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EFFECTIVE DAYLIGHTING IN BUILDINGS

PARTS I AND II

Stephen Selkowitz

Lawrence Berkeley Laboratory
University of California
Berkeley, California 94720

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DAYLIGHTING

Effective daylighting in buildings—part 1

"Skills in daylighting design analysis have been rediscovered after 20 years of dormancy, but the experience which must temper knowledge to produce effective results is frequently lacking."

Stephen Selkowitz

Lighting accounts for about 20 percent of total electrical energy consumption in the United States or 420-billion Kwh per year. This represents over 5 percent of total national energy consumption and is approximately equivalent, in terms of daily energy consumption, to the total output of the Alaskan oil pipeline. Growth in lighting power demand also places a strain on utility companies, which must site and build new electric power plants. Reductions in lighting energy consumption and associated peak power demand are thus essential elements of a national energy program to reduce our dependence on energy supplies which are associated with political or environmental liabilities.

The winter of 1973–74 saw many lights extinguished in response to an energy shortage. Energy conservation in lighting became associated with delamping, which in turn was reviewed as "doing without," and a sacrifice in the quality of living or working environments. Energy conservation practices, however, can provide equivalent or improved visual performance and visual comfort while producing substantial energy and power savings. Four different elements in this process can be identified: 1) substitution of efficient lighting systems and components for less efficient products; 2) improved lighting design practice which eliminates wasteful energy use; 3) improved operation and maintenance of lighting systems; 4) and a return to a partial reliance on natural lighting techniques and practices.

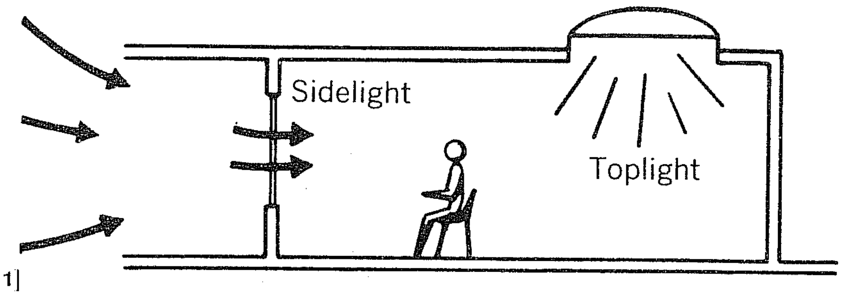
Prior to the introduction of the electric light, the best light available in buildings for visual tasks was daylight. Candles, kerosene lamps, and gas lamps must have run a distant second to daylight as a source for indoor illumination. Incandescent lamps represented a major improvement over open-flame sources, but were not capable of achieving illumination equivalent to daylight in commercial buildings because of their low luminous efficacy. At about the time that incandescents gave way to fluorescents in commercial buildings, other trends such as rising urban land costs, the advent of building air conditioning systems, and low-cost electricity combined to eliminate daylight as an essential element in building design. As a result, there has been little serious interest or activity in daylighting in the United States during the last twenty years.

International events and the resultant "energy crisis" in 1973 forced a modest reexamination of energy use patterns in the building sector. Early energy conservation checklists advocated "increased daylight utilization" without indicating how, or in what circumstances, one could expect to achieve significant savings. The same checklists, without concern for apparent contradictions, typically advocated reduction or elimination of window area as well. Five years later one finds an in-

The author: **Lawrence Berkeley Laboratory**, Berkeley, Calif. Part 2 of this article will appear in the March issue of LD&A

creased awareness and interest in daylighting but little that indicates daylighting design has yet found a comfortable niche in professional design practices.

As architects and engineers focus on thermal load reductions, lighting looms as the single largest energy consumer in the building. A renewed interest in daylighting has generated claims of very substantial energy savings in newly designed, energy conserving office buildings. Although the potential exists, it is not obvious that projected savings can be fully realized. Skills in daylighting design analysis have been rediscovered after 20 years of dormancy, but the experience which must temper knowledge to produce effective results is frequently lacking. It is the intent of this article to continue the process of raising and exploring issues relating to daylight utilization with the ultimate goal of achieving substantial reductions in electrical energy use through good daylighting design.



[1]

Commercial sector focus

Natural lighting serves several important functions in buildings. Architects have long recognized the visual power of a shaft of sunlight penetrating a dark church sanctuary or the visual beauty of a stained glass window. Our concern here is for more pragmatic use of natural lighting to offset electrical lighting requirements in commercial and industrial buildings. The primary focus in the commercial and industrial sector is office buildings, schools, commercial low-rise, and warehouses. These building types are characterized by: daytime use patterns, long hours of lighting use, relatively high lighting levels and high installed watts/ft^2. Lighting is thus a significant energy consumption factor in most of these building types and represents a large fraction of total building utility costs.

We pointedly ignore the potential daylighting savings in the residential sector for a number of reasons. Lighting energy consumption per house is typically quite small; on the order of 10 percent of household energy consumption. There is thus no strong financial incentive to conserve energy in the household lighting sector. Although 95 percent of typical household lighting is incandescent, with low lumens per watt, the hours per year of use are typically small. Light levels are quite low and occupancy per unit area is very low. Thus, energy consumption per ft^2 is much smaller than for most commercial sector uses. Visual tasks in the home are frequently not fixed in one place. This gives the occupant the ability to move nearer a window if daylight levels are not sufficiently high in a given location. Although we downplay the significance of daylight savings in the residential sector, one must add a note of caution regarding current building code trends, which tend to restrict window size in new residences. Overly simplistic thermal codes may restrict window size to the point where occupants are forced to use lights during the day. Well-designed and managed windows in the home should be acceptable on a thermal net balance alone if window management techniques are practiced and useful solar gain is considered. Thus, although total lighting energy consumption in the residential sector is significant, a number of factors suggest that the commercial sector is a more appropriate focus for a renewed interest in potential daylighting savings.

Daylight/sunlight

Natural lighting techniques encompass both the use of diffuse light from the sky, or daylight, as well as beam radiation from the sun, or sunlight. In addition, we consider both *side lighting* techniques or the use of natural light through windows, and *top lighting* or the use of skylights in buildings **(Fig. 1).**

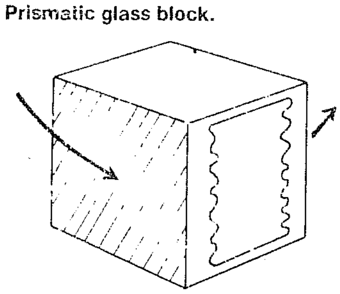
Side lighting through windows typically utilizes diffuse radiation only. Direct solar gain, although occasionally pleasant, typically leads to overheating and thermal discomfort. Daylighting levels from windows in one wall of a room fall off rapidly as we move deeper into the room, away from the window wall. A typical practical limit for daylight penetration into an office is 15 to 20 ft from the window wall. Some techniques are available for extending the depth of this perimeter zone.

Glass blocks have been used extensively to direct sunlight deeper into rooms to complement diffuse light near the windows **(Fig. 2).** Glass blocks often have ribs which provide some degree of light control for daily and seasonal variations in solar elevation and azimuth. Even deeper light penetration can be achieved by controlling sunlight directly. One concept which we call "beam sunlighting" involves reflecting direct rays from the sun from silvered reflective venetian blinds mounted in the upper two feet of a typical window.[1] The reflected rays are aimed towards the ceiling of the room to a maximum depth of approximately 30 to 40 ft **(Fig. 3).** The ceiling then acts as a diffuse reflector, providing normal diffuse illumination deep inside the room. Although the lighting quality achieved by such a scheme is satisfactory, the control of reflected light as sun angles change is a significant problem. A variety of controllable reflecting or refractor-type devices have been examined, but the real issue is one of simplicity and low cost in these devices, without sacrificing the potential performance. In addition, more sophisticated lighting controls are required for partly cloudy sky conditions, in which case the sun's intensity will change sharply over very short time intervals. This concept appears to have only limited applications in existing buildings because of window and ceiling design characteristics, and problems with shading from adjacent buildings and other obstructions. However, new buildings specifically designed with this application in mind, might realize substantial energy savings.

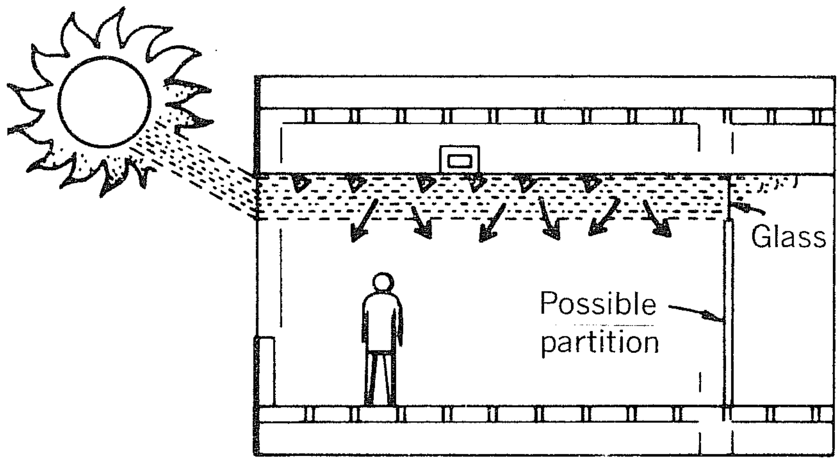
Skylights

Although skylights have been designed historically to exclude direct sun (for example, sawtooth designs or skylights with overhangs), most modern skylights lay flat in the roof plane and thus accept both direct and diffuse radiation. Light distribution within the space is significantly more uniform than with side-lighting applications. Although conventional skylights are limited to providing daylighting in one-story spaces or multistory atrium spaces, several concepts have been published utilizing direct sunlight accepted through an aperture on the roof and then distributed throughout the

[2] **Prismatic glass block.**



|3| **Cross-section of typical office space (south perimeter location) showing position and operation of beam daylighting apparatus.**



building with a series of mirrors, lenses, and other optical controls.[2] Although such schemes are technically feasible, their optical performance requirements and complexity make their use impractical.

We have thus argued for limiting the primary interest in daylighting applications to the commercial and industrial building sectors. In offices and schools with windows we are primarily interested in diffuse daylighting applications, and in single-story warehouses or low-rise retail buildings our interest is in conventional skylighting techniques.

Issues

Although the potential energy savings are significant, effective daylighting design requires that time and effort be expended to solve a series of problems and issues which currently act as obstacles to the widespread use of daylighting. There is a real danger in believing that good daylighting practice simply means the use of large windows and that use of large windows guarantees significant energy savings. Four major issues must be confronted before daylighting practice can be widely implemented in this country: 1) analysis and design techniques, 2) thermal/illumination tradeoffs, 3) sun and glare control, and 4) lighting controls. In addition, there are other issues relating to daylight design which we discuss at the close of this article.

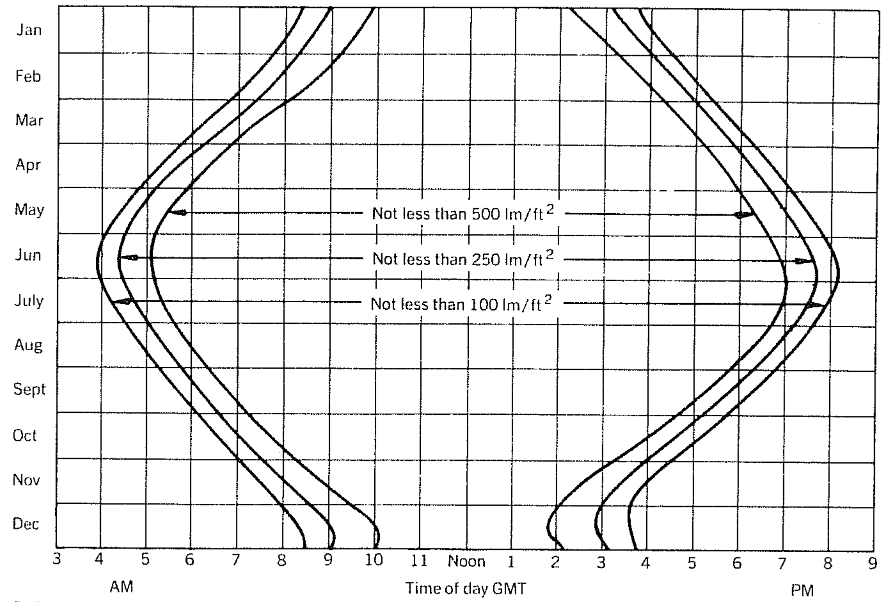
Analysis and design

Ask a building designer today how to design a room to provide 50 footcandles on a desk throughout 80 percent of the working hours of the year using daylight and you are likely to get puzzled looks and quick shuffling through textbooks and lighting handbooks. Simply stated, there is a lack of effective, widely-used design methods in the United States today. The problem is not a lack of design methods; fifty-eight are listed in a 1970 CIE publication.[3] Most, however, were originated in European countries where cloudy skies are the typical minimum brightness conditions. In much of the United States clear sky conditions prevail and many of the techniques developed for analysis of overcast skies are not suitable for use with the variable luminance distributions one finds under clear sky conditions. Primary sources of information for daylighting design in the U.S. are the IES Recommended Practices[4] and a simplified design procedure based on the same "coefficient of utilization" approach.[5] A variety of different design methods have been and continue to be used. These include computational, graphical, tabular, nomographs, protractors, diagramatic, such as sky vault projections, and physical models. Very powerful computer models are available to compute footcandle levels and equivalent sphere illumination levels in rooms, but suffer from an inability to easily model detailed effects inside a room such as furniture placement. Although current programs are relatively costly, it appears likely that computer run time can be substantially compressed with significant cost reductions. Physical modeling techniques which are already widely used by architects for other purposes can provide a very versatile simulation of detailed conditions to be expected in a typical building. A more fundamental problem than the lack of design methods is the lack of awareness and knowledge of these design methods by practicing professionals and in the schools now training the design professionals of the future. The lack of educational programs in the daylighting design field over the last 20 years has resulted in a generation of practicing architects and engineers who now have little academic or practical experience in daylighting design. This lack of professional design experience is compounded by the lack of well documented examples of buildings incorporating effective daylighting. One can find many examples of architectural design with effective lighting, HVAC and now solar heating systems in buildings, but few if any which focus on effective daylighting solutions to building design problems.

Having selected one of several daylighting design methods, the designer must confront the lack of information regarding daylighting availability in the United States. For a given location, are the skies characterized by clear, cloudy, or partly cloudy conditions? For what fraction of the working hours of the year can one expect certain minimum sky conditions to be exceeded? Data of this type exist for many European cities but for very few locations in the United States **(Fig. 4).** Measurements, which were made some time ago, in Washington, D.C., and other urban areas are now suspect due to atmospheric changes resulting from urban air pollution and changes in other climatic variables. Rather than wait several years before such new data can be collected, it may be feasible to generate daylighting availability data from the solar radiation data now being collected throughout the United States.

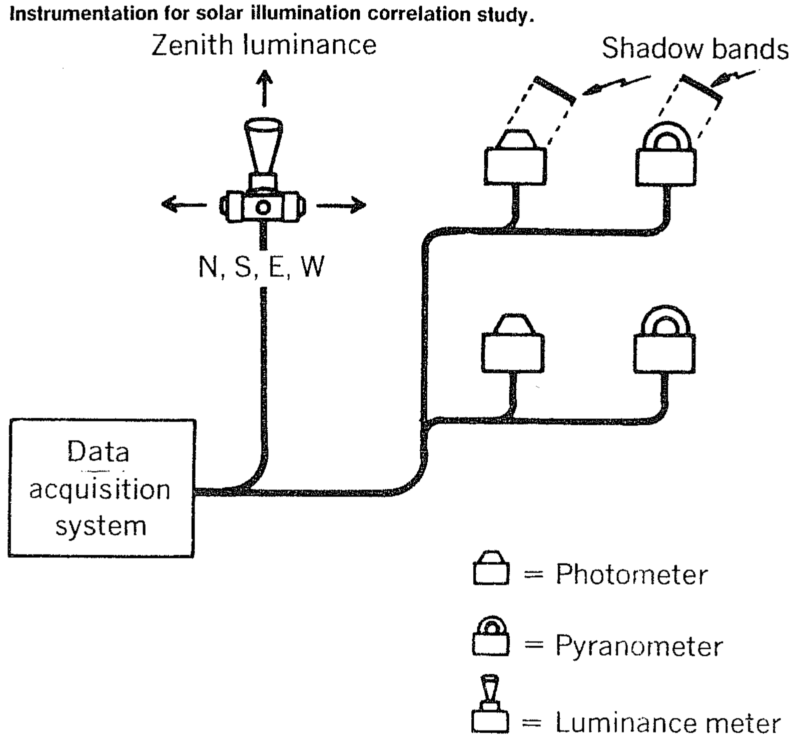
As part of a demonstration of efficient lighting systems in a building in San Francisco, we are now collecting, at 15-minute intervals, total horizontal radiation; diffuse horizontal radiation; illumination received on four vertical surfaces facing north, south, east, and west; and data from a sky luminance sensor which records sky brightness directly overhead **(Fig. 5).** These data will allow us to develop or select and then validate a computational procedure for converting the solar radiation data base into an illumination data base.

Building designs that have been optimized for daylighting use will have an impact on thermal gains and losses as well. Just as building design decisions that have been made to optimize thermal performance will inadvertently impact illumination issues, the sizing and placement of windows to maximize daylighting benefits will have thermal impacts which must be considered. A number of large computer programs are now available which will provide an annual energy analysis for large buildings. These are relatively complex programs which model building performance hour by hour throughout the year. Daylighting performance has been incorporated into several of these models in a limited way, but results have yet to be validated and at this point must



[4] **Average illumination on horizontal surface at Teddington, U.K., 51° N, 1929–33.**

[5] **Instrumentation for solar illumination correlation study.**



be considered preliminary.[6,7] A similar, but simplified, approach is available for predicting the annual performance of skylights in buildings.[8] In almost all cases, results indicate that consideration of daylighting benefits alters the determination of optimum window size towards larger windows or skylights than one would predict from a thermal analysis perspective alone. Although these general trends are predictable, there are problems and uncertainties associated with the use of the programs. The lack of validation is a major problem and the effects of some of the simplifications introduced in order to keep the computational cost to a minimum are not entirely understood. Still, it is likely that simplified daylighting models can be developed and successfully incorporated into the existing energy analysis models. The availability of such a validated computer model will have important implications for building designers who must now make decisions regarding optimization, frequently without sufficient information.

What the output from these daylighting computer models actually represents is potential savings: the amount of daylight available at the task location is computed, but not necessarily the resultant energy saved. To address the question of actual energy savings, one must know whether the lights are controlled in an on–off mode or in a dimming mode, whether that control is automatic or manually operated, how user control of window shading devices affects daylight levels in the room, how the users will respond to solar gain and glare conditions of the room, and a variety of related information. At the moment, we do not have a comprehensive understanding of these issues nor do the programs have the computational ability to address all of them in any great detail. A decision regarding the degree of detail necessary for successful modeling and simulation awaits a comparison of simplified calculation techniques and actual results in buildings.

Sun/glare control

The sleek all-glass buildings that dot most of our cities could not have been built without an array of sophisticated high performance solar control glazing systems. A whole array of sun control solutions is available to the building designer.[9] These include exterior architectural appendages: exterior sun control devices such as screens, shutters, blinds, and awnings; interior sun control devices such as shades, drapes and blinds; and heat-absorbing and solar-reflecting glasses. Reflective coatings on plastic films are available for retrofits of older buildings to reduce solar gain. Many of these materials and devices reduce solar transmission to less than 10 percent of the incident energy. A simple solution is one which is permanent and fixed: a coating on glass or plastic. The danger of this approach, however, is that it may effectively wipe out daylighting potential in a building. It is the opinion of several experts in the field that daylighted offices may require highly transparent windows which incorporate operable window management devices such as shades and blinds to control excessive solar gain.

A variety of window management devices are commercially available in the form of internal and external venetian blinds and roll-up shades and shutters. Many of these come with motorized accessories which may be automatically or manually controlled. A more extensive list of manually operated devices is available, and these will typically be less complex and less costly. There is some uncertainty regarding how faithfully they will be employed. It seems likely that office occupants will close shades and blinds to reduce excessive heat gain or glare for thermal or visual comfort. It is not clear, however, that they can be effectively motivated to operate these devices to achieve energy savings. In particular, devices that have been closed in the afternoon to reduce summer heat gain may not be opened the following morning to realize daylighting savings. Automatic controls and operators are, of course, more predictable but add complexity and cost. Recent work with venetian blinds indicates that office occupants will manage those blinds in a manner that distinguishes seasonal differences and differences in window orientation.[10] Additional studies of this type are required but initial indications are that manual operation can be effective in some building types.

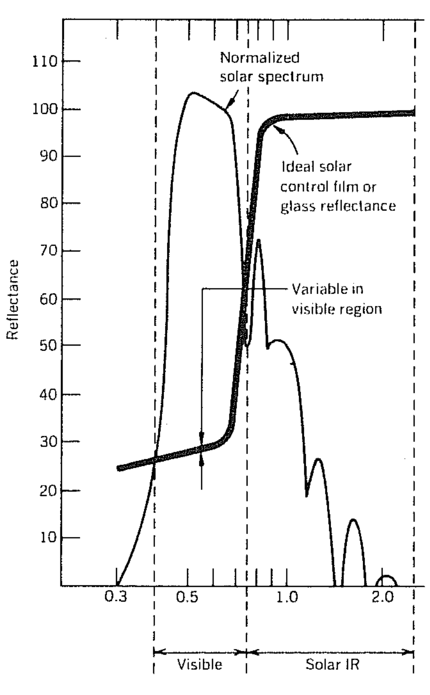
If interior and exterior shading devices are used to control excessive sun and glare, the question then becomes, what are the optimum glass properties for such a window design? Workers in a typical office have a view of the horizon or the sky in the immediate vicinity of the horizon. With standard overcast skies, the horizon is three times darker than the sky overhead. However, in the clear skies characteristic of much of the United States, the luminance distribution is inverted and the horizon is brighter than the overhead sky. Furthermore, in urban areas, haze and air pollution produce additional light scattering and thus additional glare. Since sky luminance at the horizon may be 500 to 3000 footlamberts and typical brightness in an office may be 25 to 75 footlamberts, severe discomfort glare problems may exist. Some degree of light control in glazing is probably desirable but it is unlikely that transmissions much lower than 50 percent will be desirable. Heat-absorbing and reflecting glass may also be desirable for special situations, such as sunlight reflected from water or from adjacent landscape or buildings.

The development of sophisticated glazing materials, with heat absorbing and reflecting properties, is a relatively recent innovation. We can reasonably expect to see additional improvements in the thermal and solar optical properties of glass to satisfy evolving performance demands on glazing systems. One research program being supported by the Department of Energy (DOE) is an effort to develop selective transmittance solar control coatings for windows.[11] Approximately 50 percent of the incident solar energy at a window is visible light, and the other 50 percent is invisible solar infrared heat. These selective transmitters will allow the visible to pass through the window into the room but reflect the solar infrared portion back to the outside environment **(Fig. 6)**. Coatings of this type might have light transmission values of 60 to 80 percent, but shading coefficients as low as 0.3 or 0.4. Although the concept is not new, products of this type are not available to designers today. The intent of the DOE program is to speed development and commercialization of such products and put them in the hands of building designers.

A more speculative approach to solar control in glass is the possibility of developing coatings that cause glass to act as an optical shutter, admitting light when it is desired and rejecting it when it is not wanted **(Fig. 7)**. The concept here is to take window management down to an atomic or molecular level. Similar types of coatings exist today, in the form of liquid crystal watch displays that switch from transparent to reflective, or the phototropic sunglasses which change optical density as a function of the ambient light environment. There are severe problems of product cost, lifetime and durability, but if such a product can be developed it would add greatly to the designer's bag of tricks in solving glare and sun control problems associated with daylighting design.

In summary, the building designer must balance requirements for sun control and glare control against the necessity for relatively high light transmission to achieve adequate daylighting in buildings. A variety of automatic and manually operated sun control devices are available to the designer although user response and actual product performance is not well defined. If undesired solar gain is not effectively excluded from a daylighted room, resultant cooling energy consumption may reduce or eliminate daylighting savings.[12]

[6] Ideal selective reflective coatings.



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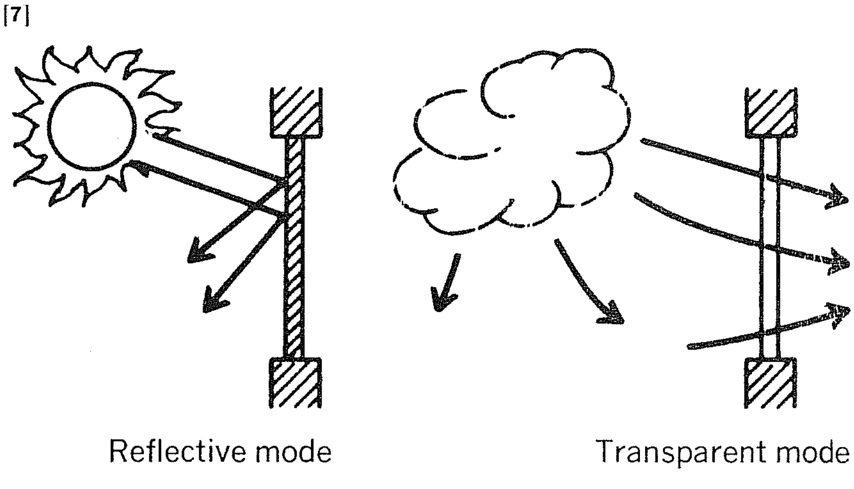

Acknowledgement

This article is an expanded version of an informal presentation made before the Ad Hoc Daylighting Review Panel, which met at Lawrence Berkeley Laboratory (LBL), November 9 and 10, 1978, to review the state of the art in daylighting activities in the United States. LBL plans and manages the U.S. Department of Energy's program in the area of energy-efficient windows and lighting systems, and is responsible for developing programs to assist in the widespread utilization of daylighting design techniques and practices.

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DAYLIGHTING

Effective daylighting in buildings—part 2

Controls, energy savings, peak power, failure tolerance, building form, and quality—all are considerations in designing with daylight

Stephen Selkowitz

Lighting controls

With effective window design and intelligent use of sun controls, good daylight distribution may be achieved in indoor spaces. Visibility will improve but no energy savings will occur unless lights are turned off or dimmed. Lighting controls are capable of saving significant quantities of energy even without consideration of daylighting. Lighting systems can be controlled over both space and time to achieve these savings. DOE's "Energy-Efficient Lighting Program" currently includes two demonstrations of the effectiveness of more sophisticated lighting control systems in typical office buildings. These systems are designed to provide more flexible user-control of light output and to prevent energy waste from overdesign required by lighting maintenance schedules and lamp lumen depreciation. One system also employs photosensors and will be capable of achieving savings in daylighted offices.

There is a tremendous range in control system performance, complexity, and cost. The simplest such systems are of the on–off type. These are readily available as off-the-shelf items at low to moderate cost. On–off switching has predictable results on fluorescent lamp life. There are potential problems with user acceptance due to the relatively sharp change in lighting level as one or more fixtures are switched on or off. Experimental results on this issue are mixed. On–off switching can be handled on a circuit by circuit basis, fixture by fixture, on individual ballasts within a single fixture, or with the use of multilevel ballasts. The latter options, although involving more expensive switching and control systems, provide effective multilevel capability, which may reduce the undesirable user response to on–off systems.

Dimmable systems are typically more complex and more costly than on–off controls.

Part 1 of this two-part series (Feb. *LD&A*, p 6–11) focused on natural lighting techniques in the commercial sector, emphasizing skylights and sun/glare control. The author is associated with **Lawrence Berkeley Laboratory**, and the article is an expanded version of a presentation made before the Ad Hoc Daylighting Review Panel, which met at Lawrence Berkeley Laboratory (LBL), November 9 and 10, 1978, to review the state of the art in daylighting activities in the United States. LBL plans and manages the U.S. Department of Energy's program in the area of energy-efficient windows and lighting systems, and is responsible for developing programs to assist in the widespread utilization of daylighting design techniques and practices.

This work was supported with funding provided by the Assistant Secretary for Conservation and Solar Applications, Office of Buildings and Community Systems. The views expressed in this paper are those of the author and do not necessarily represent the views of Lawrence Berkeley Laboratory, the University of California, nor the U.S. Department of Energy.

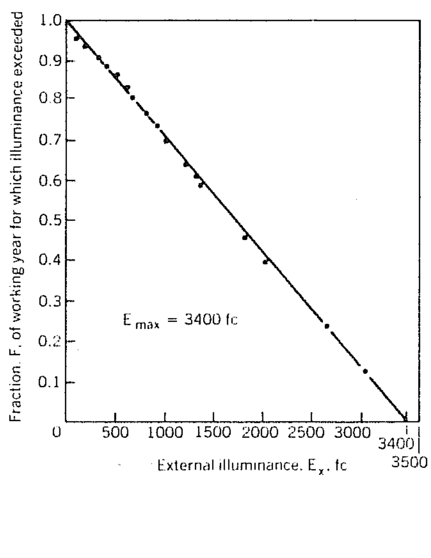
Although dimmable fluorescent systems are available for specialty applications, there are currently no widely-specified dimmable fluorescent systems in use in this country. Dimming need not be of a continuous nature. Multilevel step dimming, if the steps are sufficiently small, should avoid the user acceptance problems described with on–off controls. A new generation of fluorescent ballasts promises to provide dimming at little incremental cost. These solid-state electronic ballasts are now under development by a number of firms in the United States and are the subject of a DOE development and demonstration program.[1] They should begin appearing on the market in the next one to three years. The high-frequency electronic circuits lend themselves easily to dimming capability. As sales volume increases and the electronic ballast incorporates integrated circuits, we can expect prices to fall to levels characteristic of premium ballasts today. The electronic ballast provides not only energy savings when compared to the conventional core ballast, but an important dimming and control capability as well.

The DOE ballast demonstration includes a floor in a typical office building that has been retrofit with dimmable ballasts in both perimeter and interior offices. A variety of experiments are planned to determine optimal use of these dimming controls. For example, should photocell sensors be placed on the ceiling looking down? On the window looking out? On the work plane looking up? And in single or multiple locations? Photosensors may require time delays to prevent them from being fooled by a transient reflective object in a room, yet, must be sensitive enough to respond to changing cloud conditions that can result in rapidly varying daylight illumination within a room. All of these issues are solvable but we lack the experience to confidently answer them at this time. It should be noted that controls problems in skylighted rooms or offices are considerably simpler than the complexities of controlling sidelighted offices.

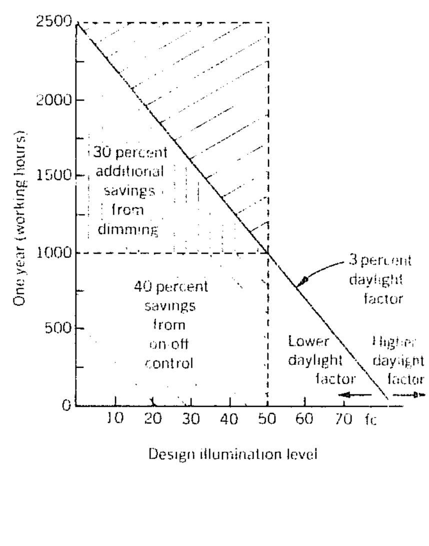
Given either a dimmable or on–off system, controls can be actuated either manually or automatically. Manual controls are flexible, combining sensitivity and judgment at their best, and are fallible, characterized by neglect or laziness at their worst. The main danger is simply that the switch or control will be forgotten and unused. Prior experiments have suggested that occupants, if given the opportunity of setting their own artificial light levels in a daylighted room, will select even higher artificial light levels than in a room without windows, apparently in an attempt to match the perceived brightness outdoors. Automatic controls will be more reliable but must be kept simple enough to avoid adding substantial additional complexity and cost to the lighting system. Microprocessor-based controls provide the capability of virtually unlimited control options, but may represent overkill in simple office environments.

The selection of dimming versus on–off switching and controls may have a significant effect on the actual energy savings achieved in a given building. Recent work at the Building Research Establishment in England has provided a procedure for determining the daylighting savings with either dimming or on–off controls.[2,3] These findings are reviewed here because of their significance to lighting control design in the United States. To compute the energy savings resulting from any type of control system, one must develop information regarding the percentage of time that various daylight levels are achieved in the space under consideration. The English have used the "daylight factor" concept, which gives the ratio of internal illumination at a position in a room to the external horizontal illumination from the sky measured at the same time. The daylight factor thus tends to be high in the vicinity of a window and falls off as one moves deeper into a room. Given availability data for the outdoor horizontal illumination available during working hours throughout the year, the daylight factor allows immediate determination of the internal illumination. A typical plot of measured footcandles outside versus percentage of the daylight working hours is shown in **Fig. 1**. Given the availability data, the daylight factor for a chosen point of the room, and the interior design illumination level, we can proceed to examine the relative savings from on–off and dimming controls. **Figure 2** shows the number of hours per year that various internal illumination levels are equalled or exceeded for a 3-percent daylight factor. Assuming that lighting is required 2500 hours per year, and that 50 footcandles are selected as the interior illumination, the rectangle shaded in the figure is proportional to the total energy consumption required for an all electric lighting system. This is possible since the 50-footcandle design value can be equated with power consumption per square foot. Note that the #3 daylight factor line intersects the design illumination value at 1000 hours, indicating that 50 footcandles is exceeded indoors for 1000 hours of the year. An on–off switch would thus be in the off mode for 1000 hours and on for 1500. The total savings would thus be 40 percent of the lighting energy consumption for an all-electric system. For the same 1000 hours a dimmable system would be off as well, saving the same 40 percent. However, as the interior illumination drops below the design point (50 footcandles), the dimming system acts in an incremental mode. It provides just enough light to raise the level from that provided by daylight to the desired 50-footcandle level. For example, when 30 footcandles are available from daylight, the dimming system adds an additional 20 footcandles to provide the desired 50, using 20/50 or 40 percent of the power required if daylight was not available. If the dimmable system has a linear light power curve, then the energy saved is shown by the shaded triangular section in the figure. This represents an additional 30 percent of the energy requirements from an all electric system. In this example, the dimmable system saves nearly twice as much energy as the on–off control system. Note from the figure that as the daylight factor is reduced, its in-

[1] Fraction of working year for which external horizontal illuminance, excluding direct sunshine, is exceeded (From reference 2).



[2] Daylighting savings as a function of type of light control.

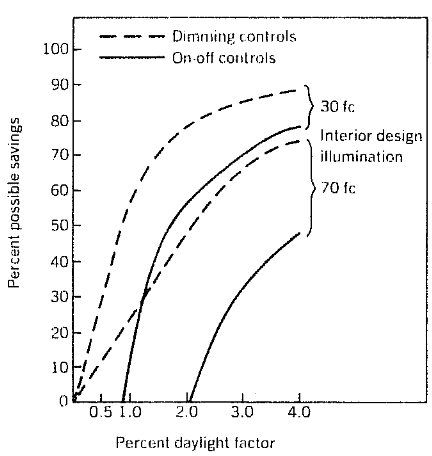


tersection point with the horizontal axis moves to the left. The illumination level at that intersection point is the peak interior illumination level resulting from daylighting experienced in the space. For design illumination values greater than or equal to the illumination at the intersection point, an on–off system will save no energy at all. However, a dimmable system will still save electrical energy proportional to the shaded triangular area beneath and to the left of the daylight factor line. These results are replotted in **Fig. 3.**

Figure 3 illustrates the savings from both dimmable and on–off systems relative to the maximum possible savings for two choices of interior design level and as a function of daylight factor. One concludes that with high daylight factors there is typically little difference between the on–off and the dimmable system. But at low daylight factor the differential energy saved by dimmable systems is substantially higher than from the on–off. In addition, as we select higher interior design illumination levels, dimming also becomes relatively important. This emphasizes the importance of selecting an appropriate illumination level. If an excessively high level is chosen, daylight savings will be minimal. It also suggests that the qualitative improvements in daylight be considered. Fewer footcandles of sidelight from windows will prove equivalent visibility to higher footcandles from a typical ceiling lighting system. Note also that we have neglected direct sunlight and externally reflected sun contributions to the interior light level. These should make the savings shown in **Fig. 3** conservative.

The appropriateness of various on–off or dimmable systems is also a function of the space occupancy and the type of commercial or industrial activity. Perhaps the simplest

[3] Daylighting savings with dimming and on–off controls for two levels of interior design illumination.



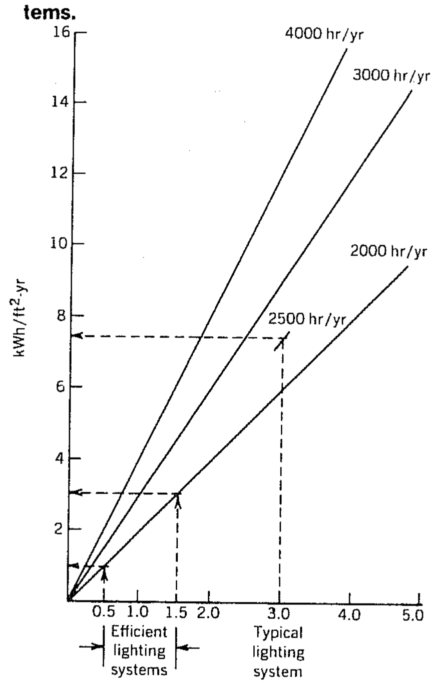
example is a warehouse employing skylights distributed across the roof. Here we can provide relatively uniform daylighting over the entire space with a simple control system due to the uniformity of daylight distribution. With sidelighting from windows in offices, the daylight becomes significant. In small offices work stations should be oriented such that the occupant faces parallel to the window to reduce glare. Light from the side provides good contrast and high visibility. With one or two occupants in a small office there should be no argument over preferred levels and the controls can be kept simple. Both ambient and task lighting levels can probably be achieved with daylighting. In a larger office we find deep bays and open landscape furniture systems. It is no longer convenient to orient all tasks appropriately to the windows and daylight levels deeper in the room may never be suitable for even average office tasks. However, in such a situation daylight may provide good ambient light levels throughout much of the year. In this case, task lighting might be provided as a permanent supplement to the ambient level provided by daylight. A relatively simple control system can then be used to control an artificial system which provides backup ambient light, while each office occupant controls the task lighting at individual stations. Given hardware costs for various types of lighting control systems, an analysis of the type shown in the previous section will reveal whether a specific control system is cost effective in achieving daylighting savings in this or other office situations.

Energy savings

It is instructive to examine the actual magnitude of savings that can be saved utilizing daylighting techniques on a dollar-per-square-foot basis. Electrical energy consumption for lighting is shown in **Fig. 4** as a function of installed watts-per-square-foot and hours-per-year use. At 3 watts/ft^2 installed power with 2500 hours per year of use we predict a consumption of 7.5 kWh/ft^2/yr (as shown in the figure). From the previous section, savings of perhaps 10 to 75 percent are realizable with a well designed daylighted system incorporating on–off or dimmable controls. We can thus save 1 to 6 kWh/ft^2/yr, which has an economic value of \$0.05 to \$0.50/ft^2/yr. In large buildings these savings become significant in absolute dollar value. However, we must also compare daylighting savings and cost effectiveness to the use of more efficient lighting systems, which will also reduce electrical consumption.

A daylighted system compared with a very efficient electrical lighting system may save

[4] Annual lighting electrical energy consumption with typical high-efficiency systems.



the same percentage in energy but will result in a lower kilowatt value and therefore lower dollar savings. Task ambient lighting systems are now available that operate in the range of 1 to 1½ watts/ft^2 installed power. With electronic ballasts and improved fluorescent lamps with improved phosphors and higher efficacy, and smaller HID systems with improved color rendition, we can expect to see lighting systems indoors with efficiencies of 100 lumens per watt, roughly a 50 percent improvement over the typical 65 lumens per watt achieved now with conventional fluorescent systems. Improved lighting controls of a conventional nature as well as nonuniform lighting practice will further reduce electric energy consumption. With these changes lighting energy consumption could be reduced from 7½ kWh/ft^2 to a level of 1 to 3 kWh/ft^2 per year. The savings of ½ to 2 kWh/ft^2 per year which we now achieve with daylighting is much less impressive than the original case, representing an inefficient electrical lighting system.

Daylighting in buildings, however, has merit beyond mere energy savings. Even if good lighting design and hardware efficiency improvements reduce the electrical energy consumption so low that daylighting provides only small effective savings, there are several important reasons to continue to push for its widespread use. These taken together may represent a more powerful mandate than the energy savings we expect can be generated in daylighted buildings.

Peak power

Residential consumers pay for the electrical energy consumed, which represents barrels of oil burned or its equivalent. Commercial sector firms not only pay for energy consumed but also pay for their peak power demand from the utility network. Charges for peak power demand may represent a significant fraction of a firm's total electric bill. For utilities with summer peaking profiles, power demand for lighting in a building will be coincident with system peaks and thus a contributor to utility system peak loads. Lighting adds to the utility peak demand, which has become increasingly difficult to satisfy. Many utilities are now implementing selective rates through time-of-day pricing policies to penalize use of energy during peak load periods. The significance of peak power issues relative to energy savings can be seen in the following example.

Consider a typical all electric office building in which 30 to 50 percent of energy consumption results from lighting. Assume that one-third of the usable floor space is in the perimeter zone in close proximity to windows. The maximum potential daylighting savings is thus one-third of the 30 to 50 percent, or 10 to 15 percent of total energy. If 50 percent of the potential is actually achieved with dimming controls, daylighting can save roughly 5 to 8 percent of total building energy consumption. Examine the peak load problem. Under summer peak conditions, typical cooling loads amount to 5 to 10 watts/ft^2, of which perhaps 3 watts/ft^2 represents lighting. With a net COP of 2, the cooling power requirement is then $2\frac{1}{2}$ to 5 watts/ft^2. Under peak load conditions if we turn the lights off in one-third of the building floor area in which daylighting is adequate, we have reduced the power consumption of the building by one-third times 3 watts/ft^2, or 1 watt/ft^2 average throughout the building. There is an additional saving of $\frac{1}{2}$ watt/ft^2 resulting from a reduction of cooling power requirements. Under these circumstances $1\frac{1}{2}$ watts/ft^2, or roughly 10 to 20 percent of building peak power is saved.

The cost of new power plant construction is frequently in the range of \$1.00 to \$2.00 per peak watt of installed power. In a new building, a 150-ft^2 office with lighting at 3 watt/ft^2 requires an investment by the utility of \$450 to \$900 in new generating capacity if the lighting is a contributor to utility system peaks. It appears that responsive dimmable controls could be installed in such a perimeter office for considerably less money than the utility investment to supply electricity at periods of peak demand. Thus, good daylighting design and effective lighting control systems not only save energy, but reduce the pressure for development for new electrical power generating resources.

Failure tolerance

Although electrical supply is adequate in most parts of the United States, we have recently witnessed the effects of citywide, statewide, and regional power system failures. Daylighting is a design option which, at the scale of a single building, reverses the trend toward greater reliance on remote centralized systems. As such, it has a flexibility and degree of failure tolerance that appear to be important but which are difficult to quantify. Activities in a building with daylighting will be less subject to disruption from a power failure or brownout than those relying entirely on electricity for illumination. It *is* possible to quantify effects of disruption on worker productivity. High light levels have been sold on the basis that the value of worker productivity is very high relative to the cost of energy to maintain those light levels. Assume that an office worker, with appropriate indirect costs and overhead charges added to salary, costs a company \$40,000 per year. The worker occupies a 100-ft^2 space in the building, works 250 days, thus costs \$160/day (\$1.60/ft^2-day, or \$0.20/ft^2-hour). Lighting, at \$0.04/kwhr costs \$0.25 to 0.30/ft^2/yr. As a result, savings in productivity in a daylighted office due to continuation of productive work for even a single hour during a blackout or power loss is equivalent in dollar value to an entire year's worth of energy savings.

Building form

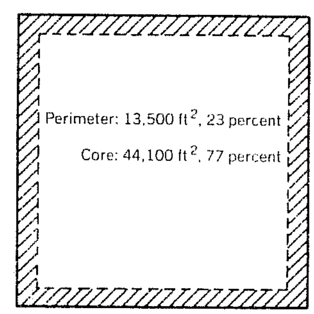
Massive buildings with a relatively small amount of usable perimeter office space and large interior windowless spaces do not lend themselves to extensive daylighting. These compact, deep-bay buildings with sealed curtain walls are also likely to be more dependent on mechanical ventilation than a more extended building form, perhaps with atria or courtyards, utilizing shallow bays for daylighting and operable windows for natural ventilation. (See **Fig. 5.**) Centralized, compact forms have been generated by the pressures of high urban land costs, increasing building materials costs, business organizational requirements, and, in part, by overly simplistic energy conservation derivatives to minimize external envelope area.

Lighting quality

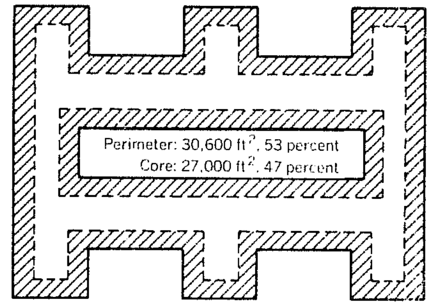
Beyond the energy related issues of daylighting, there are important qualitative issues to be addressed. The primary purpose of most lighting systems is to enhance visual performance while providing visual comfort. It is generally accepted that effective sidelighting provides less veiling reflection, improved contrast and thus greater visibility than equivalent footcandles from most overhead lighting systems. Problems of discomfort glare resulting from views of bright skies were mentioned earlier in this article and have not been adequately treated. Daylight, as a source of illumination, varies over time in a predictable manner (daily and seasonal cycles) as well as in unpredictable patterns due to cloud cover and other climatic variables. The variable nature of this source might appear to be an undesirable feature for indoor environments characterized by uniform temperature and uniform light levels. However, there is evidence to suggest that people value and even prefer the changes and variability introduced by daylight in a room over uniform lighting conditions. Daylighting from windows introduces modeling effects which, if carefully controlled, are often pleasing and desirable. Since the eye and brain evolved under daylight conditions, the color temperature is very pleasing and color rendering properties of daylight are excellent. Due to all of these positive qualitative aspects of daylight, it has frequently been suggested (but rarely put into practice) that workers with difficult visual tasks

[5] Daylighting perimeter zones for compact and extended building forms.

Perimeter zone is 15 ft deep



Compact building form
Total area: 57,600 ft^2



Extended building form
Total area: 57,600 ft^2

be placed in closer proximity to windows. Not surprisingly, the status related role of windows wins out nearly every time over visual performance and energy conservation.

Summing up

Which design professionals are responsible to see that daylighting is considered in new buildings? The architect sees the whole picture but lacks the specific skills to effectively compare lighting and thermal tradeoffs of window design options. The HVAC engineer computes window thermal loads, plans and sizes pipes and ducts, and asks only for the installed lighting watts per square foot. The lighting designer and/or electrical engineer considers the windows only as walls with low reflectance and may see the architect's design decisions and the client's budget as the key obstacle to good lighting design. There is clearly a need for better coordination and cooperation among the design professionals, better definition of their respective roles and additional education encompassing detailed daylighting design skills and techniques. There may also be a need for the "thermavision" professional proposed by J. W. Griffith, a design professional with an appropriate blend of skills in both thermal and illuminating design and engineering.

One explanation for the current situation is the lack of strong support from either the relevant professional societies or a vocal industrial base. The glazing industries and window and skylight manufacturers are reviving their interest in daylighting after having their markets threatened by overly simplistic, prescriptive building codes. The professional societies, while active at many levels in energy-related issues, do not appear to have sufficient membership or leadership interest in daylighting to support the skilled professionals in each organization who might be in a position to provide guidance and direction. The Department of Energy is expanding its "Energy-Efficient Windows and Lighting Program" to include support of projects aimed at removing the technical and institutional barriers which block widespread dissemination and utilization of daylighting practices. It is hoped that, with a relatively small initial effort, much of the nascent interest in daylighting can be activated and diffused throughout the design professions. We look forward to the time when daylighted buildings contribute on a routine basis to the dual goal of better working environments and substantial energy savings.

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