From Proceedings of the 3rd National Passive Solar Conference, published by American Section of the International Solar Energy Society, 205B McDowell Hall, University of Delaware, Newark, DE 19711.

LBL-8825
W-17

DAYLIGHTING AND PASSIVE SOLAR BUILDINGS

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ABSTRACT

As interest in the passive solar field shifts from small buildings to large structures, lighting systems will begin to receive more attention as a major energy consumer in commercial buildings. Among the options for reducing lighting energy consumption is the effective utilization of natural lighting through windows and skylights. Daylighting can provide substantial energy and cost savings, reduce building peak loads, increase task contrast and visibility, and improve overall lighting quality. However, there are many significant obstacles which must be addressed and resolved before these potential savings can be realized. Aspects of passive solar design which might either assist or impede the widespread utilization of daylighting are reviewed.

1.0 INTRODUCTION

Among the hundreds of papers presented at the last few solar and passive solar conferences, there has been little interest expressed in lighting and even less in daylighting. There are several apparent reasons for this situation. Energy requirements for heating and cooling dominate the building sector on a national scale, although lighting does account for 5% of total national energy consumption, roughly the equivalent in daily output of the Alaskan oil pipeline. A better explanation is that the focus of passive solar activity has been the residential sector and the role of lighting as energy consumer in that sector is minimal. As interest in the passive solar field extends to the commercial building sector, lighting becomes a significant building load, both directly and indirectly by virtue of its impact on cooling loads. Although the breakdown varies considerably by building type and location, in office buildings, approximately 50% of the building resource energy may be attributable to lighting. In newer buildings, as heating and cooling loads are reduced with the use of tighter building envelopes and improved HVAC design, lighting looms as the single largest energy consumer in the building.

There are four general approaches to reducing lighting energy consumption in buildings:

1. use of more efficient lighting systems and components
2. improved lighting design practices which eliminate wasteful energy use
3. improved system operation and maintenance
4. use of natural lighting design techniques and practices

Just as every solar home should contain a full array of cost effective energy conservation features, the first three recommendations above are well known, but effective, techniques and should be practiced at all times. The use of natural lighting is by no means a novel concept, but is experiencing a rebirth after a long period of dormancy.

In assessing the potential role of natural lighting in energy conserving structures and specifically passive solar buildings, two observations can be made. From one perspective the potential savings are enormous, and daylighting as a design strategy has the power to act as a major form and design determinant in the building. Not only are the energy savings potentially large, but peak power requirements may be reduced and lighting quality may be increased. Balancing this optimistic view is a long list of qualifiers and real obstacles which must be overcome before actual savings can be realized. Daylighting design, like passive solar design, is a complex multidisciplinary design problem. Most passive solar designers will do no better in producing a well daylit room than a lighting designer can do on a passive solar home. In both cases a grasp of the fundamentals is not sufficient to guarantee good design and performance. A detailed understanding of the important subtleties is necessary to achieve good results in both endeavors.

This paper reviews some of the general issues and subtleties that must be successfully addressed to incorporate good daylighting design in buildings. Although the current level of daylighting design activity is low, interest in daylighting is increasing at a rapid rate. It is hoped that this discussion of some of the pitfalls and potentials will accelerate this learning process.

2.0 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/sq.ft. 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% of household energy consumption. There is thus no strong financial incentive to conserve energy in the household lighting sector. Although 95% 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 square foot 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 down-play 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.

3.0 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.

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 15-20 feet 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. 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 30-40 feet. 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 non-trivial 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. South facing windows are most appropriate because the angular rate of change in sun elevation is less severe than on an east or west elevations. Thus, a south oriented passive solar building may lend itself well to this beam sunlighting system. A similar system has been developed and used to direct window solar gain to a ceiling thermal storage system in the MIT Solar 5 building.

Throughout the remainder of this paper, we limit the discussion to more conventional diffuse daylighting techniques only.

4.0 ISSUES

Although the potential energy savings are significant, effective daylighting requires the solution of a series of problems and issues which currently act as obstacles to widespread implementation. The use of large windows no more guarantees good daylighting than the use of south glazing guarantees effective passive solar heating. Four major issues must be confronted before daylighting practice can be widely implemented in this country. These are: 1) analysis and design techniques, and daylighting availability data, 2) thermal/illumination tradeoffs, 3) sun and glare control, and 4) lighting controls. In addition there is a set of other issues relating to daylight design which represents both opportunities and obstacles to widespread daylighting utilization.

4.1 ANALYSIS AND DESIGN

Ask a building designer today how to design a room to provide 50 footcandles on a desk throughout 80% 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 understood and used design methods in the United States today. Many design methods exist but most were originated in European countries where cloudy skies represent typical brightness conditions and have limited usefulness in much of the United States where clear sky conditions prevail. Primary sources of information for daylighting design in the U.S. are the IES Recommended Practices and a simplified design procedure based on the same "coefficient of utilization" approach.[2,3]

A variety of design methods are in use today, each with differing capabilities, and varying strengths and weaknesses. These include 1) computational, 2) graphical, 3) tabular, 4) nomographs, 5) protractors, 6) diagrammatic, such as sky vault projections, and 7) 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. Physical modeling techniques using scale models are not very useful for building thermal analysis but work very well for determining interior illumination. Models can be used outdoors or in a controlled artificial sky. Another fundamental problem is the lack of awareness and knowledge of these design methods by practicing professionals and in professional architectural and engineering schools. 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 dozens of examples of well designed passive solar buildings, but few if any buildings which focus on effective daylighting solutions to building design problems.

Having selected a daylighting design method, 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.

The collection of reliable solar radiation data has been an important part of the solar heating and cooling program and equivalent data must be generated for daylighting design. 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 radiation and illumination data simultaneously from thirteen sensors. This 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.

4.2 THERMAL/ILLUMINATION TRADEOFFS

Windows are essential elements in both passive solar as well as daylighting design. Building designs which have been optimized for daylighting use, will thus have an impact on passive solar performance. Maximizing passive solar gain favors south glazing but daylight is available at all building orientations. Daylighting is simplest where direct sun is excluded, in direct contradiction to requirements for many passive deisgns. This suggests that passive designs incorporating buffer zones such as greenhouse spaces or atria may be useful in separating the desired heat gain from the glare associated with direct sunlight. 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 including solar gain 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 be considered preliminary.[4,5] A similar, but simplified approach is available for predicting the annual performance of skylights in buildings.[6] 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. The availability in the near future of validated computer models incorporating passive solar effects and daylighting capabilities will have important implications for building designers who must now make decisions regarding window optimization, frequently without sufficient information. Requirements for compliance with a new set of building energy performance standards now under development will generate further pressure for an integrated thermal/illumination building energy analysis model that is user oriented and that has been properly validated.

The output from these daylighting computer models actually represents potential savings; the amount of daylight available in the building may be 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 a dimming mode, whether that control is automatic or manually operated, how user control of window shading devices effects daylight levels in the room, how the users will respond to solar gain and glare conditions of the room, or how control strategies to maximize winter solar gain will effect daylighting savings. At the present time, we do not have a comprehensive understanding of these issues nor do the computer programs have the computational ability to address 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.

4.3 SUN/GLARE CONTROL

A large array of sun control solutions is available to the building designer.[7] 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% of the incident energy. In many cases, the simplest 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 destroy both daylighting and passive heating potential in a building. In residential passive solar designs, clear glazing is almost always used to maximize desired solar gain. The nature and timing of internal loads in commercial buildings is such that heating requirements per square foot of floor space, particularly in an energy conserving building, are not high. A solution that provides high transmissivity with the capability of shifting to a solar rejection mode is desired. This is more important on east and west orientations used for daylighting, since solar control problems may exist year round. Solar control on a south orientation is more of a seasonal, than a daily problem; although in commercial buildings, transition seasons may present problems if the solar control devices are not sufficiently flexible. There will also be conditions when direct gain should be excluded to control glare but the associated solar heat is desirable. In these situations, heat absorbing, rather than reflecting materials would be useful.

Commercially available window management devices such as internal and external venetian blinds, drapes and roll-up shades and shutters all fulfill this requirement. Many of these come with motorized accessories which may be automatically or manually controlled. An extensive selection of manually operated devices is available, and these are normally less complex and less costly. However, there is some uncertainty regarding how faithfully manually operated devices 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.[8] 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 3,000 foot lamberts and typical brightness in an office may be 25-75 foot lamberts, severe discomfort glare problems may exist. So some degree of light control in glazing is probably desirable but it is unlikely that transmissions much lower than 50% will be desirable. This begins to present potential problems for buildings designed for passive solar gain. If sufficiently flexible window management options are not available, tradeoffs in the selection of glass shading coefficient must be made between passive solar and daylighting requirements.

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 is an effort to develop selective transmittance solar control coatings for windows.[9] These coatings would transmit the visible portion of the sun's spectrum while reflecting the short wave infrared. Selective absorptance glass is currently marketed with a high visible to total solar transmission ratio.

A more speculative approach to solar control in glass is the possibility of developing coatings which cause glass to act as an optical shutter, admitting light when it is desired and rejecting it when it is not wanted. In this concept, window management would occur at an atomic or molecular level. 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 and successful passive heating 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 daylit room, resultant cooling energy consumption may reduce or eliminate daylighting savings.[10]

4.4 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, simply by exercising control over both space and time. 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 daylit offices.

There is a tremendous range in control system performance, complexity and cost. The simplest such system is the common on-off switch. 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 multi-level ballasts. The latter options, although involving more expensive switching and control systems provide effective multi-level 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. 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. Multi-level 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 Department of Energy development and demonstration program.[11] They should begin appearing on the market in the next one to three years. 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. It should be noted that controls problems in skvlit rooms or offices are considerably simpler than the complexities of controlling side-lit offices.

Given either a dimmable or on-off system, controls can be actuated either manually or automatically. Manual controls are flexible, combining sensitivity and judgement at their best, and 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 daylit 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. Total building energy savings will result from the interaction of available interior daylight levels in each zone with the characteristics of the lighting control system.

The selection of dimming versus on-off switching and controls will have a significant effect on the actual energy savings achieved in a given building. Recent work at the Building Research Establishment in England outlines a procedure for determining the daylighting savings with either dimming or on-off controls.[12,13] The calculations and results are based on daylight availability data from England and are not representative of U.S. climates. The results indicate, nevertheless, that there are substantial additional savings realizable from dimming control systems compared to on-off types. These results are not surprising if one considers the operation of a lighting control system. For example, assume that an interior illumination of 50 footcandles is desired. At some given time if daylight provides 40 footcandles the on-off system saves no energy, while an ideal dimming controller saves 80%. If the daylight level is 60 footcandles, both systems are off and save the same amount of energy.

The importance of selecting an appropriate interior design illumination level can be seen in Figure 1 . In this figure we plot 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 Daylight factor is the ratio of interior daylight illumination to external daylight from the sky on a horizontal surface. One concludes that even at high daylight factors there is typically some difference between the on-off and the dimmable system. But at low daylight factors 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 provide 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 Figure 1 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 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 gradient from the window towards the interior of the room 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. In this situation it may no longer be possible to orient desks properly with respect to the windows, and deep within the space, the daylight levels may be very low. 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. The impact of passive solar design concepts on space organization in buildings is unclear. Should it become a partial determinant of spatial organization, it will also impact daylighting design constraints.

4.5 ENERGY SAVINGS

It is instructive to examine the actual magnitude of savings that can be saved utilizing daylighting techniques on an energy or dollar per square foot basis. Electrical energy consumption for lighting is a function of installed watts per square foot and hours per year use. At 3 watts per square foot installed power (typical of current design) with 2500 hours per year of use we predict a consumption of 7.5 Kwhrs/ft^2/yr. From the previous section, we can see that savings of perhaps 10-75% are realizable with a well designed daylit system incorporating on-off or dimmable controls. We can thus save 1-6 kilowatt hours per square foot per year which has an economic value of \$.05 to \$.50 per square foot per year. 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 available today and projected for the future which will also reduce electrical consumption. A daylit system compared to a very efficient electrical lighting system may save the same percentage in energy but will result in a lower kilowatt hour value and therefore lower dollar savings. Task ambient lighting systems are now available that operate in the range of 1 to 1 1/2 watts per square foot installed power. Projecting the introduction of electronic ballasts, improved fluorescent lamps with higher efficacy, and smaller HID systems indoors with improved color rendition we can expect to see lighting systems indoors with efficiencies of 100 lumens per watt, roughly a 50% improvement over the typical 65 lumens per watt achieved now with conventional fluorescent systems. Improved lighting controls of a conventional nature as well as non-uniform lighting practice will further reduce electric energy consumption. With these changes lighting energy consumption could be reduced from 7 1/2 Kwhr/ft^2 to a level of 1 to 3 Kwhr/ft^2 per year. The savings of 1/2 to 2 Kwhr/ft^2 per year which we now achieve with daylighting is much less impressive than the original figures of 1 to 6 Kwhr/ft^2. 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 daylit buildings.

5.0 OTHER ISSUES

5.1 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 thus costs the commercial consumer in both energy and power and 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. Solar heated buildings in areas with winter utility peak demands are the subject of such rates, which may reduce net dollar savings if backup systems are not properly designed. The significance of peak power issues relative to energy savings can be seen in the example below:

Consider a typical all electric office building in which 30-50% of energy consumption results from lighting. Assume that 1/3 of the usable floor space is in the perimeter zone in close proximity to windows. The maximum potential daylighting savings is thus 1/3 of the 30-50%, or 10-15% of total energy. If 50% of the potential is actually achieved with dimming controls, then daylighting can save roughly 5-8% of total building energy consumption. Now examine the peak load problem. Under summer peak conditions, typical cooling loads amount to 5-10 watts/ft^2 of which perhaps 3 watts/ft^2 represents lighting. With a net COP of 3, the cooling power requirement is then 2 1/2 to 5 watts per ft^2. Under peak load conditions, if we turn the lights off in 1/3 of the building floor area in which daylighting is adequate, we have reduced the power consumption of the building by 1/3 times 3 watts/ft^2 or 1 watt/ft^2 average throughout the building. There is an additional saving of 1/2 watt/ft^2 resulting from a reduction of cooling power requirements. Under these circumstances 1 1/2 watts/ft^2 or roughly 10-20% 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 sq. ft. office with lighting at 3 watt/ft^2 thus requires an investment by the utility of $450.00 to $900.00 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 of new electrical power generating resources.

5.2 FAILURE TOLERANCE

Increased centralization of vital services frequently leads to increasingly disastrous results when those services are interrupted. Although electrical supply is exceptionally good in most parts of the United States, in recent years we have witnessed the effects of citywide, statewide, and regional power system failures. Daylighting as well as passive solar heating and cooling 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 appears to be important, but which is 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. If a typical worker occupies a 100 ft^2 space in a building, and works 250 days, per year he costs the company approximately $1.60/ft^2-day, or $.20/ft^2-hour. Lighting, at $.04/kwhr costs $.25 - .30/ft^2/yr. So resultant savings in productivity in a daylit 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 years worth of energy savings. A similar case could probably be made for a passive solar building with the capacity of providing thermal comfort through the duration of a power interruption.

5.3 BUILDING FORM

Energy conservation design manuals frequently suggest compact building forms to minimize skin area and reduce conductive losses. But 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. Two building designs with the same gross floor area can have a two-to-one difference in the relative fraction of perimeter floor area as shown in Figure 2 . Centralized, compact forms have been generated by the pressures of high urban land costs, increasing building materials costs, business organizational requirements and, in part, more recently, by prescriptive building codes designed to promote energy conservation. Interest in active and passive solar systems has focused attention on site design and building orientation, typically emphasizing southerly orientations. Interest in daylighting may shift attention back to north elevations, and add further complexity to the design process. Daylighting needs alone will not normally dictate overall building design but the interplay of these contradictory issues may force a reassessment of the historical trend to centralized buildings and mechanical systems. On a larger city scale, zoning ordinances and the whole field of urban planning were historically influenced by the desire for at least minimal access to daylight and sunlight. Solar enthusiasts have a renewed concern for the same issues and a renewed interest in daylighting may assist in refocusing attention on the legal issues of the right of access to daylight and sunlight.

5.4 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 paper 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 previously 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.

Most passive solar buildings involve some degree of temperature swing around the average space temperature but in well designed buildings these swings can be held largely within the thermal comfort range.

SUMMARY

There appear to be a number of sound reasons why daylighting practice should once again be routinely considered and incorporated into building design. Although interest appears to be increasing, the real level of activity remains disappointingly small. Energy conscious building design is still equated with insulation, delamping and solar heating systems. One could reasonably conclude that hardware oriented technical solutions are easier to implement than changes that are more design process oriented. The passive solar design community prides itself with rejecting mechanically complex solutions and selecting instead building design solutions which are more climatically responsive and appropriate. Although the focus of efforts to date has been small buildings and homes, there is increasing interest in applying what has been learned to larger, commercial sector buildings. The challenge confronting designers now is to shift attention from the task of providing heating to that of developing design solutions which minimize non-renewable energy for cooling and lighting. Lighting, and daylighting in particular, are relatively new disciplines for most passive solar building designers. Just as the design of passive solar heated homes has forced a breakdown of some of the traditional boundaries between architectural design and mechanical engineering, a renewed interest in daylighting will require that building design teams acquire additional expertise early in the conceptual design phase and continuing through formal design development to ensure that daylighting solutions are well conceived and integrated with other programmatic design constraints.

Many of the design issues that have been raised relative to daylighting are similar to issues that passive solar designers must face. Specific passive design solutions may be supportive of good daylighting or detrimental to it but in either case some design time must be spent addressing the fundamental issue before making specific design decisions. Both passive design and daylighting are strong building form determinants, even though the specific forms which evolve are not the same. Both require that considerable attention be paid to microclimatic effects and site conditions. It is instructive to consider the range of variables over which passive design and daylighting intersect, for this perspective may assist the building designer in making the necessary transition from a familiar to a less familiar one. Figures 3 and 4 below provide a brief list of potential "Matches" and "Mismatches" between requirements for successful passive solar design and effective daylighting. Several are specific, many are general and some are admittedly speculative in nature. But it is probable that the effort of considering each match or mismatch to determine its implications or suitability for a specific project is a useful introduction to the process of resolving some of the complexities of daylighting design. Despite the dearth of interest and activity in daylighting over the past 25 years, one is reminded that there is a body of daylighting expertise in the U.S. and overseas in books, journals, existing buildings, individuals and organizations.

It is strongly suggested that those new to this field acquaint themselves with current and past activities and results in order to accelerate the rate at which daylighting expertise can, once again, be diffused throughout the design professions. We look forward to the time when daylit buildings contribute on a routine basis to the dual goal of better working environments and substantial energy savings.

ACKNOWLEDGEMENT

Lawrence Berkeley Laboratory (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.

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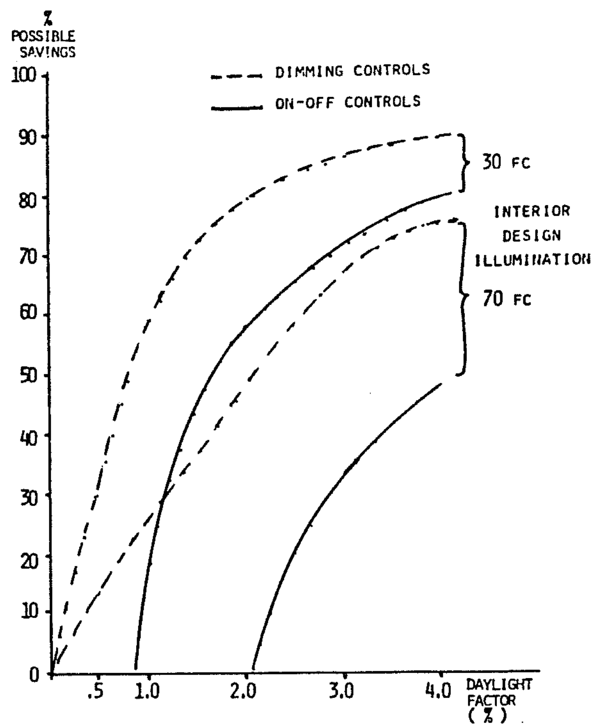

FIGURE 1: Daylighting Savings vs. Lighting Control Type (Calculated from data in Reference 13 and 14).

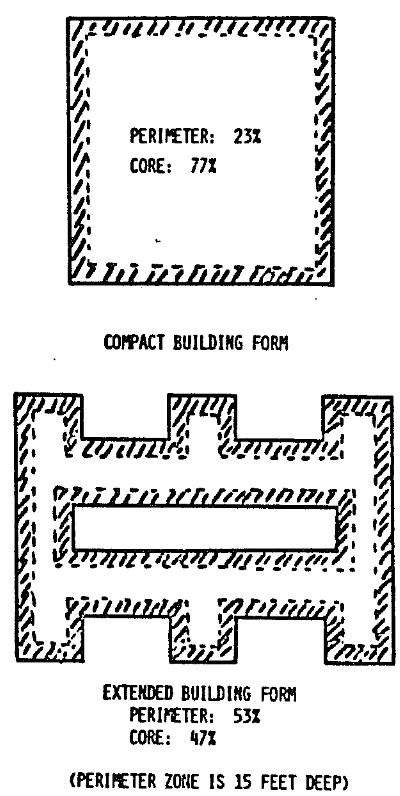

FIGURE 2: Perimeter daylit area vs. Building Form

"MATCHES"

- STRONG DESIGN FORM DETERMINANT
- MICROCLIMATE EFFECTS IMPORTANT
- VARIABLE HEAT / LIGHT SOURCE
  - TEMPERATURE SWINGS
  - LIGHT LEVEL VARIATION
- HEAT / LIGHT TRANSPORT
  - NATURAL CONVECTION/FAN AUGMENTED
  - INTERRELECTION/OPTICALLY AUGMENTED
- WINDOW REQUIREMENTS
  - SOLAR GAIN VS. NIGHT LOSS
  - DAYLIGHT VS. THERMAL LOSS/GAIN
- FLEXIBLE SUN CONTROL
  - PASSIVE - SEASONAL
  - DAYLIGHT - HOURLY
- THERMAL/VISUAL COMFORT
  - MEAN RADIANT TEMP. VS. AIR TEMP.
  - VISIBILITY VS. ILLUMINATION
- BACK UP SYSTEMS
  - CONTROLS/HEATING SYSTEM
  - CONTROLS/LIGHT FIXTURES

FIGURE 3: Passive Solar Characteristics vs. Daylighting Characteristics- matches

"MISMATCHES"

- BUILDING SECTOR FOCUS
  - RESIDENTIAL
  - COMMERCIAL
- TRANSIENT SENSITIVITY
  - DAILY/LONG TERM STORAGE
  - INSTANTANEOUS
- SOLAR GAIN IN THE BUILDING
  - DIRECT GAIN
  - DIFFUSE GAIN
- INTERIOR OPTICAL PROPERTIES
  - FAVORS ABSORBTANCE
  - FAVORS REFLECTIVITY
- ANNUAL BASIS
  - SEASONAL
  - YEAR ROUND
- SITE ORIENTATION
  - SOUTH BIAS
  - NORTH BIAS

FIGURE 4: Passive Solar Characteristics vs. Daylighting characteristics - mismatches