used in a structure, some design aspect was often absent (e.g., a control strategy). In addition, the designers could identify few projects that had included daylighting studies to determine potential savings.

The respondents cited several reasons for the tendency to exclude daylighting from project design:

1. The designers' lack of expertise and experience with daylighting makes it unlikely that these strategies will be considered routinely. It should be noted that daylighting has reemerged in the architectural community fairly recently (during the 1970s) and probably was not a standard part of A/E education prior to that time. As a result, many designers are not familiar with the basic features of daylighting. This situation has led to misconceptions about daylighting practice, including the common belief that it always involves large window expanses.

2. There is often a lack of communication between design teams so that even when A/Es have recommended using daylight techniques, the purpose has not been stated clearly and the features are either eliminated or detrimental changes are made during some later stage of the project. Also, it is not clear which team should be responsible for introducing daylight design.

3. USACE design teams are already overloaded with work and there is no time to perform daylighting studies.

4. Standard design guidance often prevents inclusion of daylighting features because it usually specifies generic components to allow competition; therefore, it is difficult to name manufacturers in a contract. Since daylighting components are available from only a few manufacturers, there is a problem with ensuring that appropriate products are specified.

The case studies examined showed that daylighting is being used successfully to reduce energy costs. These buildings were part of a DOE program to evaluate passive solar strategies. The U.S. Air Force is also using daylight strategies in construction and has published guidance for designers.

Recommendations

Daylighting can potentially conserve energy and save money over the life of a facility. Although the first cost is often higher than if these features were not used, the payback can be fast and savings will continue to accrue. At present, it is not possible to predict a life-cycle savings for any specific daylight design because operating data are not available. Studies are needed to compare the strategies and different control situations--uncontrolled, automatically controlled, and manually controlled by educated occupants.

Because daylighting has a high potential for savings at Army installations, it is recommended that feasible applications for this technology be identified. USACE designers should be given an opportunity to learn the basic principles involved in daylighting. Design guidelines could facilitate the learning process; however, developing prescriptive standards for daylighting would probably be counterproductive because daylight design is sensitive to climate, site, and functional needs.

Designers who originate daylighting features in a project should take steps to identify important elements of the concept to other parties in the design process. Architects, engineers, reviewers, and end-users all need to understand the intent of the features and the critical interdependence of daylight system components.

There is a clear need for daylighting calculation procedures that produce reliable results at less cost and time than those currently available. Off-the-shelf daylighting software could be evaluated for possible use, or computer programs could be developed for lighting energy analysis. Research and development for such programs would require a substantial investment.

METRIC CONVERSION TABLE

1 in.	=	2.54 cm
1 ft	=	0.305 m
1 Btu	=	1.055 kJ
1 fc	=	10.76 lux

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APPENDIX:

DAYLIGHT SURVEY

The following survey was distributed to USACE Districts. Responses are tallied next to each question. The Districts contacted are listed at the end of the questionnaire.

	yes	no	No response or not known
1. Are there buildings at installations in your district in which daylight design has been incorporated?	13	1	0

2. What types of daylight strategies are used?

	"F"(frequently)	"O"(occasionally)	"N"(never)
Roof monitors	0	4	6
Clerestories	4	7	3
Skylights	2	8	3
Lightshelves	0	5	9
Window overhangs	6	6	2
Vertical fins	0	5	9
Photo-activated blinds or shades	0	3	11
Sensors to adjust electrical light in response to available daylight	1	5	7
Wiring of fixtures so that lights near windows can be turned off if daylight is adequate	2	6	6
Special glazing	3	8	3

	yes	no	No response or not known
3. Is daylight incorporated into designs mostly for its esthetic and psychological value?	10	2	2
4. Are daylight strategies incorporated with the intent to save energy?	9	4	1
5. Do you consider daylight to be a resource which could be used to save energy?	11	4	0
6. Is daylight used as a light source to supplement the electric light load?	10	4	0
7. If daylight is incorporated into the design, are switching or control strategies installed to turn off portions of the electric light when daylight illumination is sufficient?	5	8	1

8. If daylighting has been incorporated into buildings, has some type of analysis been done to determine the illumination available from the daylight?	5	7	2
9. Have analyses been done to determine the change in electrical consumption if daylight were used as a light source?	4	7	3
10. Have analyses been done to determine how the HVAC system would be affected by the use of daylight as a light source and the reduction of the electrical light load?	5	6	3
11. When large glazed areas are incorporated into a building design, are analyses done to determine if the solar heat gain in the winter reduces the heating load enough to balance out the extra cooling that may be needed in the summer?	5	6	3
Comment: "No, but the capability to do so exists."			
12. If daylight is used as a supplemental light source, some lights would be turned off or dimmed to some extent, therefore, less heat would be given off from the electrical lights. Are analyses done to determine whether the reduction in heat given off, due to fewer lights on, affects the cooling and heating loads?	3	8	3
13. When a project is given to the electrical engineer, is it assumed that he/she will take into account the daylight and implement appropriate control strategies?	7	5	2
14. Do electrical wiring plans show any consideration for daylight use (e.g., automated controls)?	6	6	2
15. Are systems generally installed as designed?	10	2	2
16. Are systems generally used as designed?	7	4	3
Comment: "Doubtful, but no data on this."			

17. If daylighting analyses are done, who performs them?

5 Corp Architect 4 A/E 9 Electrical Engineer

1 Daylighting Consultant 2 Mechanical Engineer

Most respondents listed two or more members of the design team who they felt would perform daylighting analyses.

	yes	no	No response or not known
18. Is there sufficient consultation between architects and engineers throughout the design process?	8	4	2
19. In your experience, do occupants turn off lights when daylight is adequate?	6	7	1
20. Are any buildings monitored to document savings due to the use of daylight as a supplemental light source?	0	13	1

21. What limits the incorporation of daylight strategies? (Check all that apply)

- 9 Not enough understanding of what needs to be considered for proper daylight design.
- 8 Lack of interest in daylight design.
- 10 Lack of analysis tools.
- 10 Lack of time to do analyses.
- 7 Not enough understanding by end-user, therefore rejection or changes to design proposal.
- 6 Design criteria.
- 3 Increased building costs.
- 8 Energy standards.
- 5 Maintenance problems.
- 4 Payback is not quick enough due to low electricity costs to the bases.

	yes	no	No response or not known
22. Is daylight design considered only if the architect in charge of a project has an interest in it and designs for it?	7	4	3

Comment: "No, however, without architectural interest, it won't be incorporated."

	yes	no	No response or not known
23. Are energy analyses done to determine how different design strategies affect energy use?	6	5	3

24. When are energy analyses done for a project?

_1_ concept stage

_9_ 35% stage

_1_ 60% stage

_0_ 95% stage

_0_ final design

_3_ *no response*

	yes	no	No response or not known
25. Does the use of daylight tend to be considered more in projects that are done out of house?	2	8	4
26. Are building cost analyses done to see if daylight strategies pay off?	3	9	2
27. If the analyses are done and show that the daylight strategies will pay for themselves, do these strategies get implemented?	6	6	2

Comment: "Yes, but may be limited."

If not why?

Comment: "Initial cost, programming, and administration problems."

	yes	no	No response or not known
28. Do the limitations listed in #21 generally apply to smaller projects that are done in-house?	6	4	3
29. Do the budget constraints tend to be less stringent for projects done out of house?	4	7	3
30. Do the design constraints tend to be less stringent for projects done out of house?	6	6	2
31. Do the energy standards tend to be less stringent for projects done out of house?	6	6	2

If not why?

	yes	no	No response or not known
32. Are there operation and maintenance people assigned to monitor and control building systems?	7	4	3

33. Is there any type of post-occupancy education for building users or operation and maintenance personnel?	5	7	2
34. Is there any type of post-occupancy followup to see if systems are used as designed?	1	11	2
35. Are there building types in which daylight strategies tend to be more appropriate?	5	6	3

Please explain.

Comment: "Narrow, rectilinear buildings and high bay single-story buildings work well with daylighting techniques. Hangars, gymnasiums, circulation spaces, and open office plans are good candidates."

36. Who makes up the initial building program?

- 9 User of military base
- 2 Architect
- 3 Unknown.

37. Who decides whether daylight will be incorporated into a project?

- 5 User
- 4 Architect
- 2 User/Architect
- 3 Unknown.

38. When is it decided whether daylight should be considered?

- 1 Programming stage
- 9 Concept/10% stage
- 4 35% stage.

39. What types of projects are done out of house by an A/E firm? (All types.)

40. What is the percentage of out-of-house projects? 80%+

41. Please list a few buildings (and their locations) in which daylight strategies have been used. Also list the type of daylight strategies used, the type of control strategies used, and whether a daylighting analysis was done for the particular building.

OMS/AMSA, Maintenance Building, Rocky Mountain Arsenal, Denver, CO.
(The respondent) Assumed daylight analysis was done since fewer lamps than usual were installed.

Madigan Army Medical Center, Fort Lewis, WA.
Incorporated clerestories, skylights, sensors for daylight availability, and photo-activated shades.
Daylight analyses were done by the A/E.

Turtle Creek Administration Building.
Incorporated clerestories and overhangs. No daylight analysis was done.

Military Personnel Support Center, Dyes Air Force Base (AFB), Abilene, TX.
Incorporated clerestories and lightshelves for interior illumination.
Daylight analyses were done using BLAST.

Evans Army Community Hospital, Fort Carson, CO.
Skylights with movable solar shades were incorporated, but do not work since the designer did not consider snow in this location. Not known if a daylight analysis was done.

Educational Training Facility, McClellan AFB, Sacramento, CA.
Lightshelves with louvers were used. Switching did not get incorporated as initially planned.
Libbey-Owens-Ford daylight analysis technique was used for daylight analyses.

Medical Clinic, McClellan AFB, Sacramento, CA.
Incorporated a sawtooth roof with apertures facing south and lightshelves on windows.
No sensors were incorporated. Daylight analyses were done with the BRE Protractor.

Maintenance Hangar, Tinker AFB, FL.
Incorporated clerestories. Manual control. A/E did daylighting study (very expensive study).

Mission Support Complex, Vance AFB, OK.
Incorporated deep overhangs, vertical fins, and window wall. Manual control and separate circuiting.
In-house daylight study.

Fuel Cell Maintenance Facility, Sheppard AFB, TX.
Use of skylights. No separate controls. In-house daylight study.

Vehicle Maintenance Facility, Altus AFB, OK.
Clerestories are used. Manual controls. In-house daylight study.

E6A TACAMO Hangar, Tinker AFB, FL.
Used clerestories and barrel vault skylights. Manual controls.
Study by material supplier.

Physical Fitness Center, Fort Sill, OK.
Incorporated clerestories, window walls, and skylights.
No separate controls. No formal study.

Midwest City Armed Forces Reserve Center.
Incorporated window walls, deep overhangs, and skylights. No separate controls.
Attempted an in-house computer study, but never obtained satisfactory output. Daylighting features were incorporated anyway.

Troop Medical Clinic, Fort Jackson, SC.
Use of large expanse of tinted glass for sidelighting with roof overhang.
Manual controls. No special daylighting study done.

Personnel Service Center, Robbins AFB, GA.
Use of skylights over atrium. No separate controls. No daylighting study performed.

Command and Control Center, Fort McPherson, GA.
Use of skylights over atrium and circulation core. Manual control.
No formal daylighting study performed.

Of the 14 surveys returned, six of the respondents did not list any examples of daylighted buildings.

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