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THE DAYLIGHTING SOLUTION

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The Daylighting Solution

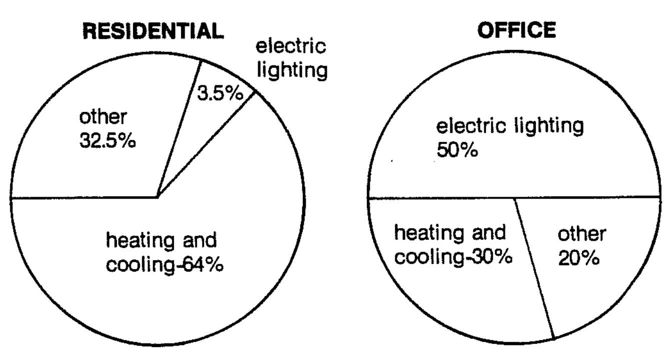
By Stephen Selkowitz and Richard Johnson

Much of the interest in solar applications in buildings has focused on providing thermal energy to offset heating loads and, in a limited number of cases, to provide energy for cooling. But, if we look at energy use in commercial buildings, we find that lighting is a major energy consumer. As the simplest conservation measures are applied to commercial buildings, heating and cooling loads will be further reduced. Lighting will then stand out as a primary target to reduce building energy consumption.

Commercial buildings invite savings from daylighting because: they generally have long hours of daytime occupancy; the lighting power demand is relatively high on a per square foot basis; and lighting constitutes a significant fraction of the utility costs to the building owner.

Daylight and sunlight have always been desirable in homes and one need not make a case for them on the basis of daylighting savings. One note of caution in the residential sector. The notion that reducing window area will reduce energy consumption may lead us to erect houses with window areas so small that daylighting levels inside become inadequate for normal daytime use. While the use of daylight in homes is not seen as a substantial energy conservation option, to ignore or eliminate the effective use of daylight in homes would be shortsighted.

A continuous clerestory above the two-story central space of the Pacific Design Center in Los Angeles lends dramatic emphasis to the geometry of the space. Direct sunlight in this instance enhances the visual drama without being a detriment to activity. Diffuse light from this central area spills into adjacent showrooms.



Residential vs commercial energy consumption breakdown for the United States.

In commercial buildings

Use of solar energy for thermal control in buildings has acquainted us with the sun as a source of Btu's. If we turn to the sun as a source of illumination, our perspective must change. While thermal comfort spans a relatively small range, perhaps 65° to 80°F, the range of illumination in which the human eye can effectively function is much broader. A person with very good eyesight can read effectively with one or two footcandles of light. Typical offices are lit to 50 to 100 footcandles. Direct sunlight is about 10,000 footcandles. The efficacy of sunlight, or the number of lumens of light delivered per watt of energy, varies from about 90 lumens per watt for direct sunlight to as much as 150 lumens per watt for light coming from a deep blue sky. The changes in efficacy result from various scattering and absorption properties of the atmosphere, and the level of particulates and pollutants in the air. As a rough design figure, the number of 100 lumens per watt is a good place to start. This can be compared to the efficiency of a variety of electric light sources. A fair approximation is that daylight is as efficient as the best electric lighting systems in its ability to deliver illumination per unit heat delivered.

As a source of daylighting, the sky and clouds rather than direct sunlight have historically received more interest, primarily because direct sunlight creates potential problems of overheating and visual discomfort resulting from glare conditions. While there is a renewed interest in using direct sunlight in buildings for both thermal and lighting purposes, proven approaches use the sky as the primary source.

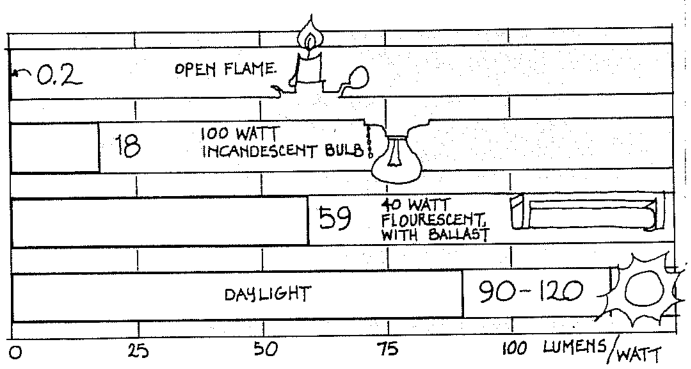


Illustration by Barbara Putnam

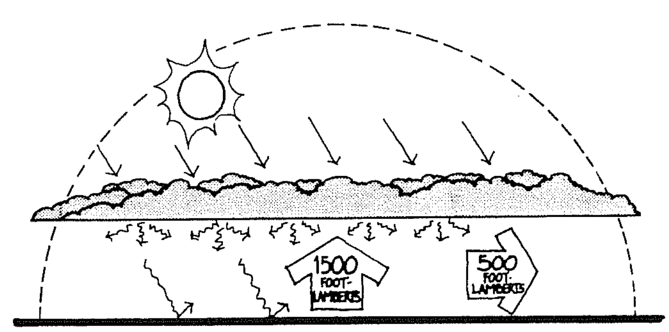
Three types of general sky conditions exist. These are: clear skies, overcast skies, and partly cloudy skies. Both the clear and the overcast sky can be mathematically modeled, and illumination can be calculated under a variety of climatic conditions. The partly cloudy skies can only be assessed statistically since conditions may vary enormously from minute to minute.

Daylight availability is the term used to refer to the frequency or probability of certain illumination levels at a given location. For purposes of daylighting design, hourly records of daylight available at various locations are important, as are estimates of solar radiation available on various surfaces for thermal applications. In fact, daylighting data may be even more crucial since daylight is an instantaneous phenomenon, which cannot be easily averaged over time. Very few empirical records exist of daylight availability in the United States. Several complete years of data were collected in Washington, D.C., from 1923 to 1924 and at Ann Arbor in the 1950's. In Great Britain data are collected routinely. Since daylight availability is so dependent on the microclimate, the data are of little use at other locations.

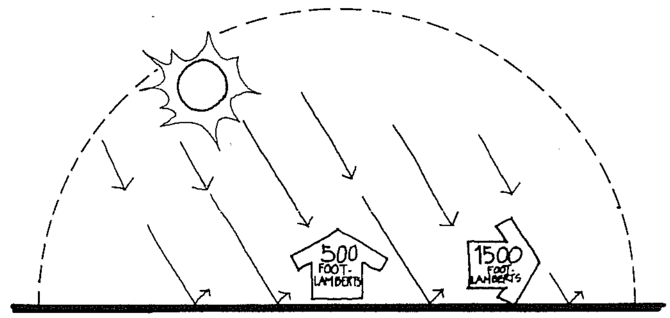
Economics

If electric lighting can provide good visual performance at very low energy use, the energy saved by daylighting will be proportionately less than if daylighting is competing against a very inefficient electric lighting system.

In 1970 it was acceptable to design lighting systems for 100 to 200 footcandles in office buildings with electricity consumption of about 5 watts per square foot. By 1980 recommended light levels dropped down to a range of 25-100 footcandles, with typical power consumption dropping to perhaps 2.5 watts per square foot. Over the next few years, we expect average footcandle levels to drop somewhat further and, together with the use of more efficient lighting hardware, electricity consumption of lighting systems to drop to 1.5 watts per square foot. These figures are for standard design. With state-of-the-art hardware and refined design, good lighting should be obtainable with the expenditure of no more than .5 to 1 watt per square foot.



The standard overcast sky is typically three times as bright at the zenith than it is at the horizon. There is no variation in sky brightness with azimuth.



The clear sky has a more complex brightness pattern, being brightest in the vicinity of the sun with the darker spot approximately 90° across the sun from the sun's position, and then generally brighter at the horizon than overhead. There are sharp differences in the illumination available on north, south, east, and west surfaces with clear sky conditions.

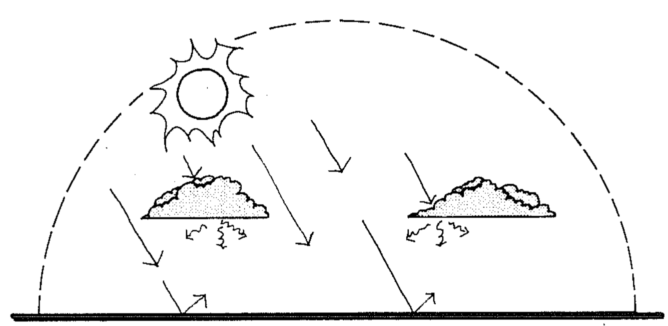


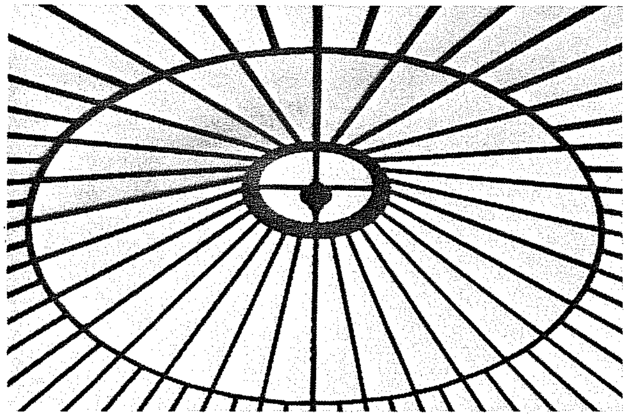
Illustration by Barbara Putnam

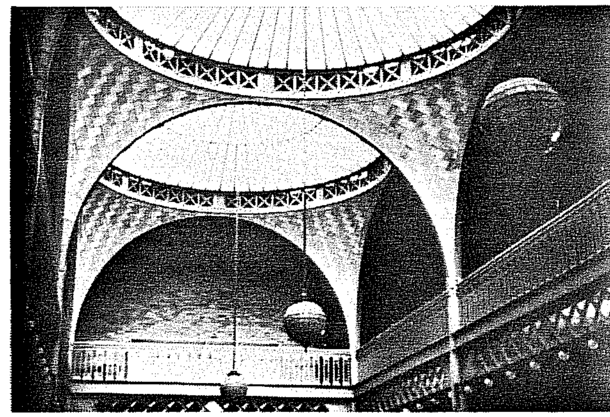
The partly cloudy sky can only be assessed statistically since conditions may vary enormously from minute to minute.

In addition to energy savings, at least four other reasons favor consideration of natural lighting in buildings:

1.) Commercial building owners and operators pay not only for the energy they consume but also for a demand charge, which reflects their peak power consumption each month. Since many utilities have difficulty in siting and building new power plants, there is tremendous pressure to restrict growth of new demand. Demand charges encourage building owners to make modifications in their buildings so that their loads are leveled. Since peak building loads frequently occur in the afternoon when both air conditioning and lighting are on, a daylit building in which the lights are dimmed or turned off should reduce building peak demand, and thus have an additional economic benefit for the owners.

2.) The provision of natural light in a space makes the occupant less dependent upon mechanical systems in the building. Compare an office worker in a room with no windows, and totally dependent upon electric lighting and mechanical ventilation, to a worker in a perimeter office with operable windows and daylight. In the case of





The traditional concern for daylighting in architecture is evidenced by the Hearst Mining Building on the University of California campus, Berkeley. The skylighted central circulation space of this 1907 design provides modeling for the rich architectural detail in patterns that shift by day and by season. The dome skylight is shown on the left.

a power failure, the worker in the interior office would have to quit working and leave the building. The value of a worker's productivity for one hour per year is approximately equal to the annual energy costs of lighting in the space that the worker occupies. Thus the ability to continue work for the single hour per year in a daylit office would equal the entire potential energy savings that daylighting might provide in offsetting electric lighting.

3.) Every indication is that electric costs will continue to rise at rates equal to or exceeding the general rate of inflation. Reducing the use of electric energy for lighting provides a degree of inflation proofing.

4.) The illumination on a horizontal surface expressed in footcandles is the generally used measure of lighting design. In fact, this measure tells us very little about the ability to see or perform a visual task, and lighting professionals have developed other metrics that more nearly measure visual performance rather than the illumination at a point. Studies have shown that one footcandle from a window may provide visibility equivalent to three footcandles from overhead. Other qualitative aspects of daylight such as its color rendition and modeling effects are generally pleasing to building occupants. View and visual connections with the outdoors are related benefits that accompany most daylit spaces.

Control of daylight

With a natural light source varying from a few footcandles to ten thousand footcandles outdoors over a period of a few hours, how does one design a fenestration system that moderates the variation within the room? Historically, daylight design has specified minimum performance conditions occurring under overcast skies and relating to the minimum illumination in the worst point in the room. However, these recommendations were developed in Great Britain, which does not have the extremes in both daylight and temperature levels that are experienced in the United States. In addition, the British philosophy was based on daylight as the primary source of light to be supplemented by electrical lighting. Although one might extend this practice to the United States, our own building design practices suggest a more obvious starting point with electric lighting as the norm and daylight as offsetting some fraction of electric lighting use. The selection of average, maximum, or minimum design conditions is a major philosophical and practical matter. Designing to meet required conditions under minimum sky conditions means that one may have to worry about controlling excessive light, heat, and glare during much of the year. Designing to meet maximum outdoor illumination conditions will mean that indoor levels will be below those desired throughout much of the year.

Building designers can control the intensity and distribution of daylight in a space by manipulating a number of architectural variables. Both local climate and immediate site conditions affect daylight availability. Although daylight is nominally a free source of light, it may be difficult to use if the building location is near tall buildings, which obstruct the sky and sun. There will be orientations that are more or less advantageous in terms of access to daylight. Sometimes adjacent buildings can be used to an advantage if they are sufficiently light colored to reflect light without causing unpleasant glare. Other landscape factors such as blacktop, gravel, or water, will either detract from or enhance the available daylight resource. Seasonal changes such as the presence of snow on the ground will also vary daylight significantly.

Since the advent of cheap electricity and fluorescent lighting, building form has favored large rectangular plan buildings with a single perimeter zone and large interior zones. It is possible to increase the proportion of building area with proximity to windows simply by altering the building form or proportions. The use of floor plans with projecting wings, enclosed courts, and other design configurations with extended perimeter zones will increase access to daylight in the building.

The selection of fenestration systems has a major bearing on the amount of light let into a space within a building. Glazing high on a wall, for example, produces deeper penetration than glazing low on a wall. Strip glazing produces more uniformity across the room than would individual windows. Reflective or tinted glazing will reduce the daylight available in a space proportional to the visible transmittance of the glazing materials. This may be desirable in some cases to control glare. However, very low transmittance glasses are unlikely to transmit sufficient light into the room to provide usable daylighting throughout much of the year. In general, some type of solar control with a more dynamic response is preferable.

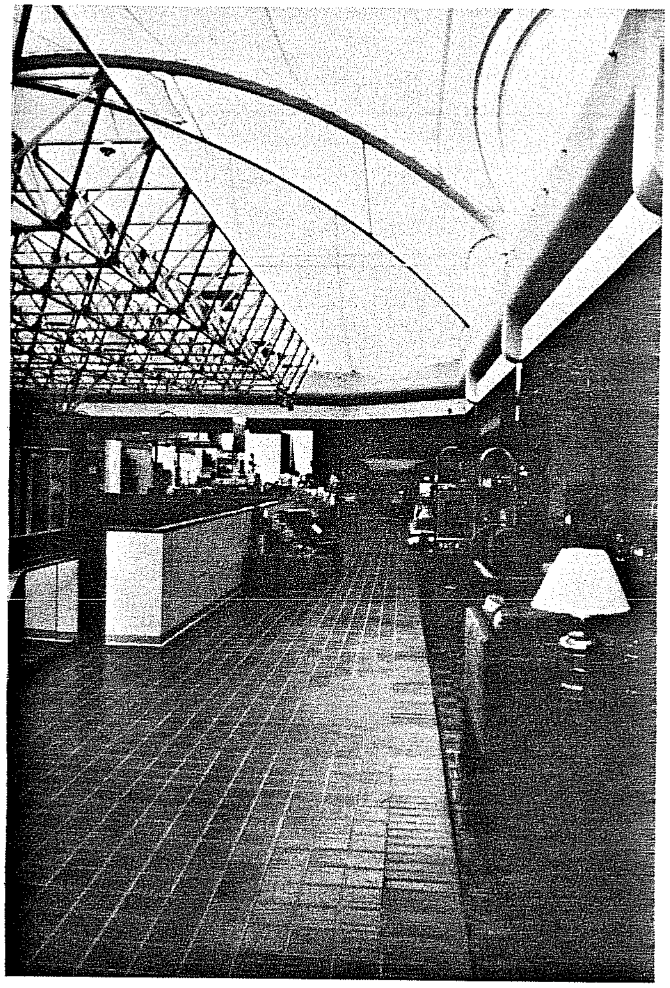
An ideal sun control will let in maximum daylight under overcast conditions and minimize heat gain and glare, while admitting adequate light under conditions when direct sunlight strikes that elevation. Roof overhangs and window shading projections shield windows from direct sun yet allow some skylight to enter. Vines and trees properly chosen and planted may act as an appropriate filter to reduce the intensity of sunlight at a window or skylight. A variety of sun control approaches and devices exist for interior and exterior applications on windows and skylights. Some of these are fixed, such as films and screens, and others are operable such as shades and venetian blinds.

Another class of device, popular in Europe, is the automatically operated, motor driven, movable exterior shading system using blinds and awnings. Equipped with photo sensors, the control systems respond to daylight levels to shield an entire building facade from direct sunlight and modulate daylight entry under a variety of conditions.

A final element of control lies in the details of room design and furnishings. Room surfaces should generally be of light colors with high reflectances. Window surrounds should be splayed so that the light gradient from window to wall is gradual rather than abrupt. Task location and orientation of occupants is still another variable. Occupants should preferably sit in the classical position with daylight coming from the side.

The daylighting contribution will not result in electric energy savings unless the electric lights are turned off or dimmed. This requires appropriate lighting control hardware and a deviation from the standard practice in building design, which in the 1960's and 1970's resulted in single switches for the entire floor in a building.

Control of electric lights must be carefully integrated with control of daylight. People will respond to light not as a photometer responds, measuring absolute level, but rather by comparing brightness at the task location and at different points of the room. If a room appears to be gloomy, the occupants may be compelled to turn additional lights on even though adequate footcandles are available for the task. It is thus essential that design for effective daylighting address qualitative issues of lighting control.



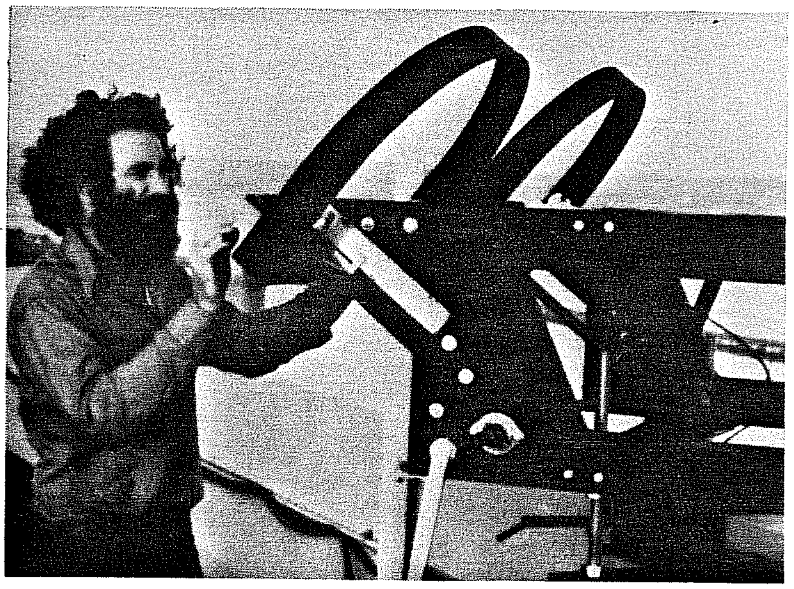
Softly diffused daylight through a tensioned fabric roof bathes the merchandising area of a Bullock's department store in San Jose, California. High daylight levels eliminate the need for electric light and are advantageous to merchandise display.

Fenestration functions

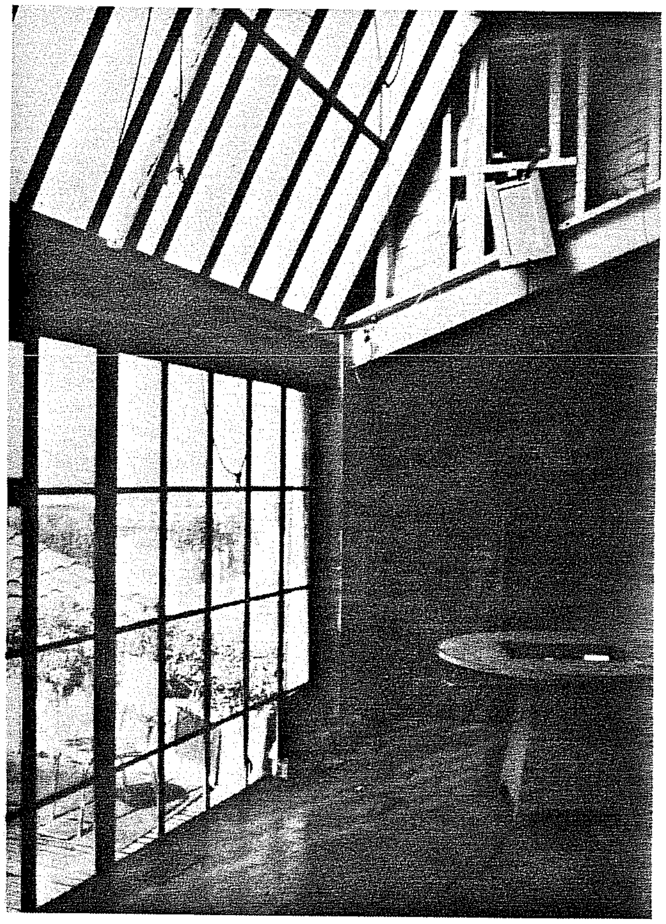
From an energy perspective, we would like to maximize useful winter solar gain, minimize unwanted summer solar gain, minimize

Data Gathering

One method to increase the availability data base for daylight would be to convert solar radiation records to illumination. In theory, this can be done if the climatological parameters of the atmosphere are known at the time of each measurement. In practice this is a fairly difficult problem, since those climatological parameters are frequently not measured. Instrumentation has been installed on the roof of a 30-story office building in San Francisco. Radiation and illumination measurements are being made simultaneously on several different surfaces to derive correlations between the two. These studies will have to be repeated at other sites to establish a more general applicability.



winter thermal loss, and maximize the use of natural ventilation opportunities and daylighting. However, it is necessary to produce adequate thermal and visual comfort under all use conditions. The technical considerations in building design for daylighting are not clear cut or apparent. As with other solar oriented architecture, shadowing obstructions must be avoided. But thermal gain is maximized with direct solar radiation, while useful daylighting may be maximized with diffuse radiation. Thus useful daylighting is available on all elevations exposed to the skyvault. However, those elevations in direct sunlight will normally require shading or diffusing devices to bring lighting intensity down to usable levels. It is clear that energy conscious design involves a skillful development of interrelationships in the first stages of site planning.



Diffuse north light is a widely recognized tradition for artists' studios. Studio space in the San Francisco Art Institute typically utilizes large north-facing glazed areas.

Through the use of roof monitors or skylights, daylight can be brought to any part of a single story building, imposing few restraints on horizontal dimensions. Multistory buildings, being limited to the daylighting contribution from windows, obviously have distinct limits to the depth of the spaces.

Executives whose work day is largely consumed by discussions and conferences generally command the perimeter offices with the best daylight. Those whose work is more visually demanding, such as secretaries and draftsmen, are then relegated to the interior spaces. Daylighting design would suggest exactly the opposite.

Once the fundamental site and floor planning problems have been considered, the designer's attention turns to the treatment of elevations and in particular, the fenestration. Even with the architectural vocabulary limited to clear glass and solar shading devices, the solutions are not always simple. However, the wide variety of architectural glass available today offers a practically unlimited range of design solutions. The thermal and lighting requirements of the building in relation to the local climate will, nevertheless, narrow that range of options. Since most office buildings are interior load dominated, the norms of residential passive design don't always apply.

For example, it may be desirable to shade south glass from direct solar gain at all times of the year. Fixed shading projections to serve this purpose may also screen the window from the skyvault, severely curtailing daylight penetration. Other solutions may be required to diffuse or diffusely reflect the direct sunlight.

Glass on east and west elevations is always a problem in both thermal and daylighting design. Fortunately, the problem is difficult for something less than half the day. At low solar angles about the only effective solution is an opaque shading device. An operable shading device allows modulation of light penetration according to the changing outdoor light conditions. Solar reflecting glass provides a compromise that may be effective in some situations, but the low transmission of visible light severely limits its use for daylighting.

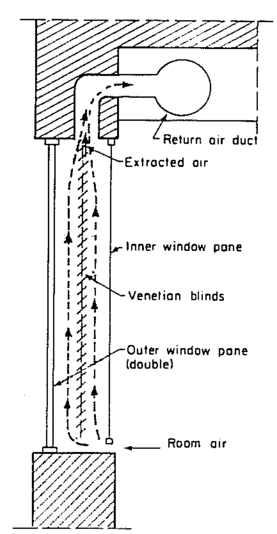
The alleged culprit of the energy crisis, north glass, is frequently the preferred location for daylighting applications. The quality of north light allows for very simple and direct fenestration treatment with clear glass. The lower first cost factored into the total energy equation makes a very attractive case for north glass if winter thermal losses are controlled. The available means to handle fenestration for solar and daylight control mostly enjoy a long tradition and are generally well known.

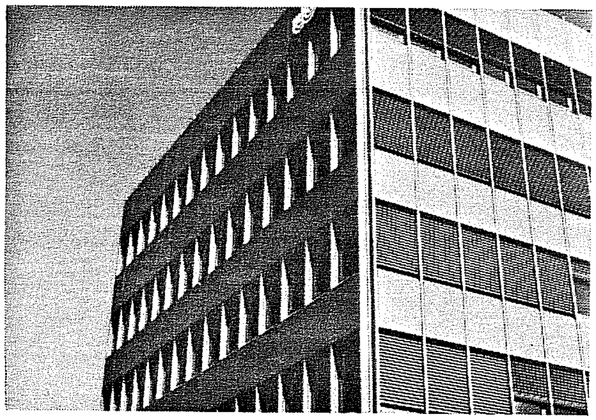
Design tools and methods

A number of different design methods exist. Each of these methods has an array of design tools, which range from simple to complex and include computational or mathematical versions. In addition, three-dimensional scale models represent a powerful design tool that may be unfamiliar to designers who have previously concentrated on thermal calculations. Lighting scales exactly, and, with attention paid to geometry, size, and surface reflectance, measurements made with a scale-model building will accurately predict the expected daylight levels in the full-sized building. Physical models have two unique attributes, which cannot be duplicated with any calculation technique. The first is the ability to assess with the human eye the aspects of lighting quality within a

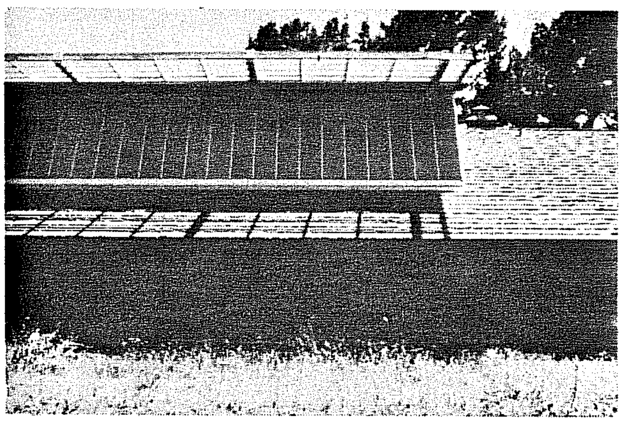
European Approach

One approach to fenestration has been applied in Europe but is not well-known in this country. It is called the air flow window or exhaust air window. Instead of using sealed double glazing, a flow of room air is introduced in the cavity between the glazing panes. Venetian blinds are installed in the cavity, which serve the conventional function of modulating sunlight and daylight. By intercepting direct sunlight, the blinds serve as a solar collector surface. The moving air stream transports the thermal gain for redistribution, storage, or rejection. Solar gain can thus be controlled while clear glass is used for its daylighting advantage.

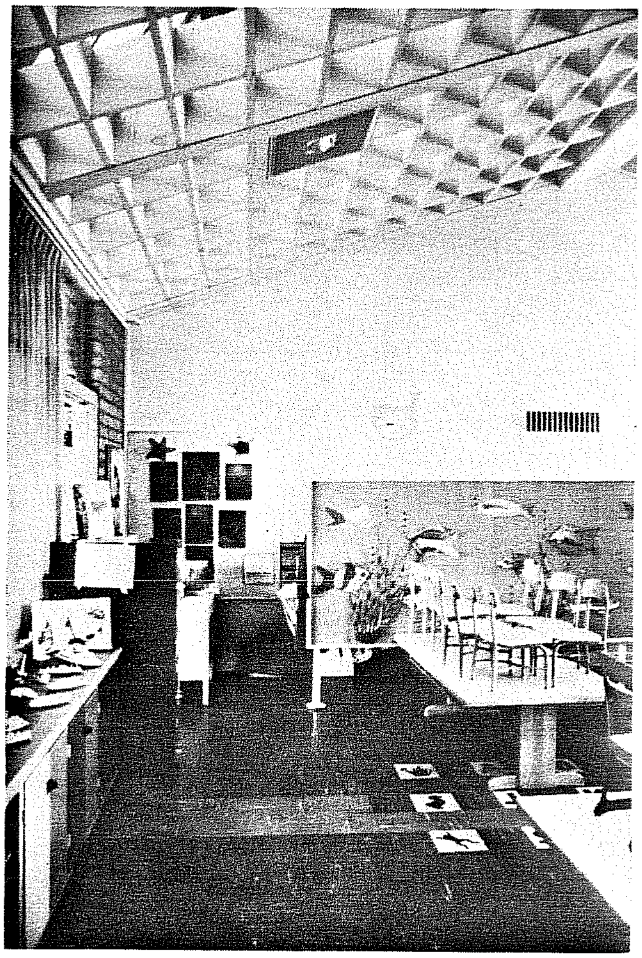




Exterior venetian-style blinds manufactured by Nichols-Homeshield, Inc., 1000 N. Harvester Road, West Chicago, Ill., under license agreement with Emil Schenker A G of Switzerland have a convex slat with rolled edges. When the blinds are at 37° position, glare and heat gain are reduced while an outside view is retained.



An exterior view of Mira Vista Elementary School in El Cerrito, California, shows the skylight and exterior solar screen.



Daylighting design for schools produced many innovations during the 1950s. In the Mira Vista Elementary School, daylight is diffused through a grid in the classroom ceiling. The grid, in addition to diffusing the light, reduces light contrasts that might cause visual discomfort.

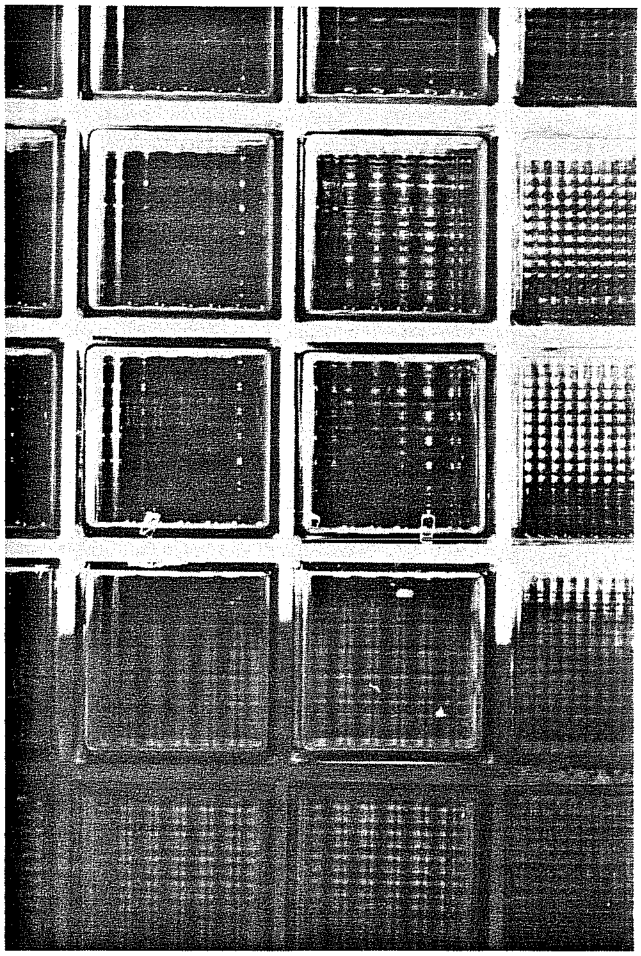
space. Second, in circumstances where novel designs use both diffuse skylight and direct sunlight, there are no existing computer models for modeling performance, nor is it likely that such models will be worth creating. Physical models provide solid quantitative data, which can be obtained in no other way.

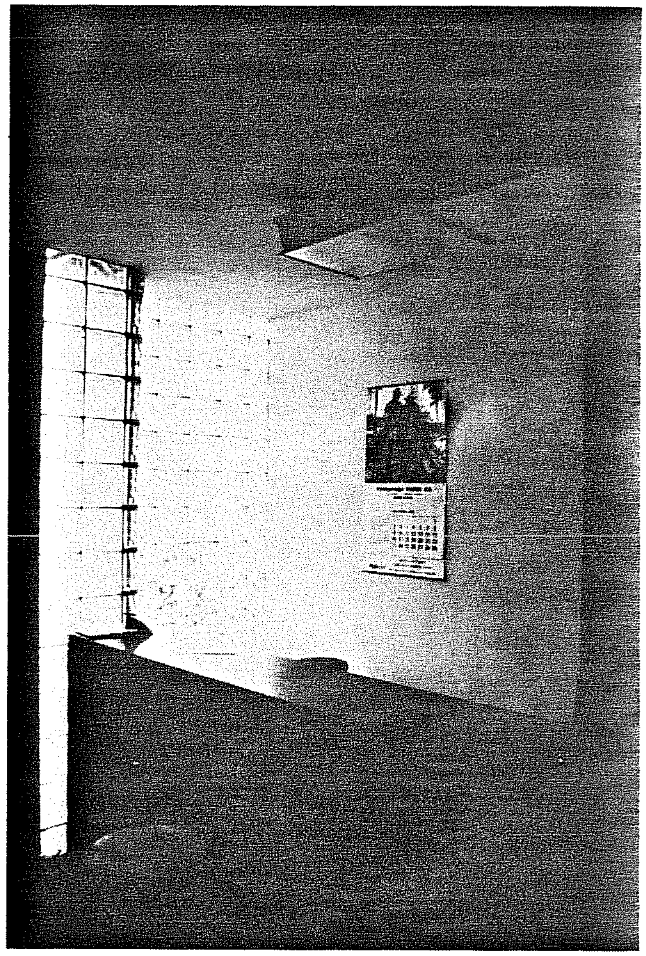
Model measurements may be made outdoors under actual sky and site conditions or indoors under controlled conditions. To compare results in an outdoor model measured on Monday with results measured on Tuesday, one needs to compensate for any difference in the sky and sun conditions when the model measurements were made. In practice, it is fairly difficult to adjust for these changing conditions. A controlled source of light to substitute for skylight and/or sunlight, and measurements with the model under these controlled conditions can be provided with an artificial sky. Although several artificial skies were used extensively in the United States in the 1950's all were abandoned or dismantled. A 24-foot-diameter hemispherical sky has been completed recently at the Lawrence Berkeley Laboratory. The sky is designed to model both overcast and clear sky conditions and will accept a sun simulator to produce the effects of direct sunlight on models.

There are three major approaches to predicting quantitative levels of daylighting in a building using various mathematical or graphic techniques. The lumen method is the approach most commonly used in North America. In this method precalculated room coefficients are used in conjunction with the availability data to predict daylight levels in the back, middle, and front of the room. The method was based on model studies and can account for both clear and overcast skies as well as shading devices and overhangs. Its weakness is that it assumes a strip window across the wall and thus cannot predict changes in daylight distribution along a direction parallel to the wall or as window locations change.

The second approach is called the daylight factor method. In this approach daylight levels within a building are expressed as a percentage of the daylight available from the sky only on a horizontal surface outdoors. Typical values in a room range from 0.5-10 percent. This method was developed in Great Britain under typically overcast sky conditions and thus does not allow for other sky conditions although new work is attempting to extend the procedure to include clear skies. The method can handle obstructions but does not account for losses from various types of shading devices such as venetian blinds. The daylight factor method has been transformed into a series of different types of calculation aids. In some cases it is a matter of simply looking up values in tables. In other cases protractors are placed on floor plan and elevation drawings and allow the value of the daylight factor to be read directly. Neither the daylight factor method nor the lumen method adequately deals with unusual situations such as direct sunlight reflected off light shelves.

Another approach involves the direct use of computers to calculate the illumination at a point directly from first principles. Computer programs such as these also calculate illumination in rooms based upon artificial lighting systems. Although these are computationally powerful, in general, their accuracy is limited by the input data that they require.





Glass block both diffuses light and provides thermal insulation. Glass block design varies for different applications. Some blocks include a series of internal prisms that redirect beam components for deeper space penetration. This small storefront in Berkeley, California, exemplifies the widespread application of these blocks in an earlier era.

Lighting controls

On/off controls are the simplest kind of lighting controls. On/off controls would seem to work best in perimeter private offices or where a limited number of individuals share the same small office space. Their use becomes somewhat more difficult in a large open landscape area where many people share the same lighting source. We immediately run into the problem of whether on/off controls should be automated or manually controlled. Automatic operation has the advantage of routine operation according to programmed requirements whereas manual control is effective only part of the time. However, manual control allows the user to determine the proper conditions under which light should be turned off, rather than a sensor in the ceiling, which does not always react as intelligently as the human eye-brain combination. Dimming control systems provide more gradual adjustment in electric light output and are generally more appealing to office occupants. However, the hardware is somewhat more complex and expensive, and at this time there are only limited options available. New developments with the electronic ballasts for fluorescent lights should change the situation over the next few years. In general dimming controls will save significantly more energy than on/off controls. There will be many hours when a dimmable system will be operating at less than full output while an on/off system would be on and operating at full output. The smaller the fenestration area and the higher the design footcandles level desired indoors, the greater the difference in savings between dimming and on/off systems.

Daylighting, along with other solar-oriented considerations in building design, is a longstanding tradition broken only in our brief era of low-cost fuels. This historical precedent in conjunction with currently available technology in electric lighting and control hardware offers the potential for both energy savings and more humane building design.

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